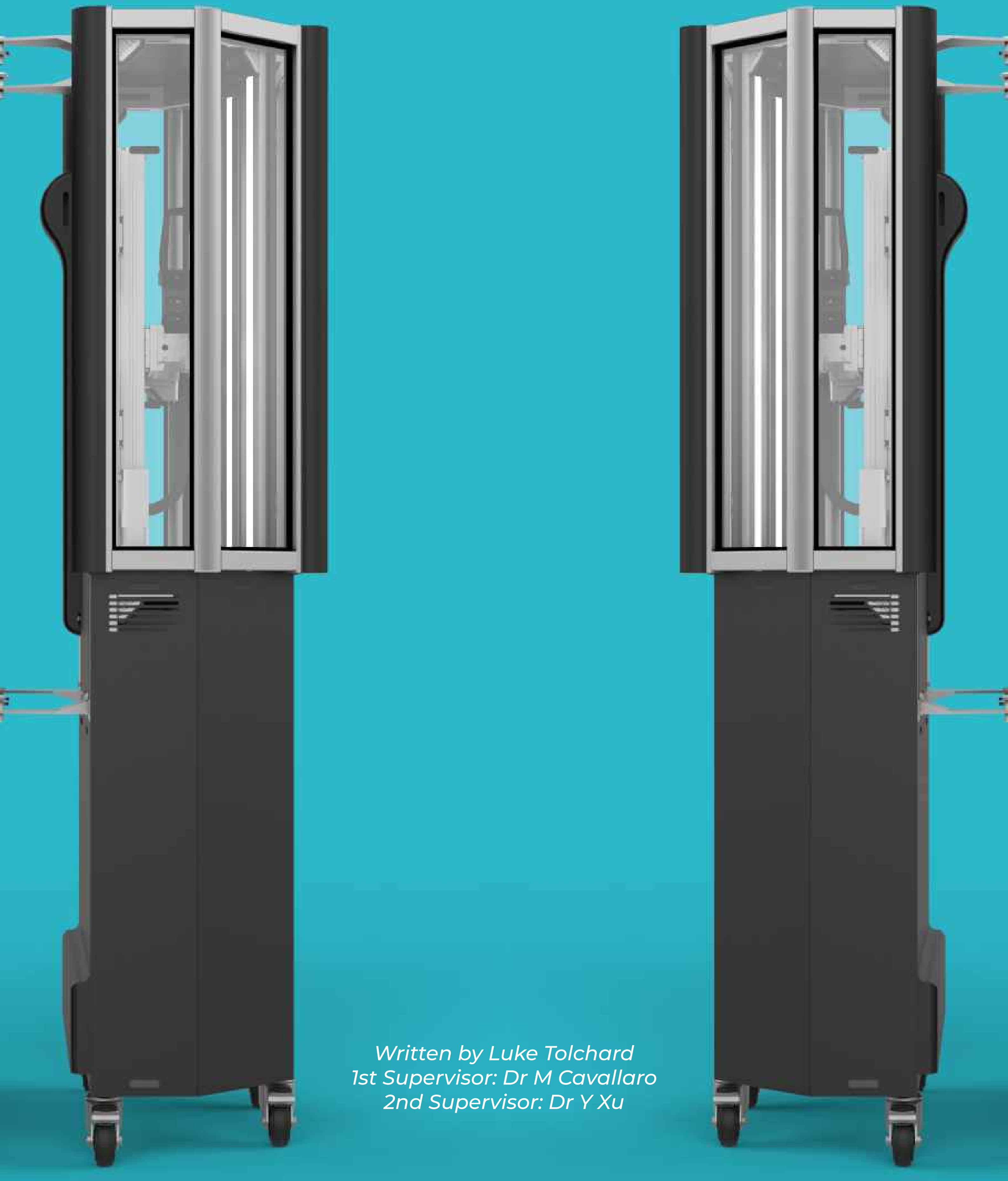
MANUFACTURING SYSTEM FOR 3D PRINTED PROSTHETICS



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IN COLLABORATION WITH

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ABSTRACT

Prosthetic manufacturing has seen advancements for upper limb amputees. However, there is a noticeable gap for innovations in prosthetic (socket) design for lower limb amputees (LLA) and the production methods that are currently implemented show reasoning for the lack of innovations within this area. The material requirements that are needed when 3D manufacturing an LLA socket have not been found yet and there are no dedicated production systems available for this unique task.

In this report, the current issues faced by amputees and those who deal with creating prosthetics is unveiled. The Author explores different avenues and thoroughly analyses what the current market possesses in regard to 3D manufacturing of prosthetics. Through design consideration and communicating with industry professionals, the iterative designing of the final product is shown within the report with detail about each design consideration and an explanation of why it is the ideal solution. As the Author gained additional knowledge throughout the project this evolved the final design into what it is now.

Keywords: 3D Printing, Amputee, Linear Actuator (LA), Liquid Additive Manufacturing (LAM), Lower Limb Amputee (LLA), Polar Architecture / Coordinates, Prosthetic, Shore Hardness, Sockets, Transtibial (TT)

Along the way, there has been so much assistance from a vast amount of individuals that it is impossible to thank them all. So to keep it brief the Author would like to thank his Supervisor, JS from Festo, Standa, and those who gave feedback at IRE. Without you, this project would not have been possible.

CONTENTS


(Zastrozhnov, n.d.)

01 INTRODUCTION

Most individuals that lose a lower limb will opt to have a prosthetic made for them. The process from start to finish is a long one filled with hundredths of steps, long waiting times, and costly procedures. Amputations are one of the most major surgeries undergone on a day-to-day basis. Every year more than 1-million amputations are performed (Access Prosthetics, 2017) with over 94% of amputations being of the lower limb (Pooja & Sangeeta, 2013). Those who suffer the loss of a limb can quickly slip into mental illness and develop health issues thus it is of the utmost importance for companies and medical professionals to get them, quite literally, back up on their feet.

Innovations within the field of prosthetic production have aided shorter manufacturing times and the surge in 3D scanning technology has aided professionals to produce prosthetics that are more custom to an individual. However, the manufacturing of prosthetics is widely unchanged, still being produced inhouse by a skilled prosthetist using plaster casting techniques. As medical professionals are saving more lives by performing amputations there will become a point when the supply of prosthetics cannot keep up with the demand and waiting times and cost will rise out of control.

Following this realisation, the author aim is to create a 3D manufacturing system capable of printing custom prosthetics within a day. Understanding that innovations are lacking with the manufacturing stage, the focus of this paper is to create an optimal solution. 3D printing has opened creative freedom and has developed into a disruptive technology in numerous industries. The 3D production of arms, hands, and fingers has truly seen a benefit; but the issues with lower limb prosthetics is that the mechanical requirements of the completed product must withstand much more than a 3D printed arm does. Unlike an arm, the prosthetic leg must cope with changing pressure and forces as an individual progress through their gait. As seen in Figure 1, only 30% of the average gait has both legs supporting the body. A leg goes through load and unloads phases and the prosthetic leg has uneven pressures moving throughout the step. Choosing the correct material to be deposited by an extruder to cope with the mechanical challenges that are possessed when walking has not been found yet. Thus, have always led to carbon fibre, which is expensive and time-consuming to work with.

Once a material has been found deciding upon the correct architecture system to use will have dramatic implications upon the final product. Ultimately, the choice will result in faster production and at lower costs whilst making a socket personal and comfortable to wear.

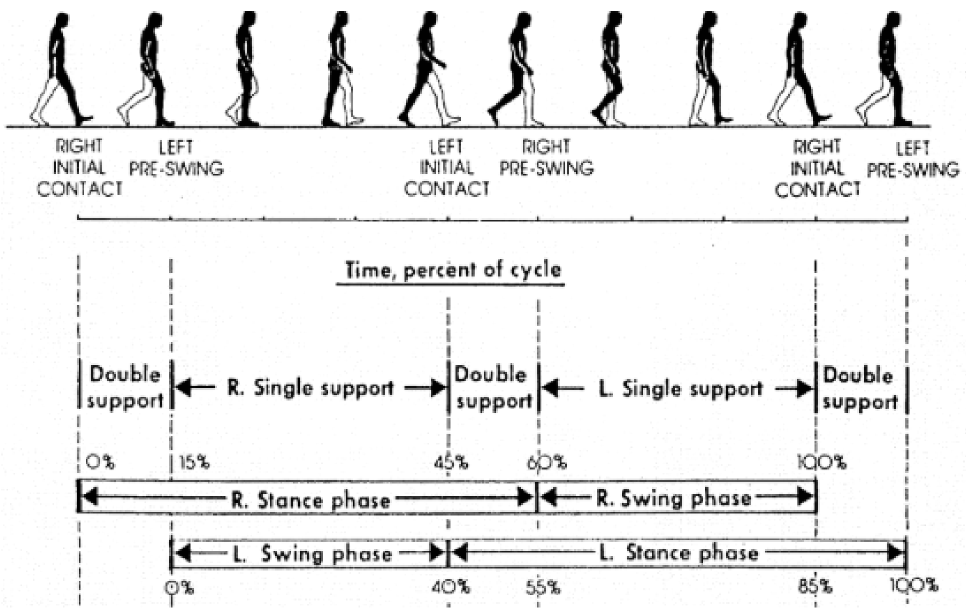


Figure 1: *Gait Analysis (DeLisa, 1998)*

PROJECT BRIEF

INCREASING COMFORT FOR TRANSTIBIAL AMPUTEES WITH IMPROVEMENTS TO PROSTHETIC DESIGN AND FUNCTION THROUGH 3D MANUFACTURING METHODS

TARGET MARKET

The author has created a product for the producer of the prosthetic socket as ultimately, they will gain value from the 3D printer. The company/organisation would also reap additional benefits, such as:

1. They would not have to pay for all the materials that are currently used during the creation of a prosthetic socket
2. They would be able to turn around more products, therefore, increasing income
3. The product will be less expensive
4. They can produce longer-lasting prosthetics which insurance companies would be willing to pay the full price for

MARKET GAP

Investigating what the market has to offer in terms of producing prosthetics, there is a noticeable shift towards 3D printing. The underlying issue with 3D printed prosthetics is that until recently there have been very few innovations in the material that makes getting a 3D printed lower limb prosthetic a feasible option. Chromatic 3D's FlexTune™ material makes for an ideal candidate to produce prosthetic sockets due to the excellent material properties merited by the thermoset polyurethane.

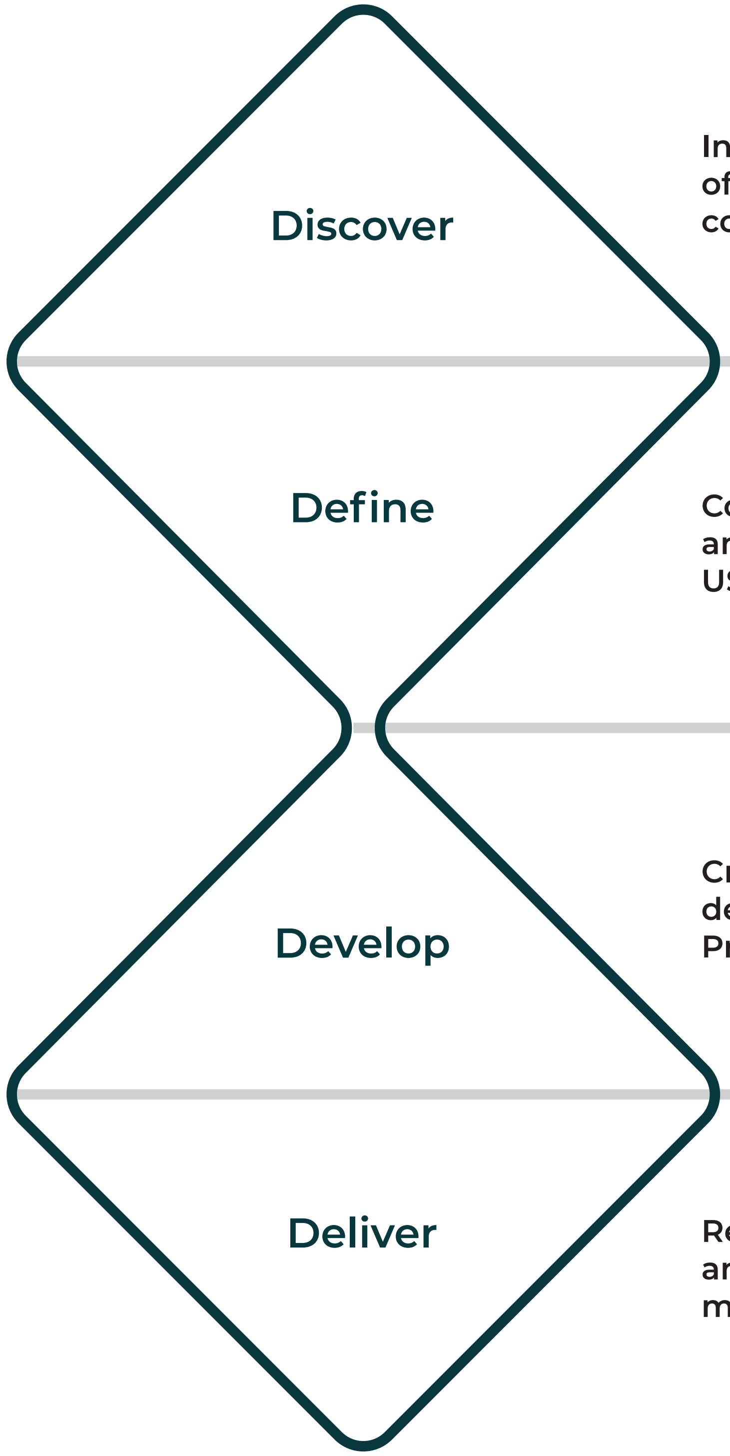
3D printing is the next frontier in all industries and is allowing for creative freedom in the medical industry. The current market is not suited for mass prosthetic manufacturing, making a clear opening for LAM 3D printing systems which use polar coordinates due to adventurous printing efficiency for cylindrical objects making 3D prosthetic production a realistic option. Furthermore, the combination of these different technologies would be a world-first.

PROJECT TIMELINE

The designer created a Gantt Chart in term one with the ideal progress of the design process. Due to unforeseen circumstances and a national emergency, the original timeline has been altered to better reflect the new ideal.
(See Appendix-1.0 and 1.1)

DESIGN METHODOLOGY

The Double Diamond design methodology was developed by the Design Council in 2002. This well-structured design process helps to keep the project on track. The Double Diamond allows for divergent and convergent thinking in a non-linear way. This creates a more structured design process where idea generation and definition can be better thought out.



Investigation into the topic of prostetic production and communication with industry experts

Converging on a topic area and defining what the USPs of the product are

Creating concepts and developing ideas through: Prototyping; Testing; and iteration

Refining the chosen product and delivering the final manufacturing device

Double Dimond - (Drew, n.d.)

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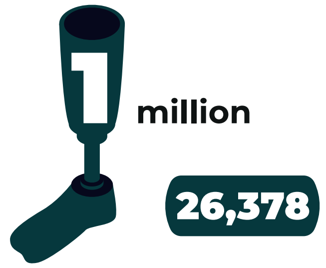
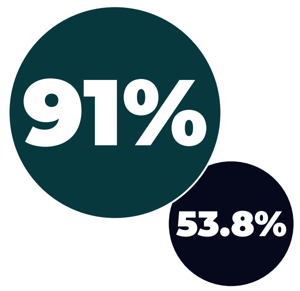
(Dimmock, n.d.)

02 THE PROBLEM

2.1 QUICK STATS



World *- 1-million yearly amputations*
UK *- 26,378 LLAs* in 2017*



91% of all amputations are lower limb
53.8% are Transtibial

Annually in the US, the healthcare systems spend $12b on amputees

Vascular disease is the leading cause of death for Lower limb amputees

30% of amputees suffer from depression and anxiety

Takes over 3-weeks to produce a single prosthetic for an LLA

Diabetics are 15 times more likely to get an LLA & die within 2-years

** LLA(s) - Lower Limb Amputation(s)*

(Access Prosthetics, 2017)

(Donnelly, 2019)

2.2 ANALYSIS OF THE SERVICE

Analysing the process of getting and producing a prosthetic has shown that there are many issues with the current service provided by all companies that deal with prosthetics and amputees. When an amputee is getting fitted for a prosthetic socket the procedure requires highly skilled individuals. In the paper, '*Lower Limb Prosthetics*', it goes on to mention. "*The increasing complexity involved in prosthetics technology and the development of unique materials, computer programs, and fabrication techniques/applicability require the specialized knowledge of the prosthetist. The American Board for Certification in Orthotics, Prosthetics & Pedorthics and the Board for Orthotic/Prosthetic Certification provide benchmark certification levels for competency in the field*" (Kapp & Miller, 2009).

Figure 2: *Timeline to be able to use a prosthetic (Prosthetic & Orthotic Care, n.d.)*

Using Figure 2 as the timeline for an average transtibial amputee, though, other variables can alter this timeline. "Usually, a prosthetic fitting begins two to six months after surgery" (Amputee Coalition, 2015). The fitting process takes one-quarter the time the healing process does. This would be down to the different methods and the high skill needed to produce a prosthetic.

The process of producing a socket varies slightly between companies but follows a similar pattern *(Figure 3 for images)*. This example uses P&O Care (Prosthetic & Orthotic Care, n.d.) :

1. First Assess the leg and don an elastic sock
2. make any necessary markings after further analysis on an additional layer
3. Record measurements
4. Apply an initial layer of plaster
5. Compress the limb by applying a vacuum sock and drawing out the air
6. Let the plaster dry
7. Wrap the compressed and hardened initial layer in more plaster
8. Let the final layers of plaster harden
9. Remove and check the cast

The process above is to produce just one mould which gets destroyed in the manufacturing of the socket demanding this step to repeat for the next test socket. With each test sockets comes another hundred-manhours to produce and test-fit the artefact. The current process is slow, time-consuming and at the expense of the amputee. The process of plaster casting an individual's leg is the chosen method by the majority of companies which is very invasive and can cause discomfort for the amputee. Those who have to endure this process have reported the irritation involved with this stage and unfortunately will likely undergo this process several times before getting their final socket.

For most amputees, a lot of physical changes occur after the amputation. In Christina's YouTube video she takes her audience through the process of getting a test socket. The process of test fitting a socket requires the amputee to go through many different prototypes before getting their final socket produced. Bryan Potok posted on a blog stating that it is normal for an amputee to require multiple visits to the prosthetist for test sockets (Potok, 2018). Kenney Orthopedics writes, "three to nine months of repetitive changes and alterations to this part of your body", regarding the amputated area (Kenney Orthopedics, n.d.).

Once the test socket has been confirmed the final stages of manufacturing involve carbon fibre being formed over, yet another, positive mould of the amputee's stump. This stage requires the largest portion of the prosthetists time as they need to pay close attention to the details of the product to ensure it is within specification.

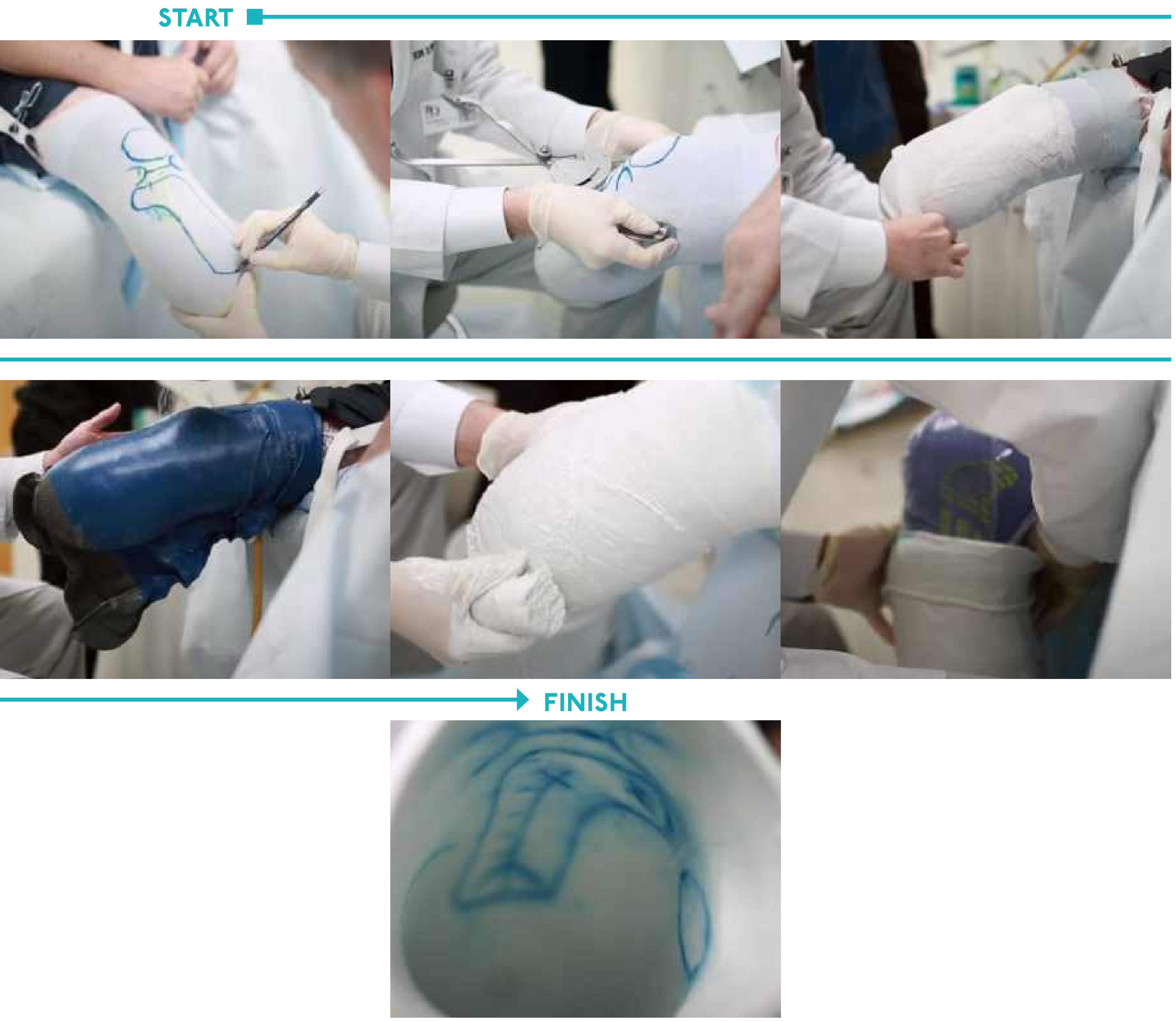


Figure 3: *Pictures of the casting process performed by P&O Care (Prosthetic & Orthotic Care, n.d.)*

2.3 CURRENT MANUFACTURING TECHNIQUES

Few companies have taken the time to invest in digital technologies when considering the manufacturing of prosthetic sockets. Ottobock is the only large-scale company found during research that has a digital process during any stage in the production cycle. Their Ipso Cast [Fig.4], a product for transtibial amputees', is used for digital scanning. This is accomplished simply using a handheld laser distance measurer. However, this innovation stops here.

Figure 4: *Ipso Cast for TT amputee (Ottobock, n.d.)*

Once the stump has been scanned it then requires the prosthetist to CNC the amputated area out of plaster which requires further modification. Arguably, this process takes longer on average than a traditional plaster cast as the 3D model needs to get physically produced.

The next stage that follows the plaster model, no matter which process used to get to this stage, is the same. The prosthetist will form (for the final socket) several layers of carbon fibre (CF) over the model after making adjustments to the positive. As soon as the curing and cooling process of the CF has ceased it requires further modifications and touch-ups to ensure the product is fit for the user.

There are companies out there who have digitised the entire process. The most notable being ProsFit who use HP's MJF 4200. The machine is up to 10x faster than "*today's competing [3D printers]*" as claimed by HP. An e-mail with Gergana, from ProsFit, confirmed that they are using powder-based 3D printing to produce prosthetics [Appendix-2] and print using Nylon or Polypropylene. Out of all the companies researched, ProsFit is the only business that has also produced a software [Fig.5] for a 3D scanned limb to be edited in (to which an .STL file is sent to ProsFit for further analysis before printing).

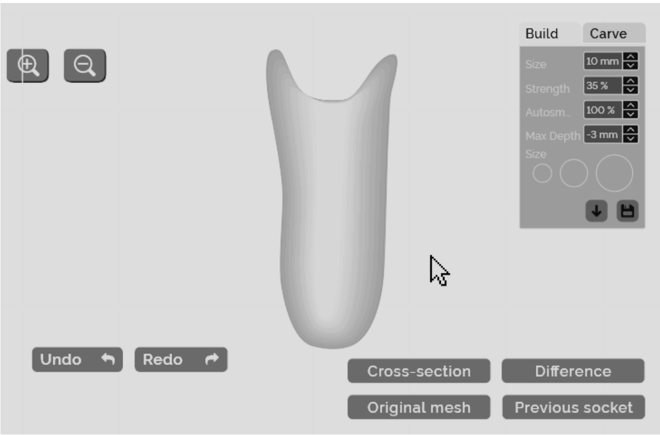


Figure 5: *PandoFit Cloud (ProsFit, n.d.) (Edited image)*

The solution of 3D printing a socket has evolved separately in different companies suggesting that there will be a future where it is the chosen manufacturing method. Though current solutions, as hard as they try, do not provide the correct material or manufacturing properties to make 3D printed prosthetic sockets a feasible option.

2.4 NO PROGRESSION

Seeing someone with a prosthetic may look like the advancement of medical science, however, the widespread way that modern prosthetics are produced has remained the same since the late twentieth-century. Since then prosthetists were creating prosthetic sockets using plaster casting techniques. Although the process has matured it is insulting to see that the process has not progressed away from this.

At the start of the century, the technical know-how, experience, and software (CAD/CAM) have been available for engineers and medical professionals to produce effective 3D manufactured prosthetic sockets. A 3D printer named 'Squirt Shape™' [Fig.6] (Prosthetic Design Inc., 2018) has been around since the early two-thousands able to 3D print transtibial sockets but no notable evolution has occurred from this. Even in the short video provided by PDI, it shows the capability of 3D manufacturing as the printer produces a socket within a day.

Figure 6: *Squirt Shape™ (Prosthetic Design Inc., 2018)*

As a civilization capable of reproducing organs by 3D printing, somehow the industry has skipped over 3D printed prosthetic sockets. The drive for socket manufacturing advancement is absent and it is likely due to a 'Good Enough' solution already accessible by amputees'. A good enough solution is not acceptable in this day-and-age; being able to send men and women into space but not able to create a customisable prosthetic socket is intolerable.

While there are some companies out there which are experimenting with the idea of 3D printing prosthetic sockets, the majority of the time it leans towards research rather than a solution. For instance, In the testing laboratory of TriFusion Devices and Essentium, Kathleen Hawkins, a BBC reporter, tests out the advancement in FFF 3D printed prosthetics (BBC Click, 2016). They use microwaves to weld layers of a 3D printed product together which in theory are as strong as injection moulded components. They are tackling the issue of delamination by using this process but when Kathleen tests out the product, unfortunately, one socket did not fit correctly and the other snapped by the end of the two-minute test [Fig.7].

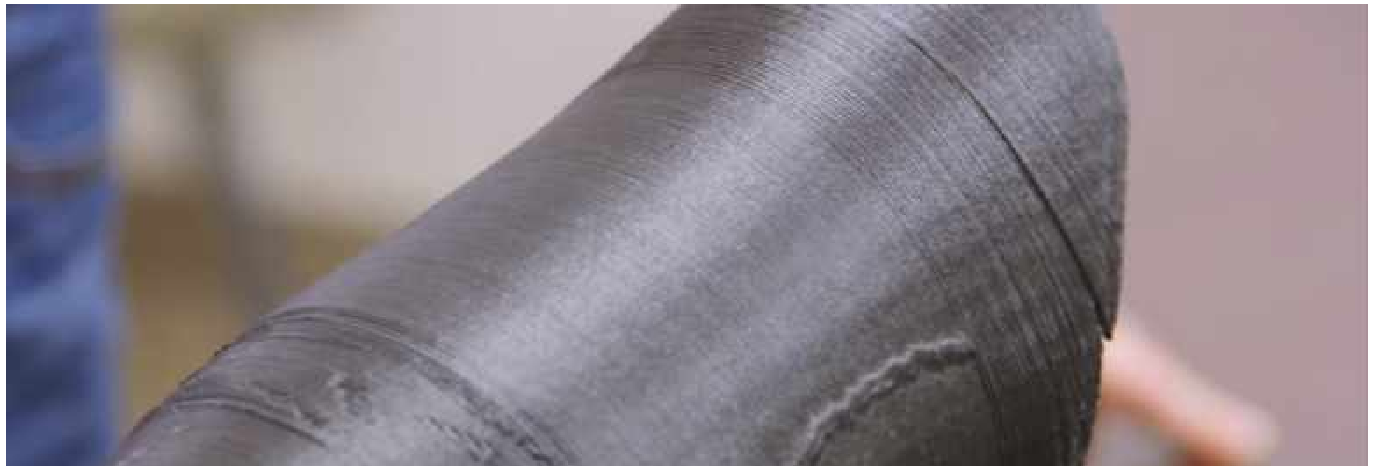


Figure 7: *Image of the delaminated (left) prosthetic socket (BBC Click, 2016)*

2.5 MARKET STAGNATION

The use of 3D printing when it comes to lower limb prosthetics are perhaps the best public lie. When a company claims to have a 3D printed prosthetic the usual example is as shown in Figure 8 where the prosthetic has been traditionally made and an ornamental 3D printed cover is used. The idea of a 3D printed prosthetic leg has not progressed much outside of decoration. Companies like ProsFit are trying to make this a reality but lack the correct manufacturing and materials to effectively change this process.

Figure 8: *Decorative 3D printed shell (ALL3DP, 2019)*

Another reason for stagnation is due to the medical staff that advise the amputee on what to get. As there are no 3D manufactured sockets that have truly proven themselves to medical professionals, they are not willing to risk the patient the financial blow or likely injury when the socket is susceptible to breaking.

Innovations in the field of 3D manufacturing are not focused on producing prosthetics, what focus there is has ultimately disregarded lower limb prosthetics, creating a large void to explore. It is important to note that the 3D manufacturing of upper limb prosthetics is progressing faster than ever. In 2018 the most expensive and ground-breaking prosthetic was produced for Johnny Matheny [Fig.9]. An upper-limb prosthetic costing $120-million and funded by the US defence (Templin, 2018). Where legs are concerned there is focus on motorising the joints to mimic the ankle and knee to better simulate walking although not much can be said for the socket.

Figure 9: *$120-million prosthetic arm (Grobart, 2015)*

2.6 WHAT IS NEEDED

Digitising the process from start to finish would provide benefits to all parties involved in this process. Whether that is getting a better socket for less or not requiring the prosthetist to slave over a single product for a week. Finding the correct solution to manufacture these artefacts is needed and would ultimately change the way prosthetics are produced in future.

Using 3D scanning along with 3D manufacturing would reduce the manhours needed to produce a custom prosthetic socket, theoretically having a socket ready within 24-hours (Tolchard, 2019). The radical improvement to production time that 3D printing can offer means that amputees can get to physiotherapy with their prosthetic within 3-months of amputation. The time it took to produce Hawkins's prosthetic was 7-hours. So, within a day from her scan, she had her prosthetic. Unfortunately, the prosthetic delaminated showing that the FFF lower limb prosthetics are unfeasible.

3D printing would assist in reducing the amount of time taken to produce a test and final socket for the amputee, meaning that they can start to live a normal life once again. Choosing the correct material to be deposited with the right mechanical properties will convince medical professionals that 3D printed sockets are viable. Not only would the production of the socket be quicker but having a digital scan of the amputee's stump would mean the company would never require the patient to have multiple visits to get their leg rescanned (unless major changes occurred).

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(ZMorph Multitool 3D Printer, n.d.)

03 CURRENT 3D PRODUCTION ISSUES

3.1 FUSED FILAMENT FABRICATION (FFF)

Though this method of manufacturing is greatly cheaper than other solutions its downfall is due to structurally inferior prints. The biggest issue faced with FFF printing is delamination [Fig.10]. In '*Embedding Sensors in FDM Plastic Parts During Additive Manufacturing*' the Author goes on to write in regards to delamination, "*These defects have an impact on the structural performance of the component and the consequences appear to be mostly related to dimensions, poor surface finishing of the part, structural and mechanical anisotropies, a decrease of mechanical properties, such as stiffness and strength, density and continuity between adjacent layers and between matrix and reinforcements*" (Sbriglia, et al., 2016). This exact issue was found when Hawkins tested out the FFF printed prosthetic sockets.

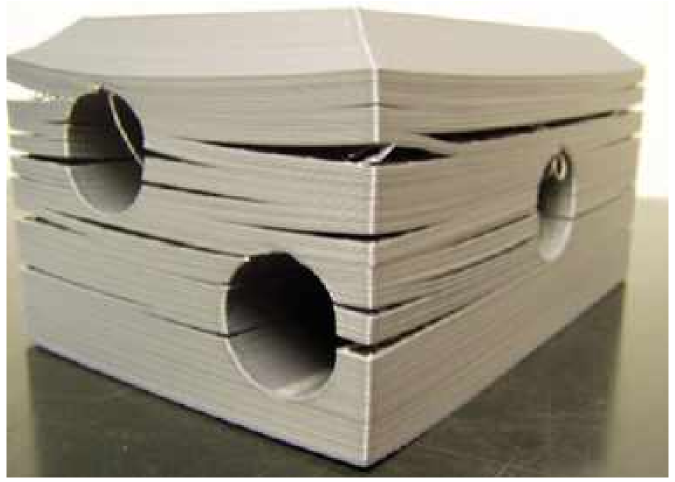


Figure 10: *FFF delamination (Sbriglia, et al., 2016)*

Moreover, the use of plastic FDM printing in the conventional sense is flawed. The plastic filament must be deposited in layers and then the fusion of each layer is dependent on the extrusion nozzle compressing the new layer on top and partially melting the prior layer. Delamination occurs when layers are not properly fused.

3.2 MULTI JET FUSION (MJF)

To make MJF printing a feasible, cost-efficient solution, the print volume must be filled up with as many products as possible. MJF suffers from, once a print has finished, you are required to dispose of the excess material as it has either been contaminated or, for other reasons. Moreover, the machines are considerably larger than FDM printers. Though this approach of producing components is less prone to delamination, this can still occurs due to nonuniform stresses built up during the print [Fig.11] which leads onto failures and is a reason why additional treatment is needed once the product has been printed.

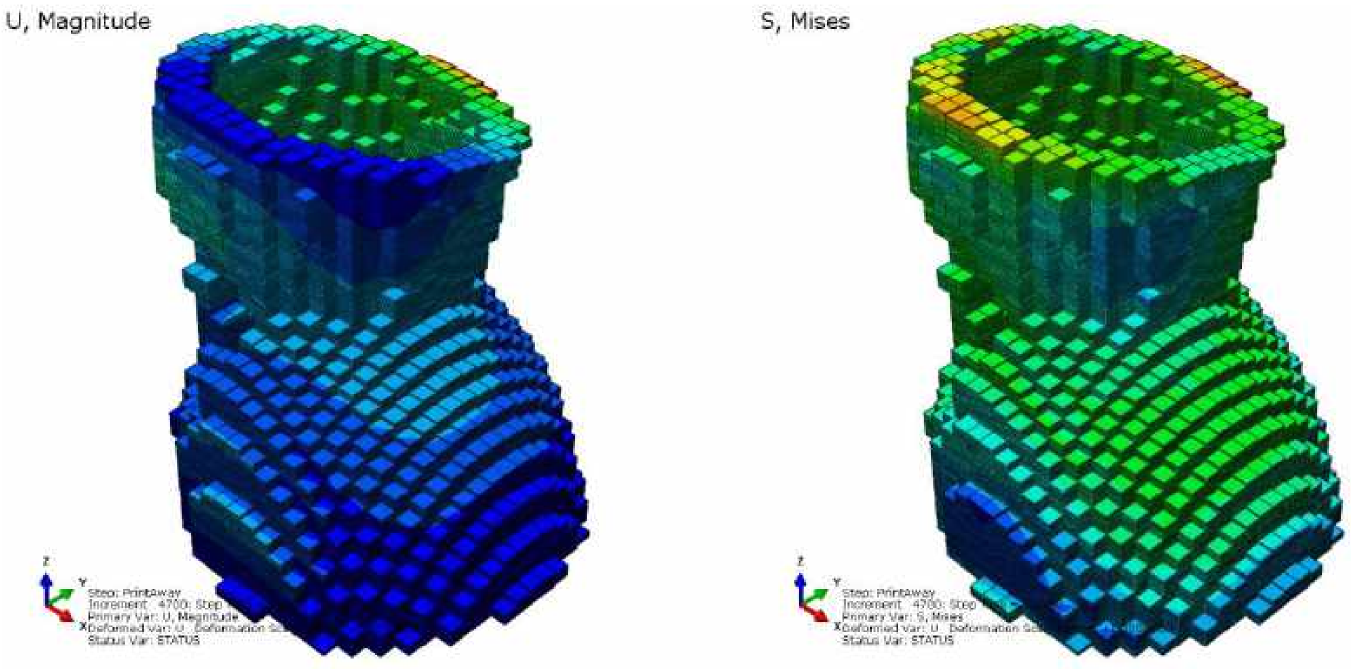


Figure 11: *Displacement and residual stress result at the end of the print using a fine voxel mesh model (Fradl, et al., 2017)*

3.3 SELECTIVE LASER SINTERING (SLS)

SLS ultimately suffers from the same problems as MJF. Moreover, the machines are vastly larger than common market 3D printers. As an example, in 3D Distributed's YouTube video on the Renishaw RenAM 500M (3D Distributed, 2019), though not specified anywhere the machine is comparable to the height and depth of a refrigerator whilst being three-times as wide. The size of the machine does not reflect it's print volume, at a maximum of 18,750 cm3. Furthermore, like MJF you are required to fill the print bed with artefacts to make it cost-effective. Once the print has concluded most the residual powder is unable to be used leading to waste (but can be recycled).

In the YouTube video of the RenAM 500M the sales agent from Renishaw states, "95% of parts coming off [the machine] is going to want some form of post-processing. But most of the time it is going to want traditional machining". If a socket was to be made from this machine it would be so vastly expensive, time-consuming, and impractical no-one would consider manufacturing one for the mass market.

3.4 UNDERLYING ISSUES WITH ALL PROCESSES

No matter which processing type is chosen there is one issue that is threaded through each manufacturing process. Seen here in Figure 12 the way around adding flexibility for a socket is by reducing the wall thickness. This is poor design consideration as this can lead to stress concentrations or fractures within the thinned area. To make a socket forgiving in areas should not require the amputee to face potential harm.

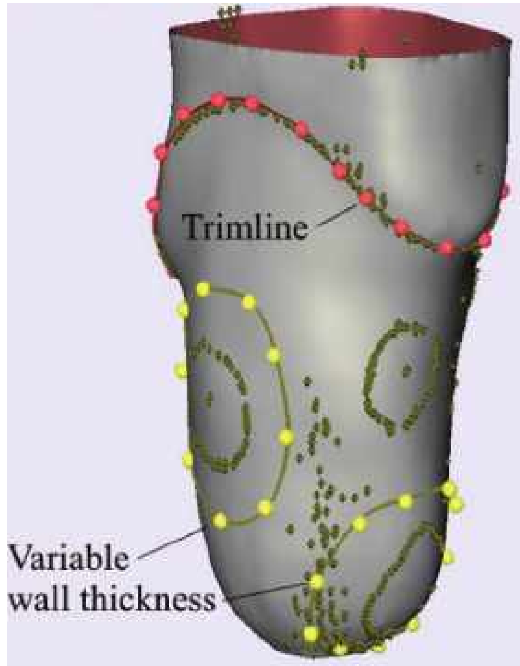


Figure 12: *Variable wall thickness (Rogers, et al., 2007)*

Another overarching complication is the material these processes use. PLA, nylon, and metal provide a single shore hardness throughout the print which is the reason designers alter wall thickness to mimic different shore hardness. You cannot manufacture a socket out of metal, for instance, to be flexible in the traditional sense which leads design alterations, not reconsidering the material used. A multi-shore hardness product is necessary to increase comfort for LLA's who heavily rely on their socket(s). LLA's will often take off their prosthetic due to irritation or another form of pain (mild or irritating), this is common to see from an amputee named Jo. On her YouTube channel (Footless Jo, n.d.) she frequently takes off her prosthetic as it (at least in early videos) began to cause problems for her. She has had several new sockets produced for her since starting YouTube all providing slight fixes to increase comfort but all are made of carbon fibre which has a single shore hardness.

The only process capable of a multi-shore hardness print is FFF. These printers use two or more extruders with different materials being fed into each one. This can provide a multi-shore print, but does not solve the problem of delamination and is deemed worse as the materials are not able to bond successfully and, therefore, artefacts break/delaminate frequently.

It is concluded that both current material and manufacturing solutions are inferior when printing prosthetics sockets for LLA's. Understanding there is a need for multi-shore hardness sockets ultimately relies upon the material that is deposited. Current production techniques are unable to suffice the needs of a socket and thus have always led back to carbon fibre.


(Rader, n.d.)

04 POSSIBLE SOLUTION

4.1 WHY POPULARISED ARCHITECTURES ARE NOT VIABLE

There are two popularised architectures on the market, Cartesian and Delta. In terms of prosthetic production, most printers are based on the cartesian architecture where there are linear actuators (LA) in the XY-axis (horizontal) and Z-axis (vertical). Regarding the German RepRap (GRR) L320, the linear motion systems are provided by Bosch Rexroth in a cartesian set-up. The XY-axis moves the ViscoTec ViscoDuo-FDD 4/4 LAM deposition head and the Z-axis moves the print bed (Appendix-3 for further detail).

Concerning the size of the machine, the cartesian and delta systems require a vast amount of space for a relatively small print volume. Though delta printers excel in hight their printing accuracy towards the edge of the print area diminishes. Cartesian, on the other hand, fail to effectively print in height which prosthetic sockets are characterised by.

When a cartesian or delta printer prints a cylindrical artefact, it is required to 'step' or 'zig-zag'. This motion slows down the speed at which the part is produced. This problem is a noted article on the Soliforum where there is a thread of people complaining about the speed reduction when printing cylindrical objects and trying to come up with ways to improve this (HestonKent, 2014). Polar, on the contrary, does not suffer from this problem as it is able to accommodate these features by rotary printing.

4.2 WHY POLAR IS THE CORRECT SOLUTION

Looking at the profile views of a prosthetic socket [Fig.13] the shape is similar to a cylinder. Polar 3D printers deposit material on to a rotating platform which yields greater accuracy and efficiency for cylindrical artefacts. Furthermore, something that no other printer can compare to is the print volume for the size of the machine. As an example of this, Polar 3D has created a small, 10lbs, desktop printer capable of printing 26,358 cm3 within a platform less than 30 x 20 x 30cm (Baguley, 2015).

This architecture system would yield greater production advantages as well. Polar 3D printers commonly have a smaller form factor, not being as tall as Delta and taking up less floor space than Cartesian printers.



Figure 13: *Different views of a transtibial socket (Physiopedia, 2020)*

4.3 WHAT MATERIAL IS NEEDED?

GRR has the L320 [Fig.14] in their arsenal which uses DOW SILASTIC™ 3D 3335 Liquid Silicone Rubber (LSR) [Fig.15]. With this material, GRR produce orthotics for shoe insoles and several other soft-products. After each layer, it is required to cure by passing over the print with a '*high-temperature halogen lamp*'. The use of the lamp makes the product less eco-friendly and reduces the speed advantage that the L320 has over other print techniques. The material itself is only rated at Shore A 44 and 46 (The Dow Chemical Company, 2018) not making it suitable for prosthetics. Hidden away in the specification sheet, it takes *over 4-hours for the finished print to cure properly*. Whatever production time benefits this material brings it is completely negated by the cure time and passing phases.
Example: 3-hour print + 4-hour cure = 7-hours total.

Figure 14: *German RepRap L320 (German RepRap, n.d.)*

Liquid deposition or LAM poses significant advantages compared to other material production types. Delamination is completely negated as that layers of material are chemically bonded/fused creating one structure.

Figure 15: *German RepRap L320 liquid storage tanks (German RepRap, n.d.)*

Chromatic 3D (C3D), a company powered by DSM, have developed a thermoset polyurethane (PUR) called FlexTune™. This material designed for LAM has the material specifications required to print for prosthetic sockets. Examining patents published by Cora Leibig (CEO of C3D) the properties of this material depends upon the mixture's ratio of Polyol and Isocyanate. Under Claim 17: The shore hardness ratio can vary from Shore A hardness of 20 to 120 and a Shore D hardness 30 to 120. *(Appendix-4 for hardness comparison)*. What this material can provide is a very rigid structure and allow for areas of increased flexibility without reducing the wall thickness. This will increase the comfort based upon the amputee's needs. Whereas before in Figure 10 flexibility was achieved by varying wall thickness, using C3D's material would offer more compliance/finetuning of the area without sacrificing the structural integrity of the socket.

This material would further increase the speed at which an artefact can get produced. (Leibig, 2019), In section [00151] it states, that as soon as the previous layer has reached a gel state the next layer can be printed on top. [00153 b.] states, that if there is more catalyst then the Gel Time is reduced as there is now a higher reaction rate. In section [00154] the 'Gel Time' depends on the surrounding temperature (Tolchard, 2019). This has the value that it cannot be delaminated as the layers are chemically bonded together, unlike the other 3D printing techniques in 3.1 - 3.3. Moreover, the part comes off the print bed ready for use, Leibig states, the cured PUR product is smooth to the touch which is a benefit of LAM deposition and therefore would be ready to use straight away


(Navigator LinkedIn Sales, n.d.)


(ELEVATE, n.d.)

05

THE BENEFITS

5.1 CUSTOMISABLE

A product that can match the exact needs of a user would have tremendous advantages over the competition. The use of 3D scanning followed by LAM would produce a socket that fits the user precisely. Moreover, customisation by utilising the unique properties merited by FlexTune™ is, therefore, possible to manufacture a socket to have relief points, or, to provide added rigidity to support the amputee which would yield higher confidence when using the product. To address the needs of comfort is demonstrated beforehand; the possibility to create a product with so many levels of finetuning for amputees has never been seen before.

5.2 LONGER LASTING

As mentioned in 4.3, the material, unlike other additive manufacturing techniques, chemically bonds to the previous layer creating a solid, isotropic, artefact which mitigates fatigue. The One Shot Socket created by Blatchford, as an example, has been estimated to have a warranty period of 36-months (Tolchard, 2019). Coincidently, other carbon fibre (CF) products such as carbon road bikes have a similar warren period, just stretching over 2-years. This suggests a theory that carbon products, though strong, are brittle and manufacturing a socket out of CF is more to do with weight-saving than longevity. Amputee coalition clearly states that prosthetic legs "*last an average of three years*" (Amputee Coalition, 2015). FlexTune™ would be able to solve this problem as the socket can be designed with longevity as a core feature.

5.3 MAKING A LESS EXPENSIVE PRODUCT

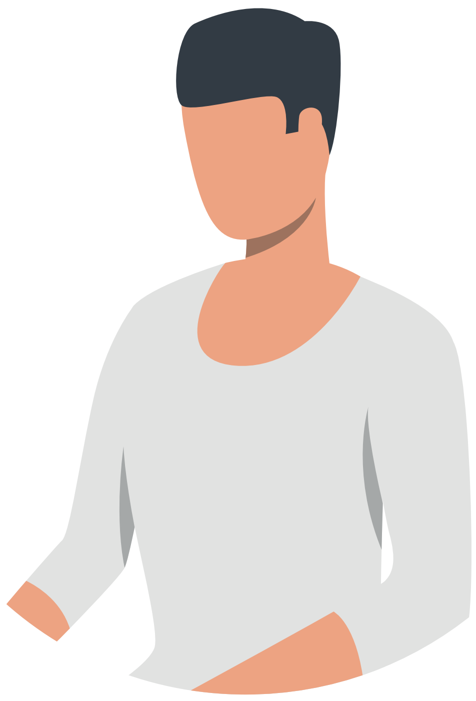
Creating a less expensive product has several benefits which are further covered in 5.6. Producing a socket from CF requires so many steps, different processes, manhours, and resources that simply deciding to use this material increases the cost of the end-product.

Using FlexTune™ as the chosen material for the socket increases the product lifespan as the structurally superior socket is less prone fatigue. This means the customer is not required to purchase a new prosthetic every 3-years. Jo (Footless Jo) also mentions in, "*10 MORE Things I WISH Someone Said BEFORE Amputation!*", about how expensive this process becomes and says, "*Losing a leg. It's not cheap!*" (Footless Jo, 2019).

The production methods used when 3D printing is significantly less expensive than working with CF, factoring in other costs like environmental consideration and damage when using CF, energy consumption during manufacture, manhours needed, and much more. Replacing the material and altering the production method of the sockets will save companies, and individuals, a substantial amount of money.

5.4 PERSONAS

Developing personas assist in the creation of the manufacturing system. This is because this method of real-fake people (based on research) helps to develop a need for a product. The personas are Customer and Professional, this will assist in getting a view from each side.



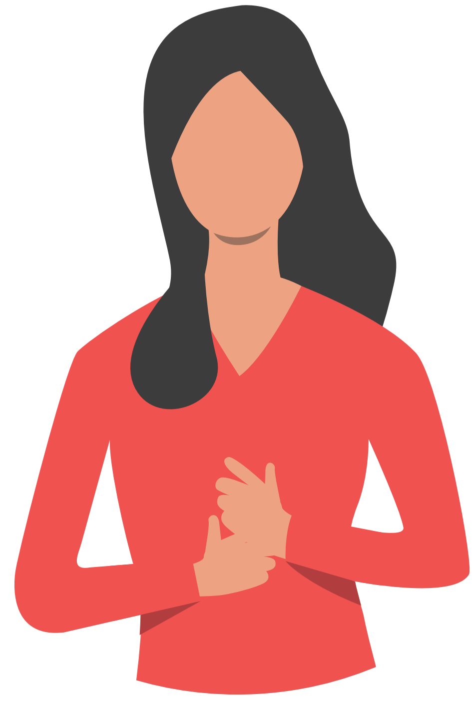
CARLO
PROSTHETIST

Carlo is a prosthetist of a large company that deals with a lot of amputees. He has worked there for the past 10-years and risen the ranks.

He is finding that the number of requests for prosthetics is beginning to overwhelm his division and having to postpone individuals to later dates.

In his workplace, there have been noticeable shifts to modernise the process of fitting prosthetics, especially for LLAs. However, prosthetic sockets production has vastly stayed the same and requires his team to work long hours to meet deadlines.

Even with this modernisation he and his colleagues are still time-restricted and cannot serve as many patients as they would like.



ANGELINA
TRANSTIBIAL AMPUTEE

Angelina is a recently made amputee following a lifesaving operation after a car accident 3-months back.

Her leg has healed suitably and is provided with the opportunity to get a prosthetic leg.

She wants to get back to her normal, active, life as soon as possible but waiting times are limiting how fast she can get her life back to normal. She is concerned about the physical change that occurs when she is not active.

Her insurance company has offered to cover some of the cost of the prosthetic and physio, but she is left with a dilemma. Get the prosthetic and risk financial hardship that comes with it, or, enquire for a wheelchair and save up money for over a year.

Edited - (FreePik, n.d.)

5.5 BENEFITS

The ‘Who’ for which this product would benefit is not linear. The company and amputee would benefit from this product. The shorter time is taken to get the amputees’ data and manufacture the socket, the cheaper the socket becomes as fewer manhours are needed (which makes up the largest portion of the overall cost). As the socket will be 3D printed it is guaranteed a perfect fit for the amputee within the first few attempts requiring fewer materials. Families that have had to go through the trauma of their child losing a limb would reap the financial benefit of cheaper production. The Jordan Thomas Foundation have given minimum and maximum costs for an 8-year-old amputee getting new prosthetics every 1.5 to 2-years until they are 18-years-old (Sharington, 2017).

Minimum burden on families: **$3,500 x 6 = $21,000**
Maximum burden on families: **$50,000 x 6 = $300,000**

From tackling one problem it solves many other issues. Being able to provide a perfect fitted socket for cheaper and in less time will:

- Organisations can serve more amputees as a result of shorter production times;
- Testing and fitting stages will progress quickly to the final socket;
- The amputee can start physiotherapy quicker;
- Insurance firms will save money on the socket and offer more towards rehabilitation costs;
- Financial advantages for families;
- Offer prosthetics to lower-income individuals/families;
- Longer-lasting prosthetics;
- Increased comfort due to higher personalisation;
- This product, though specialised towards prosthetic socket production for lower limb amputees, can have impacts for all prosthetic manufacturing and other industries such as Automotive; Space and Sciences; Soft Robotics; etc.

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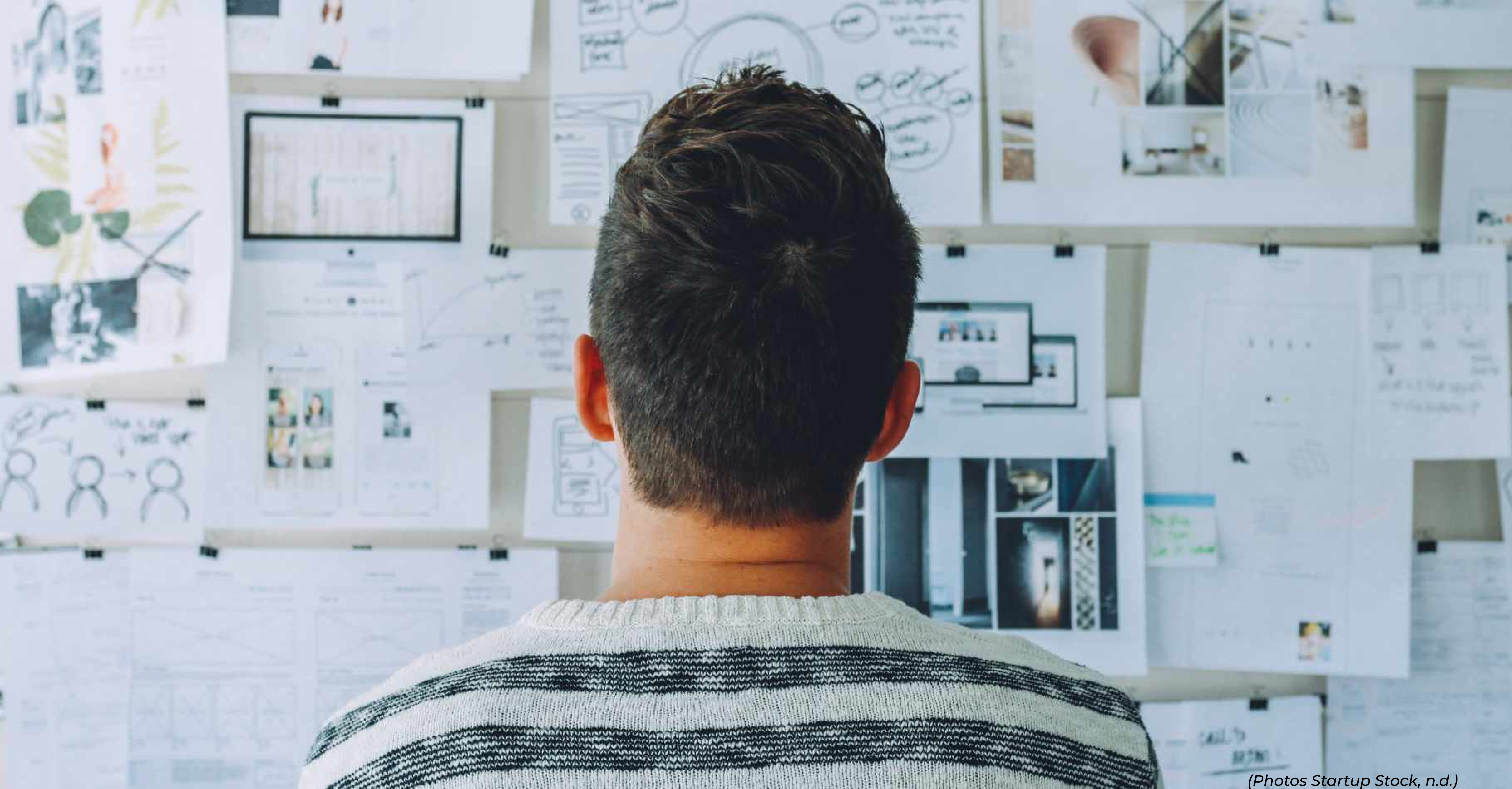


(Photos Startup Stock, n.d.)

06 IDEATION

6.1 PROTOTYPE - VERSION 1

Once a design direction was chosen the designing of the product could begin. To start the design process the product specification must be written. In the authors mid-term Interim Report under Appendix-11 [and in Appendix-14 of this report], an Initial Design Specification (IDS) has been written. This is what was used to design the initial physical and 3D models.

Following the IDS, the designer created 3D digital models. The first model created [Fig.16.1 - 16.4 & Appendix-10] was trying to generate a design idea for the print bed and base of the 3D printer would look like. The original design was to use a glide upon rails which were moved by a screw.

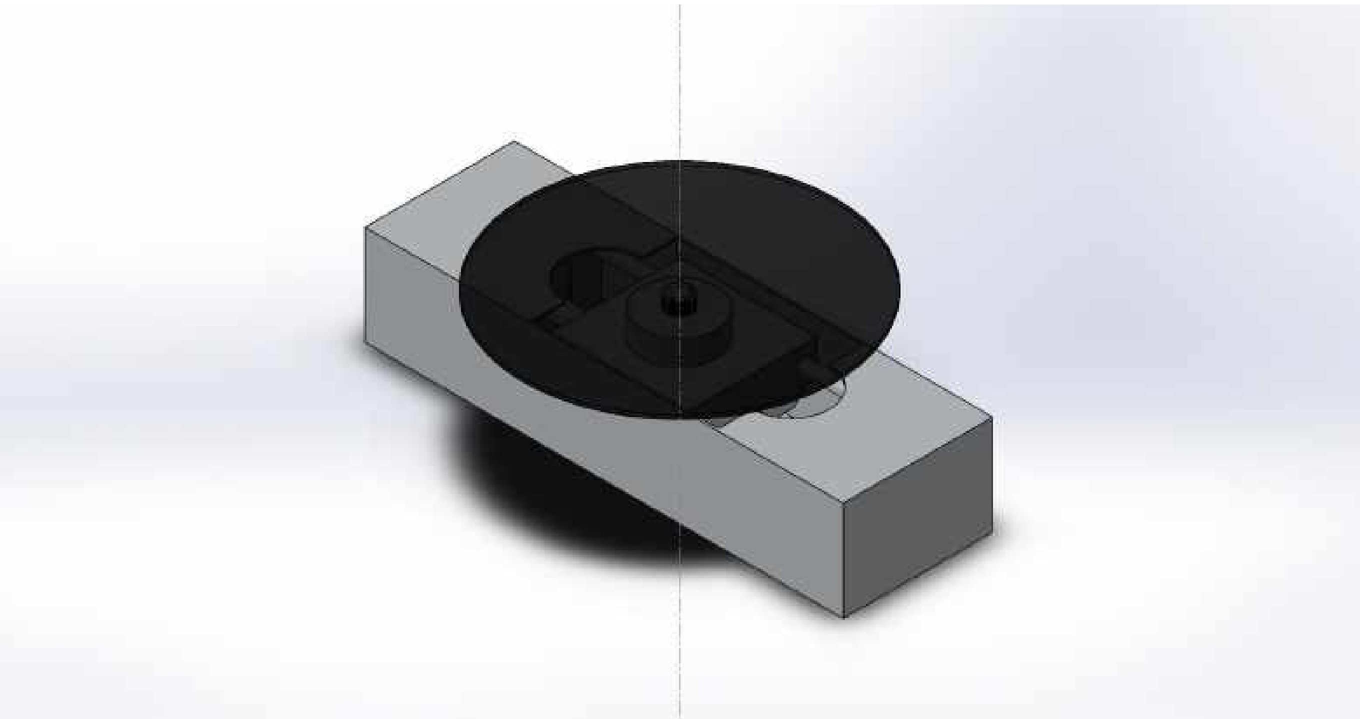


Figure 16.1: *Iso view of initial product print bed and base*

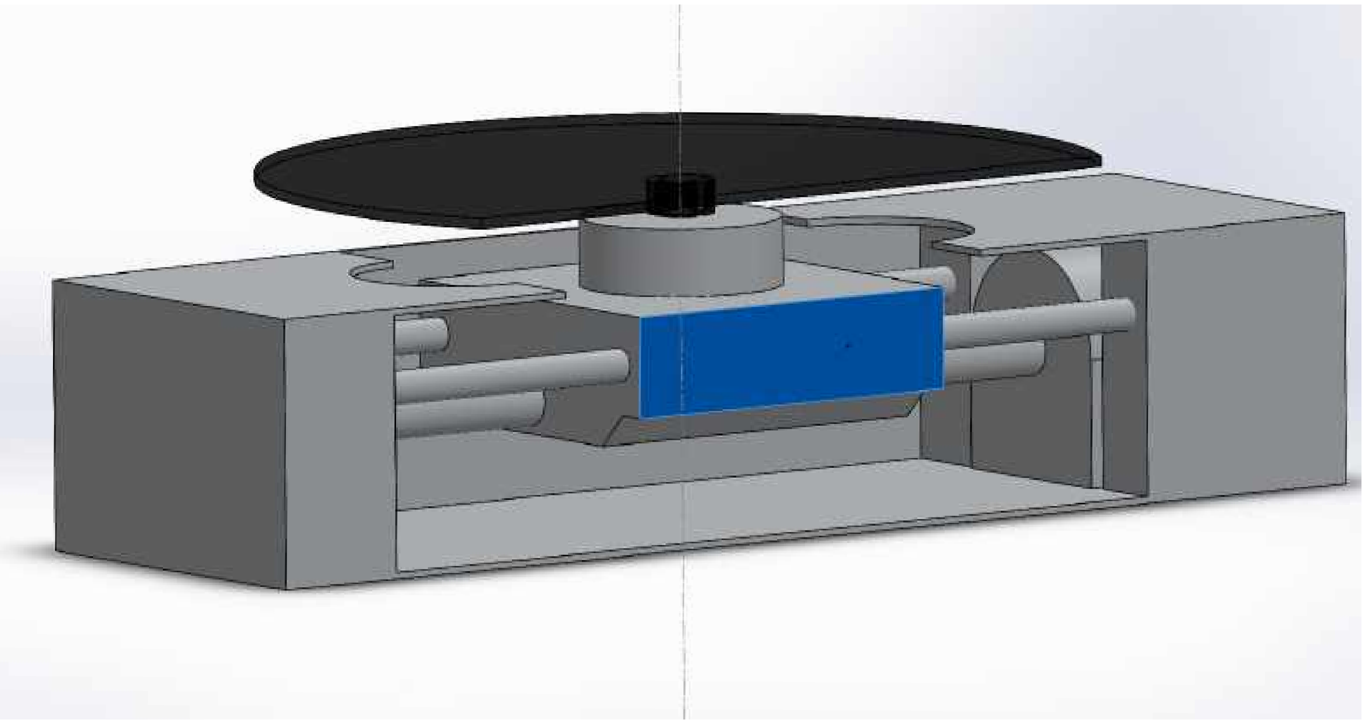


Figure 16.2: *Cut-away view of initial product print bed and base*

The Designer 3D Printed linear glides to discover what the best option would be for the movement of the print bed. Appendix-11 shows greater detail for considering LAs.

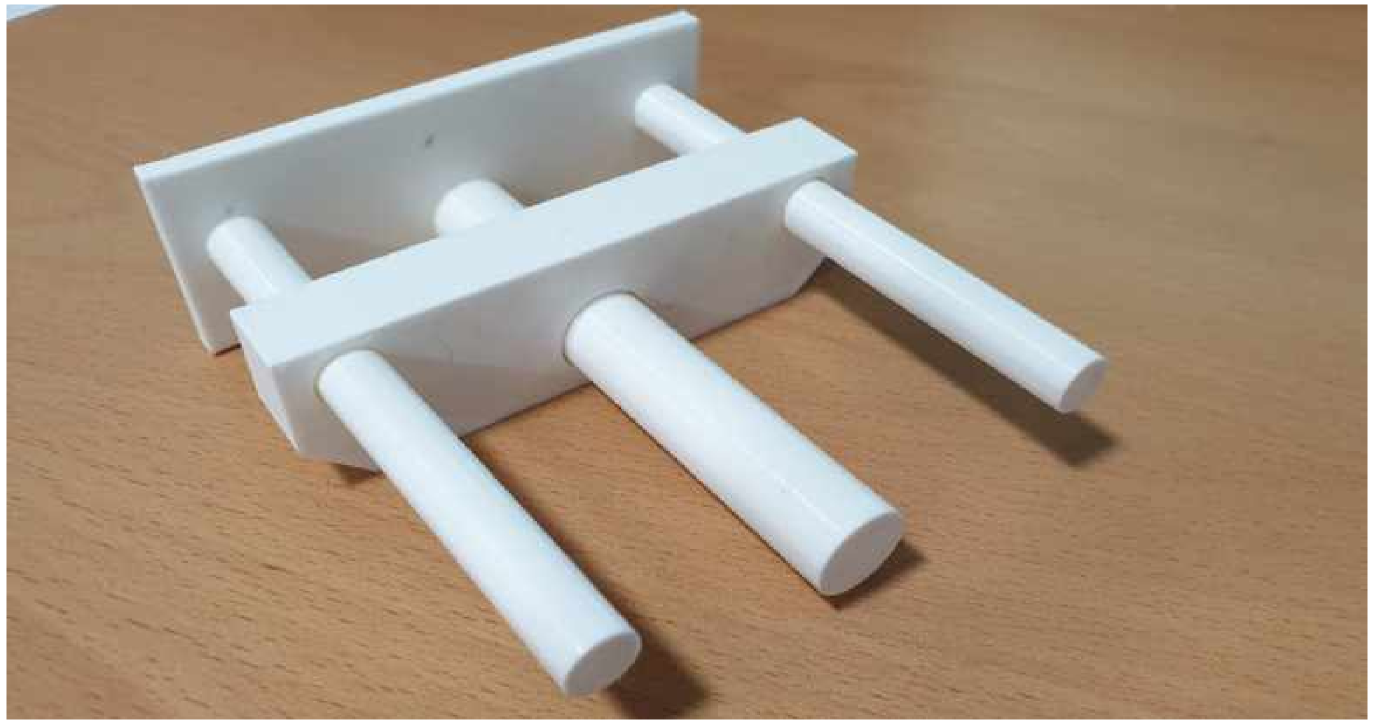


Figure 16.3: *Iso view of initial product print bed and base*

Figure 16.4: *Cut-away view of initial product print bed and base*

6.2 PROTOTYPE - VERSION 2

Moving onto a different design, this one was to take inspiration from GRR L320 [Fig.17] where the print bed moves vertically via the Bosch Rexroth CKR [Appendix-5]. The design complication here was that the COM (Centre of Mass) would be too far away from the axes. With the original design requiering the print bed to move in the ω-axis, X-axis, and Y-axis, this would have put too much mechanical strain on the one LA so the idea was scrapped.

Figure 17: *Underneath the GRR L320 print bed (Top 3D Shop, 2019)*

Figure 18 and Appendix-12 feature the shape optimisation timeline where the goal was to remove 40%< mass and a safety factor of 1.2 (this included a 6.5Kg mass on top).

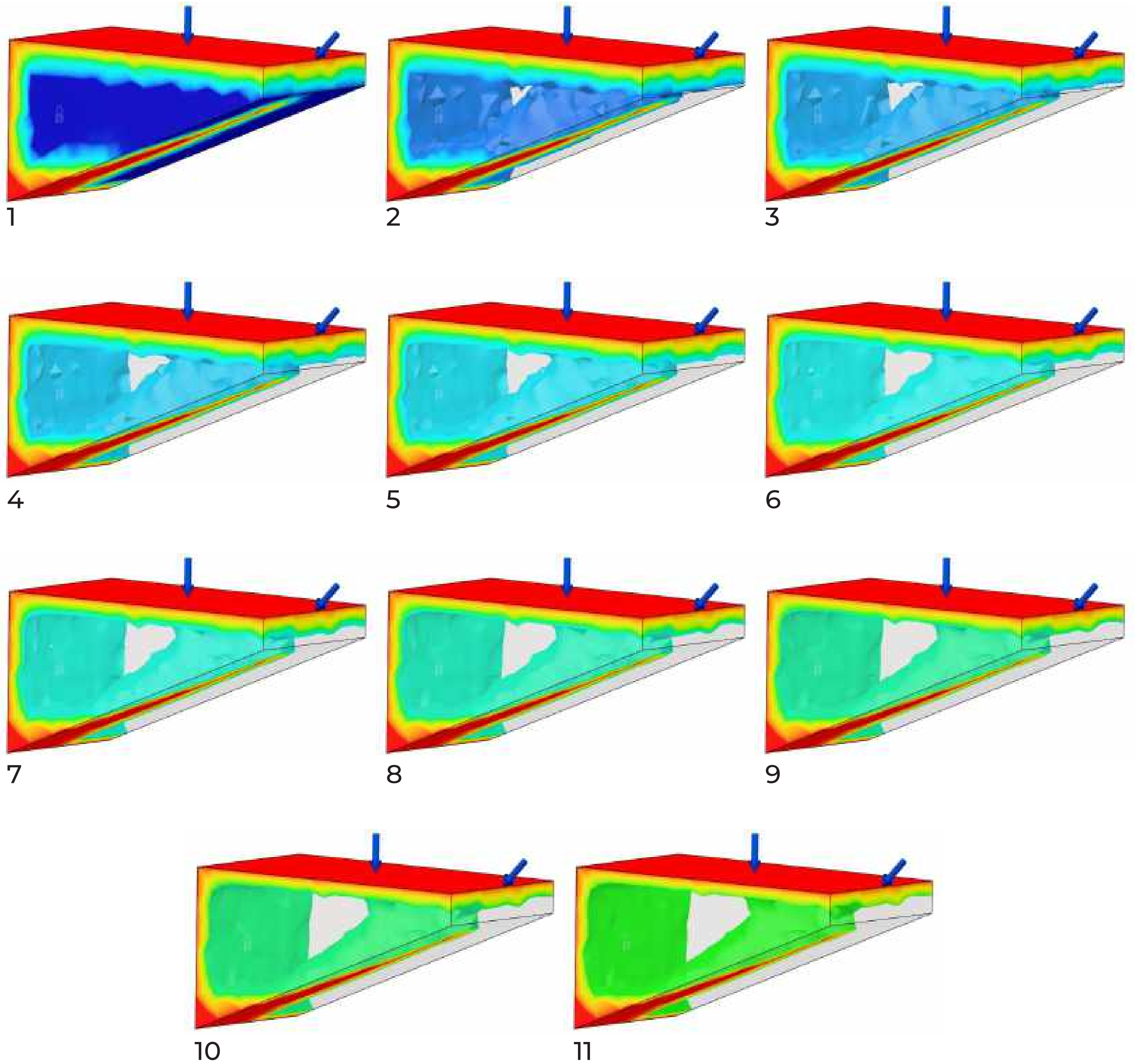
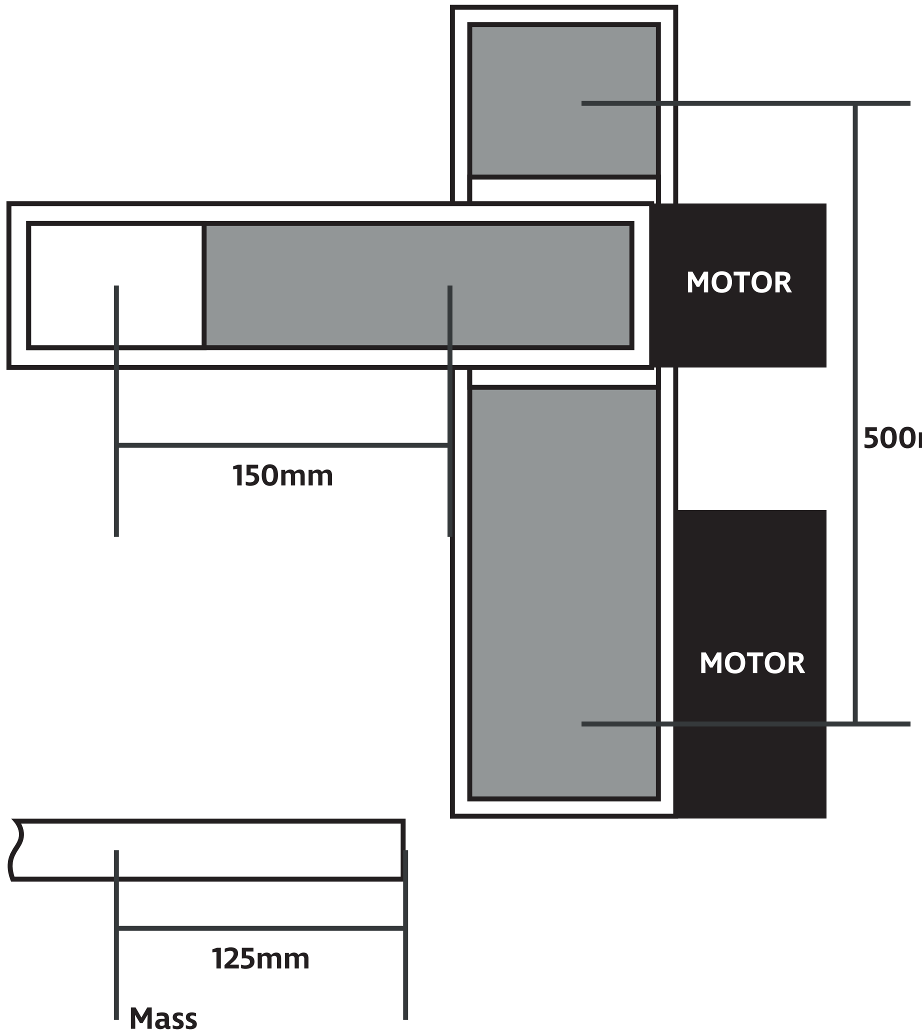


Figure 18: *Shape optimisation for print bed*

6.3 PROTOTYPE - VERSION 3

From discussing this current design approach with the Author's supervisor, it was determined that this product was going in the wrong direction. The goal for the designer was to focus on the overall form of the 3D printer. This was to include the component set up as seen in Figure 19.1.

Version 3 of the design incorporate a cantilever system where the extruder would move in the X and Z-axis and the print bed would be stationary and move in the ω-axis. *(It was later decided that this design approach was not the correct solution as the mass of the extruder would risk rotating the X-axis [Fig.19.2] which would have diminished printing result).*



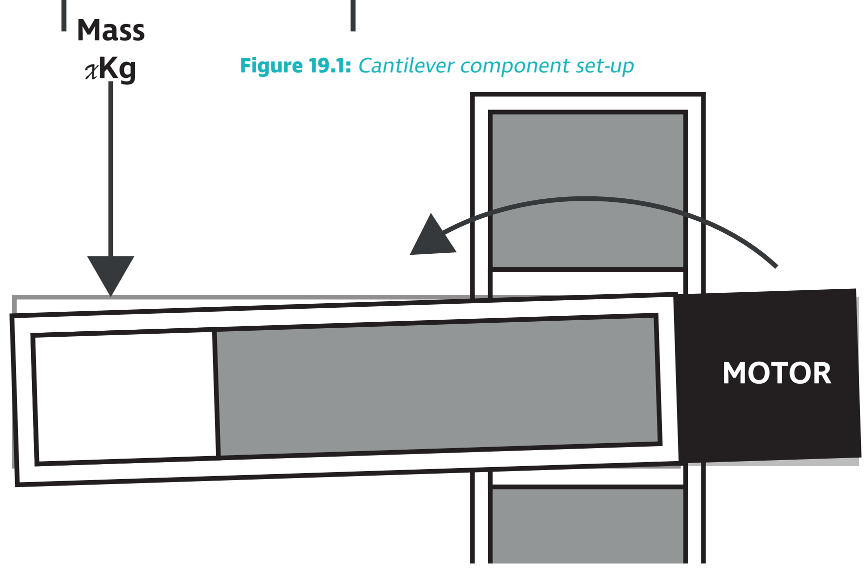


Figure 19.1: *Cantilever component set-up*

Figure 19.2: *X-axis rotating due to weight*

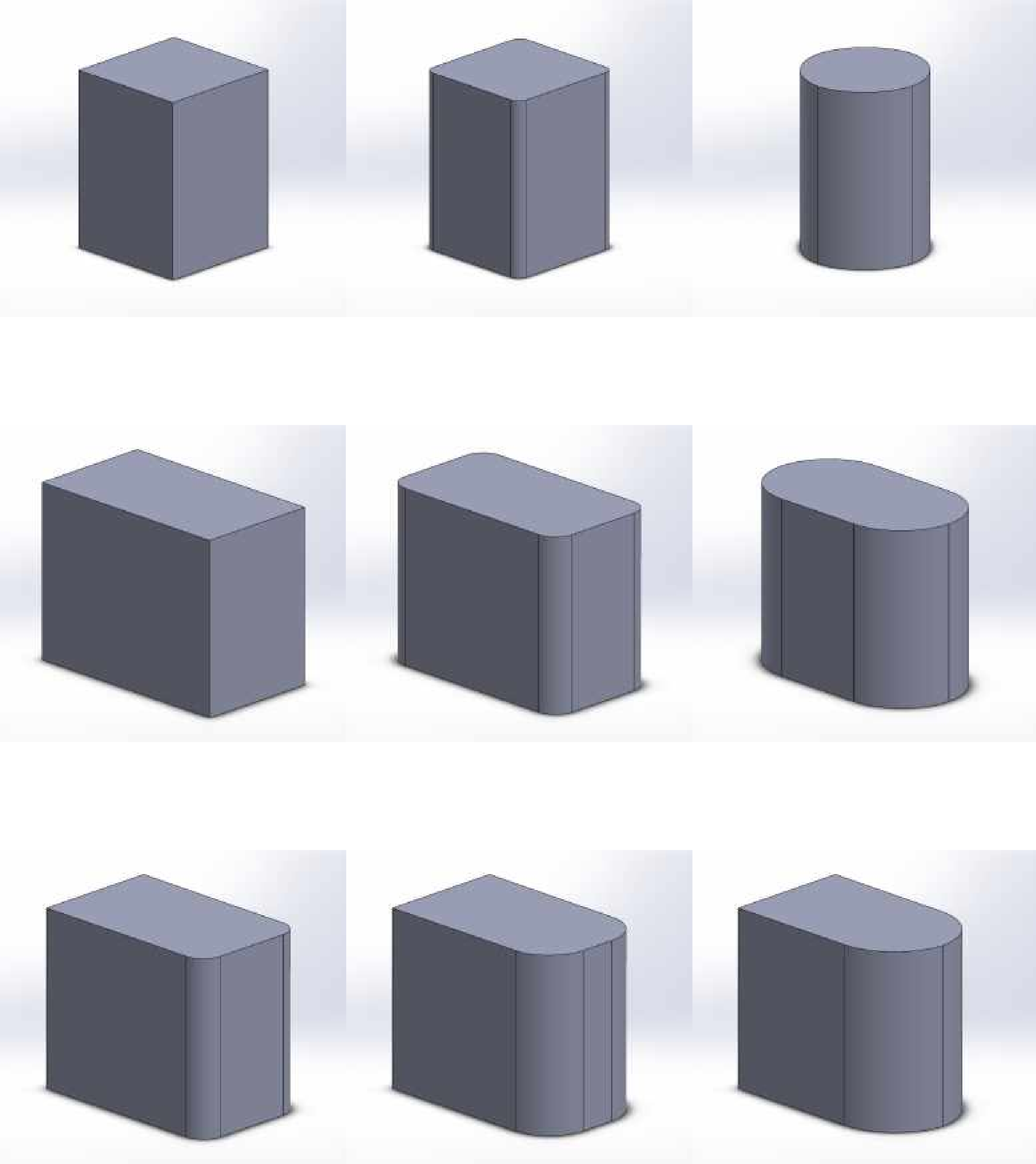


Figure 20.1: *Templates for form design*

Using several basic shapes [Fig.20.1] the following designs were created [Fig.20.2 - Fig.20.5].

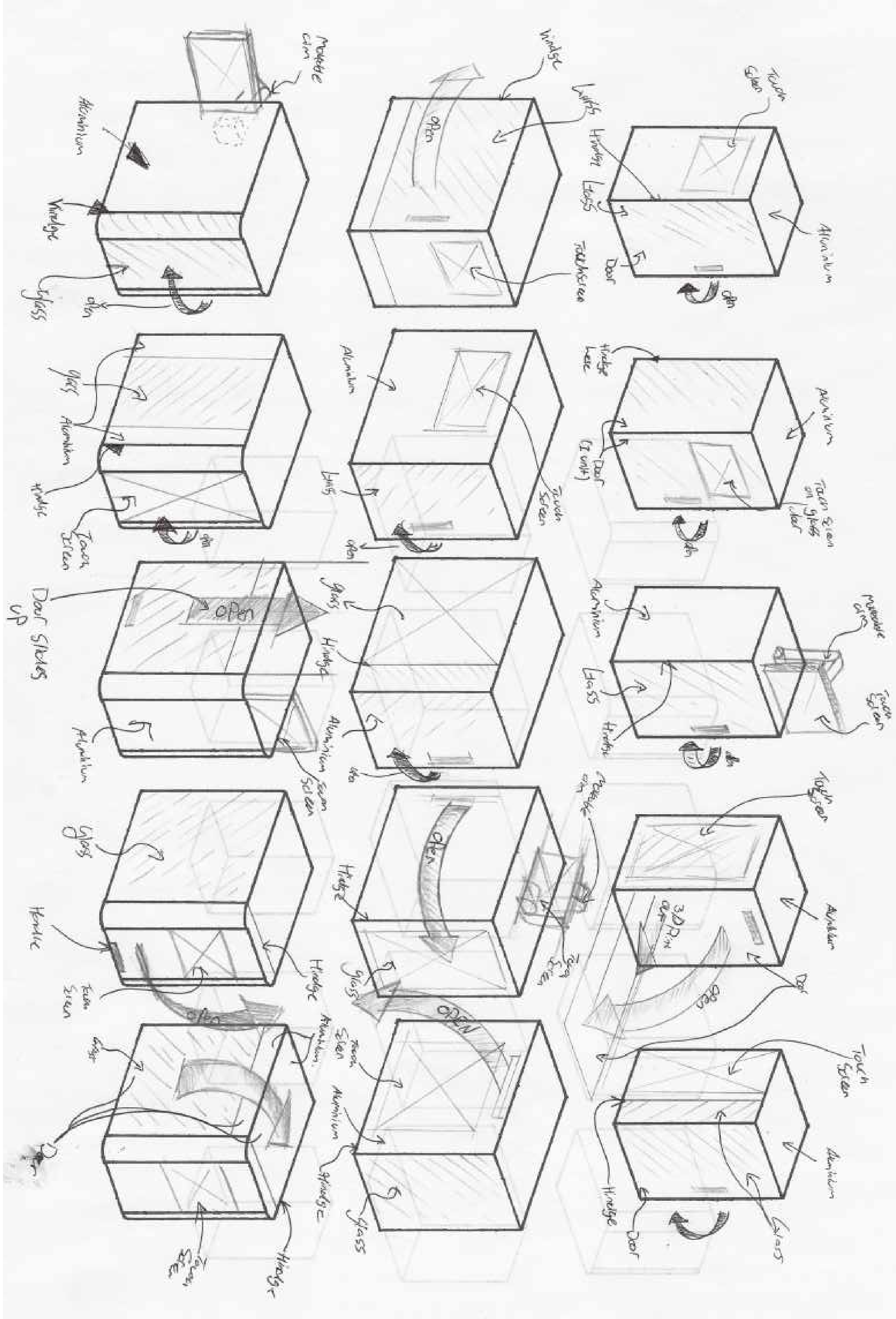


Figure 20.2: *3D form design for the 3D printer*

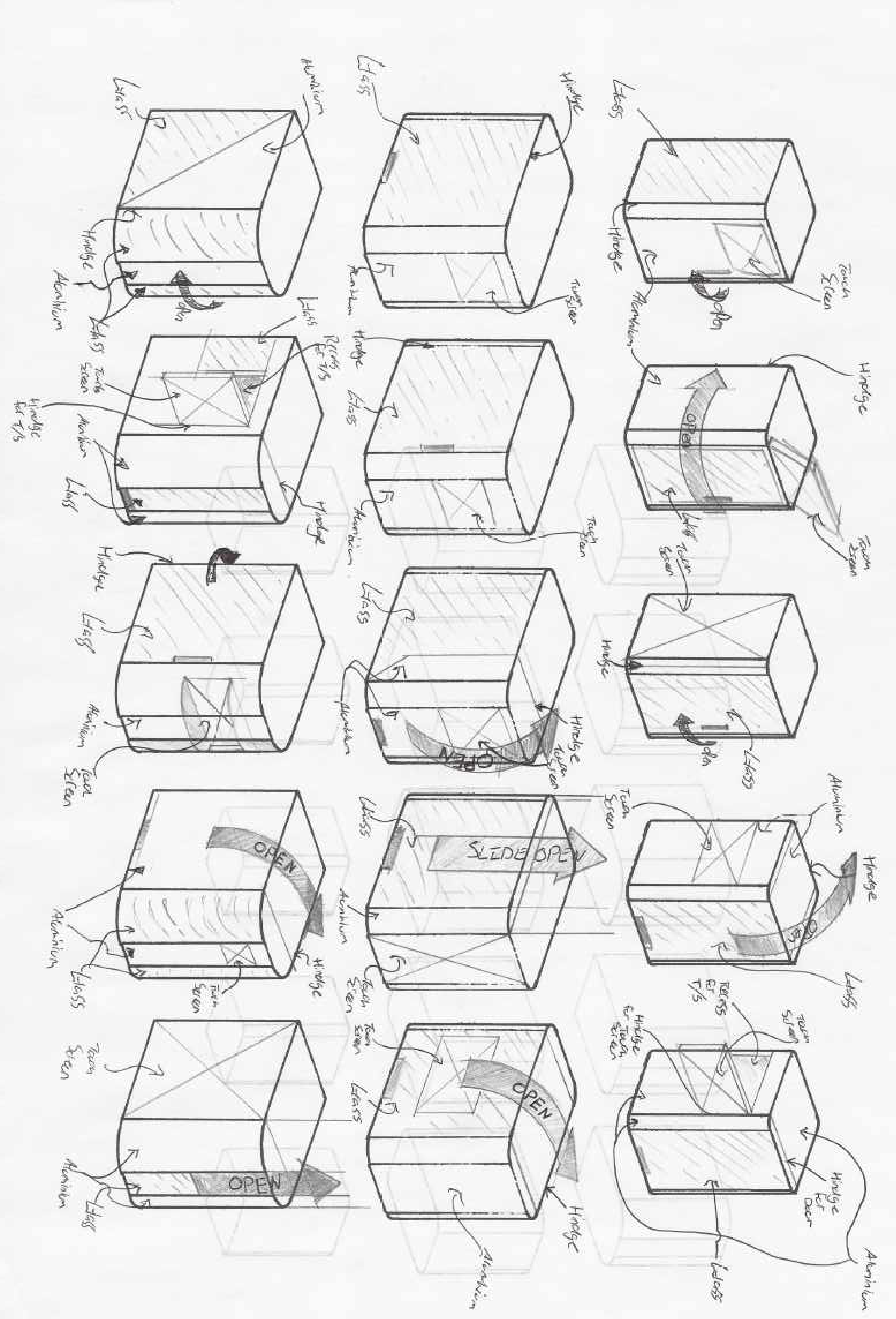


Figure 20.3: *3D form design for the 3D printer*

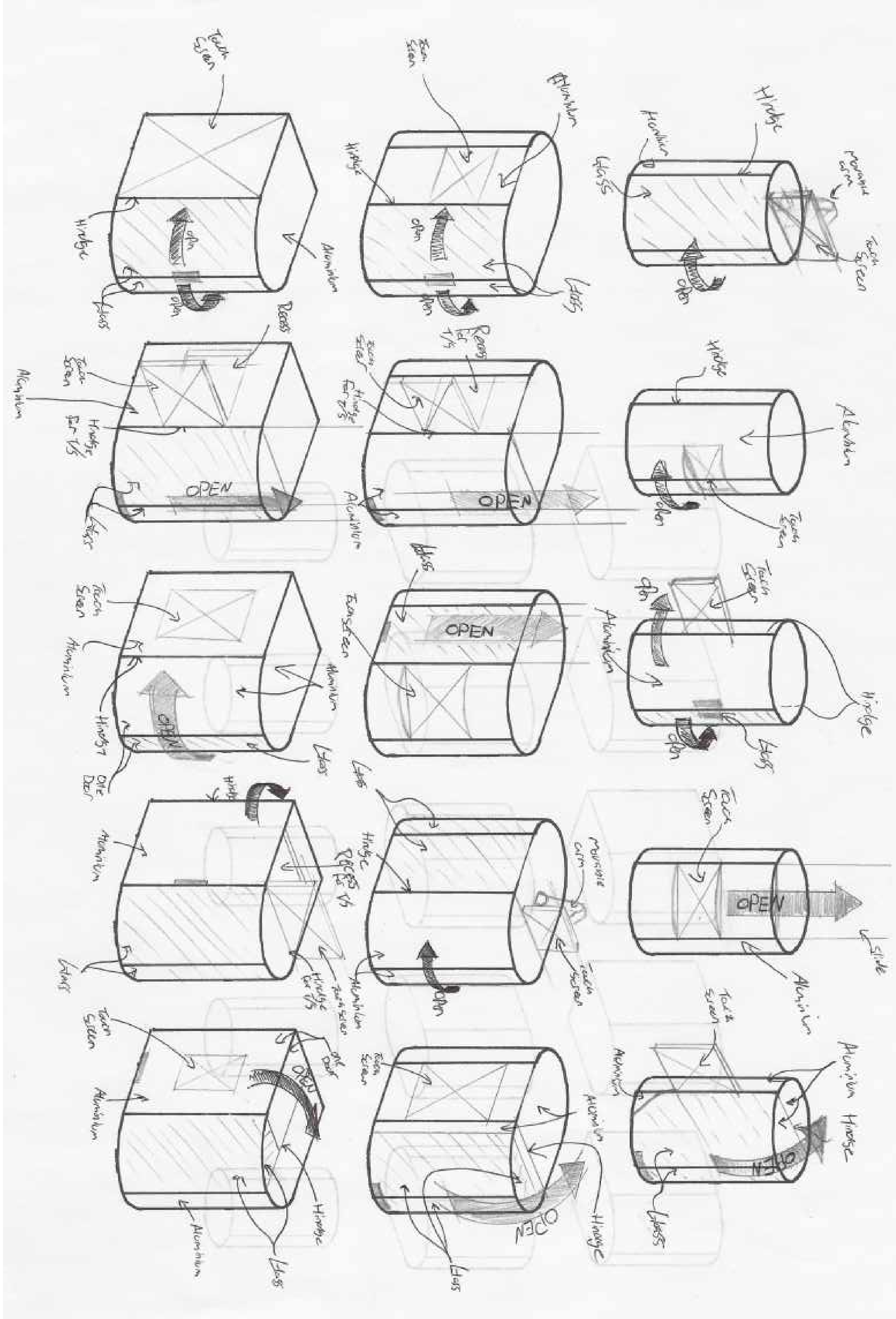


Figure 20.4: *3D form design for the 3D printer*

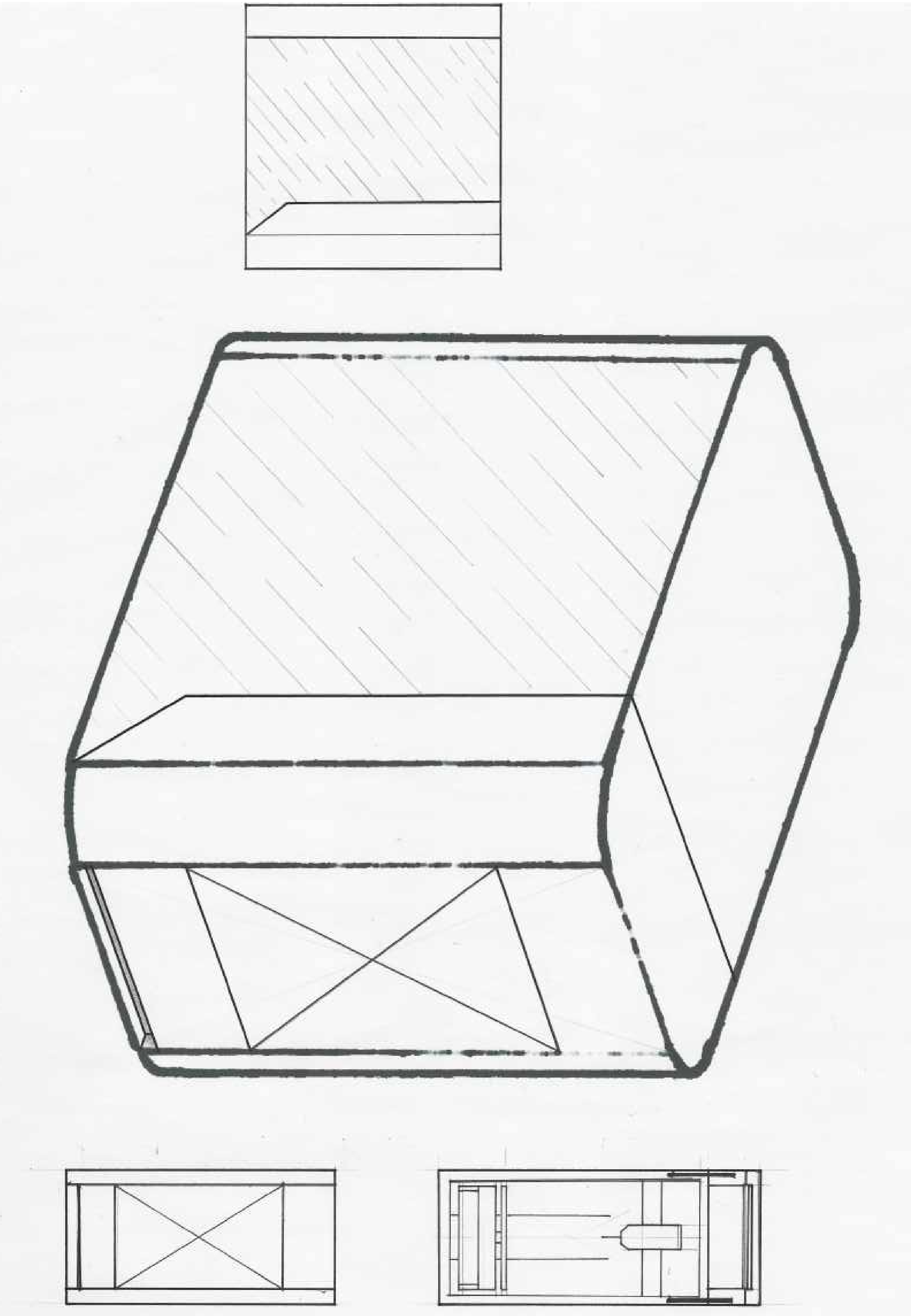


Figure 20.5: *3D form design for the 3D printer*

Deciding upon a design, which was chosen for aesthetic reasons, the next step was to create a basic CAD model of Figure 20.5 to determine if it would be a successful candidate for further refinement. As seen in the below images, Figure 21.1 - 21.3 were made from Aluminium and featured a glass panel which was chosen for aesthetic and cleanability reasons.

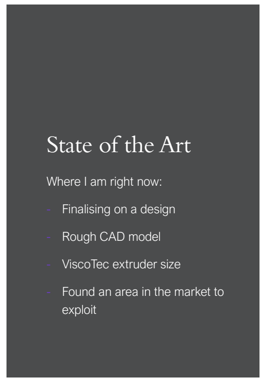
Figure 21.1: *Initial CAD model of the 3D printer - closed door*

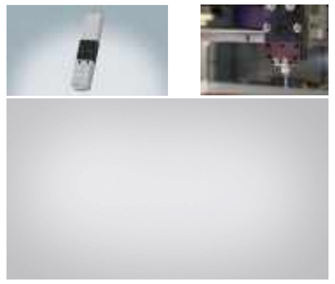
Figure 21.2: *Initial CAD model of the 3D printer - open door*

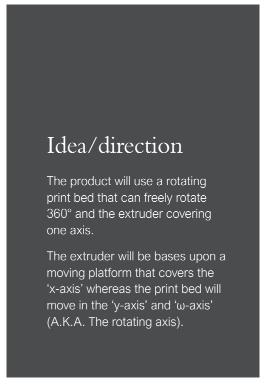
Figure 21.3: *Initial CAD model of the 3D printer - with print*

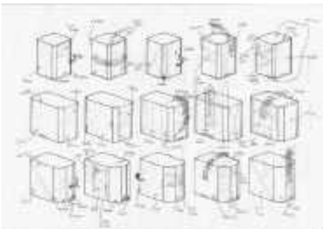
6.4 PRESENTATION OF VERSION 3

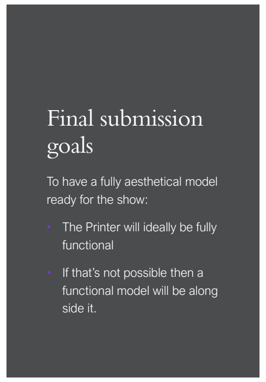
On February 3rd, 2020, the Author presented in front of his project supervisor and students about the product that I have developed thus far. Constructive criticism on the Author's product [6.3] was received which progressed the product further for '*Version 4*'.











Presentation to group

6.5 PROTOTYPE - VERSION 4

For this development, the design concern was that having a heavyweight (the extruder) moving around would sway/rock the machine. The get around for this was to move the print bed in the Z and ω-axis and have the vipro-HEAD 3/3 moving along the x-axis. This choice was determined by the market research carried out. Looking at C3Ds YouTube video, they use a modified GRR x400v4 [Fig.22] (discovered in the Authors Interim Report, Figure 3). This machine moved the platform by using 4x ball screw and nut combinations on the four corners of the print area.

Figure 22: *German RepRap x400 v4*

There were several design considerations that the designer made and tested in physical and digital format.

The first step was deciding upon a movement system to move the print bed. I ideated some ideas for using the ball screw method like the x400v4 uses [Fig.23].

The designer quickly realised that this would not be feasible as it requires four additional motors which for a level printing platform would necessitate all the motors to be in sync which adds complexity to the coding and design of the product.

There was consideration to copy how the L320 moves its print be, however, that decision was not carried forward as mentioned in 6.2.

As understanding the product dimensions was beginning to become a challenge to visualise in the real world the designer created a sketch model using the IDS and additional measurements. Creating this was very free-flowing, adding and subtracting material as and where needed. This led to the sketch model seen on the next page [Fig.24.1].

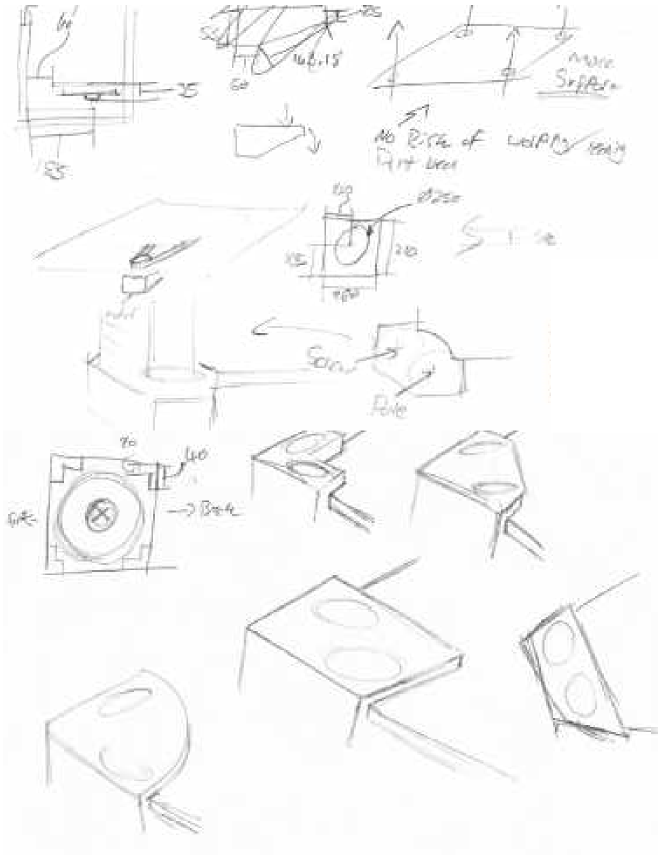


Figure 23: *Ball screw movement system*

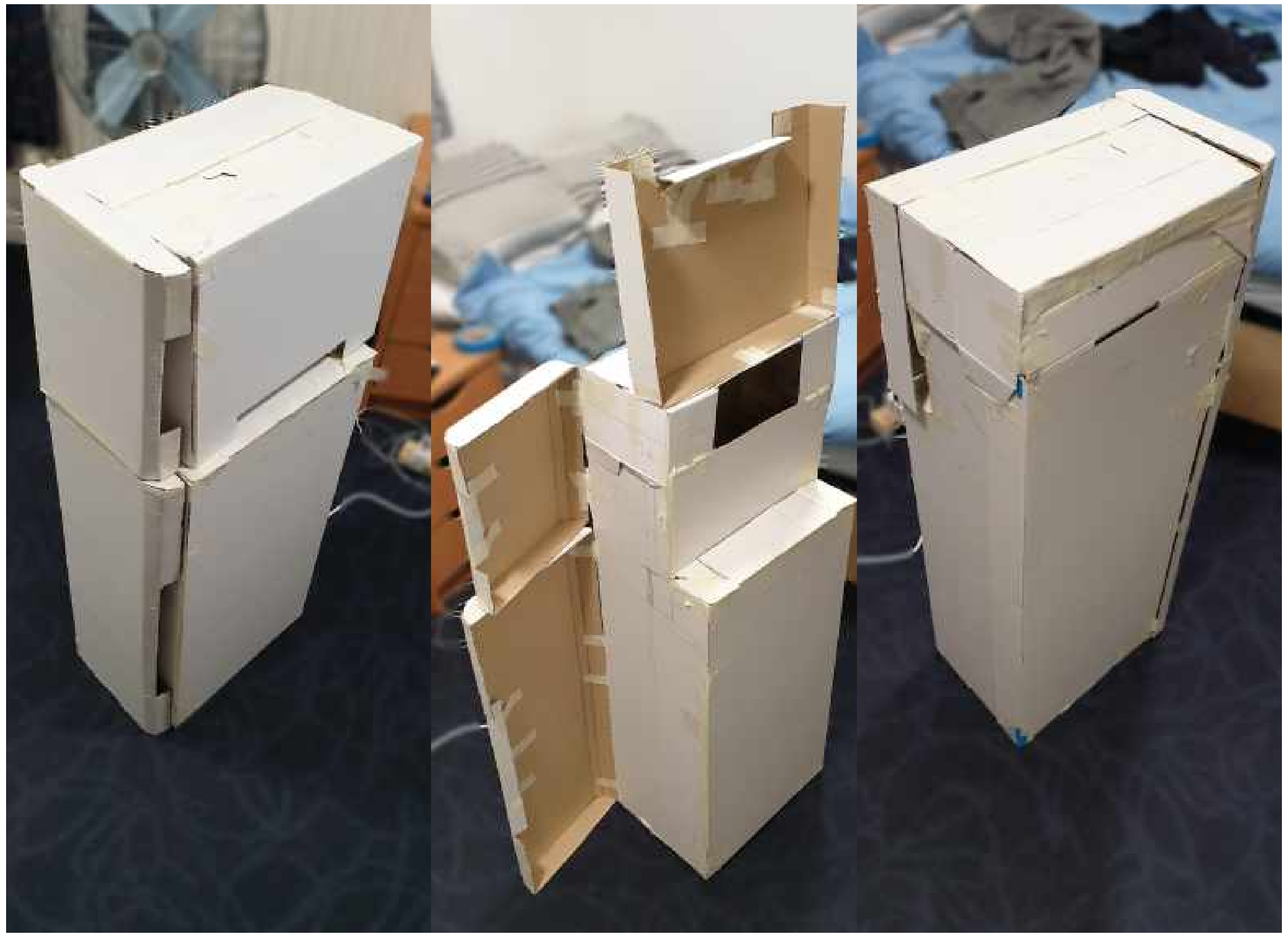


Figure 24.1: *Sketch model of Version 5's 3D printer*

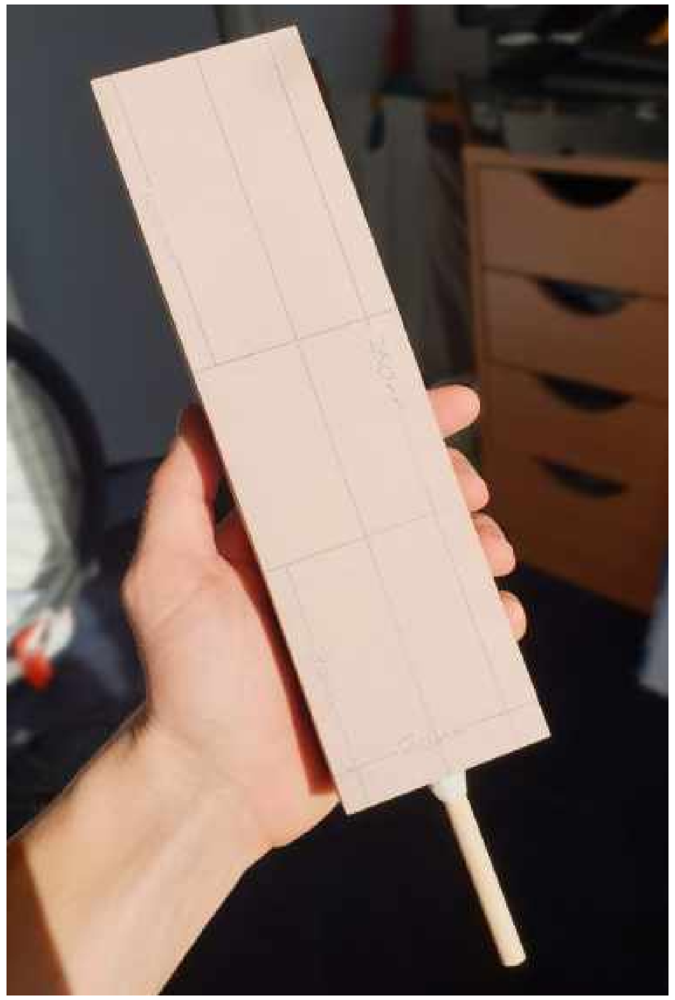


Figure 24.2: *ViscoTec vipro-HEAD 3/3 model*

Figure 24.3: *Print bed size reference*

A deadline for Industry Review Evening (IRE) was fast approaching and the author wanted to have a CAD model available to show alongside the sketch model. Once a reference model was made it was easier to create a more accurate CAD model. There was still considered on what system to use to move the print bed in the vertical axis.

From speaking with workshop technicians at Brunel University London one of the technicians mentioned that the use of a scissor lift would be perfect for this application. The author went away to develop a scissor lift mockup in physical and digital format [Fig.25].

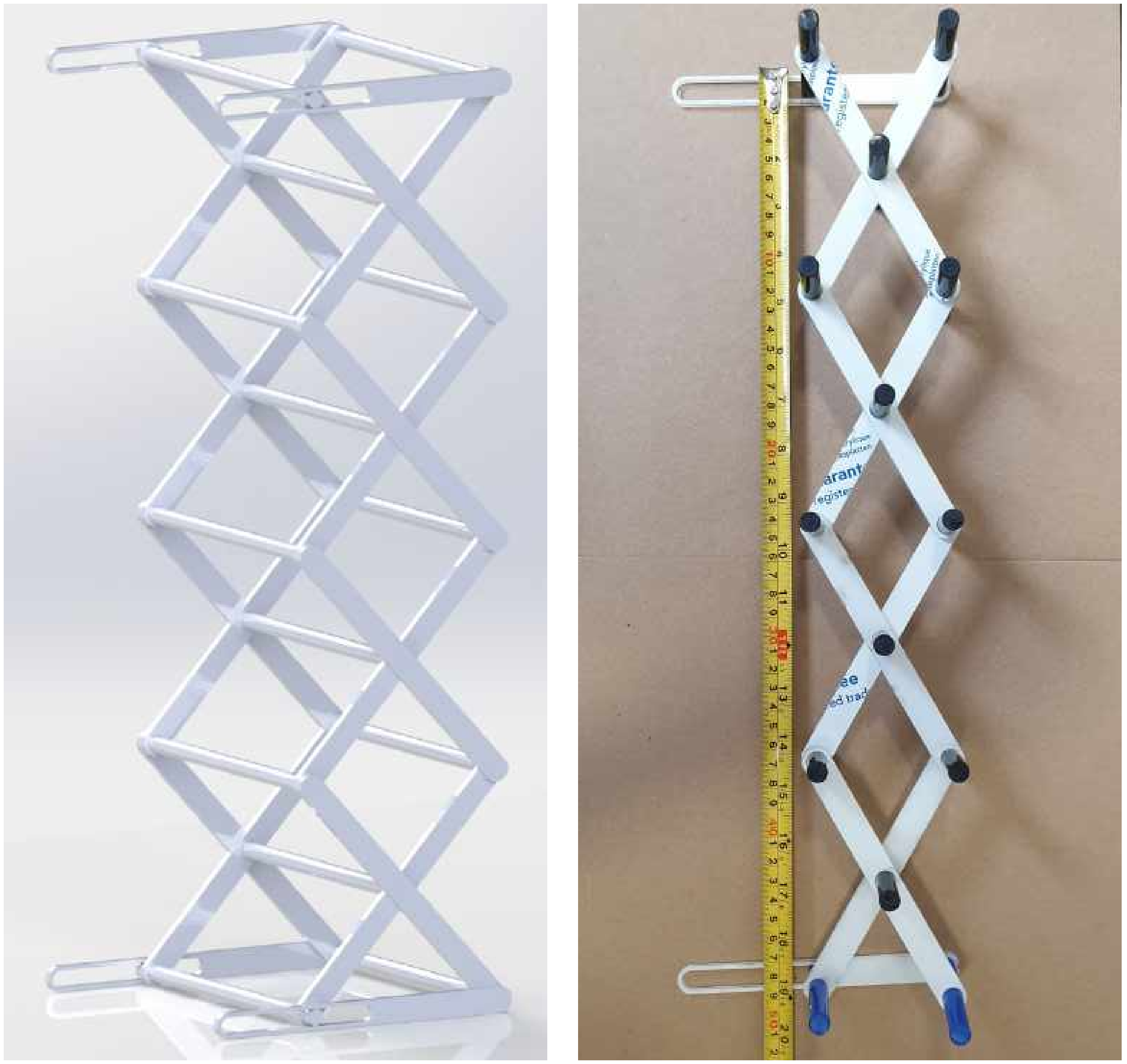


Figure 25: *Scissor lift design*

Following the creation of the scissor lift the advice given by the project supervisor was to use as many standardised components as possible. Bosch has created a desktop application called MTpro where it is possible to build structures using their aluminium profiles. For this build, I used a standard 40x40mm strut profile [Fig.26].

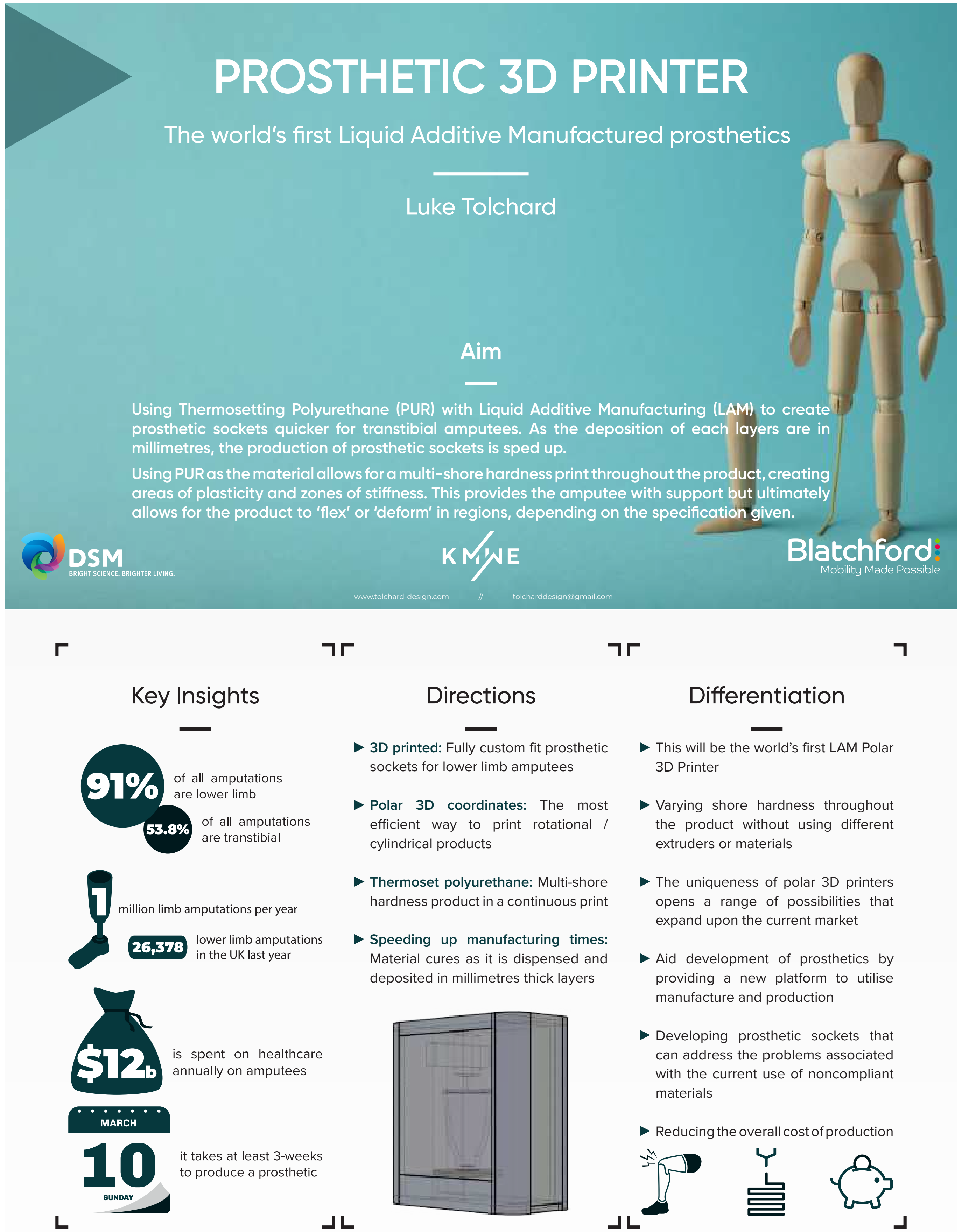
Figure 26: *Frame of initial 3D printer*

The deadline for IRE approached before any more detail could be added to the model [Fig.27]

Figure 27: *Product renders*

IRE

(Made in Brunel, 2020)



The Author's presentation board for IRE

During IRE the feedback that was received for the project was overwhelming. A vast amount of interest led to gaining valuable feedback on the project. During this evening was when the Designers approach to the brief changed once again and lead onto the final product development. This was hinted by comments stating that the machine would be too unstable and that moving the print bed could result in printing issues.

07 FINAL DEVELOPMENT

VERSION - TABLE-TOP PRINTER

7.1 ROTARY STAGE DEVELOPMENT

The issue faced when designing was that the Author was attempting to build the entire system as one instead of focusing on one component before moving on. As the desired coordinate system was polar the Designer started the build by creating the rotary stage.

The first iteration included a rotary stage from Automotion Components which cost £3,387.94. This component was always intended to be swapped out for a more price-sensitive component. The stage assembly was going to include three spring adjustment points which the user of the machine could adjust to a given torque to get the print bed flat [Fig.28].

This changed to five non-adjustable areas which would ensure a flat print bed [Fig.35]. The reason for altering was that as the print bed is made out of glass and the additional support was needed because of the small central support in the middle. A rubber sheet has been selected as a separation layer between the glass and aluminium which will add friction and will not damage the glass print bed and at a thickness of 2mm, it can provide some slights adjustability to level the print bed. The print bed attaches via blocks that clamp the print bed down as seen on the perimeter of Figure 29 and 30.

This product required too many mounting attachments for the print bed holder and ideally, a shift to 3 prongs was needed as it would provide easy print bed adjustability. Throughout the designing of the product, the Designer was searching for a better-suited product to use. Furthermore, the motorised rotary stage did not offer any external mounting points to attach the product to a surface, thus another reason to change it.

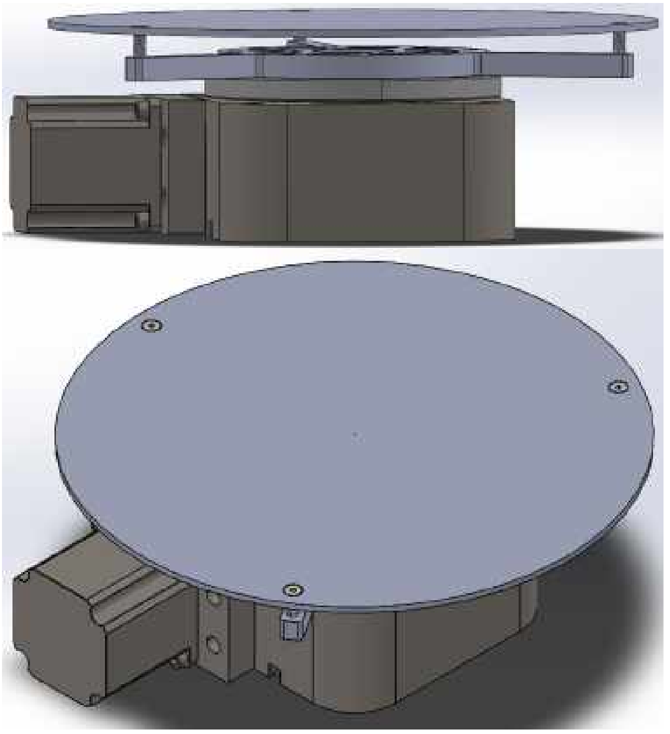


Figure 28: *Initial rotary stage*

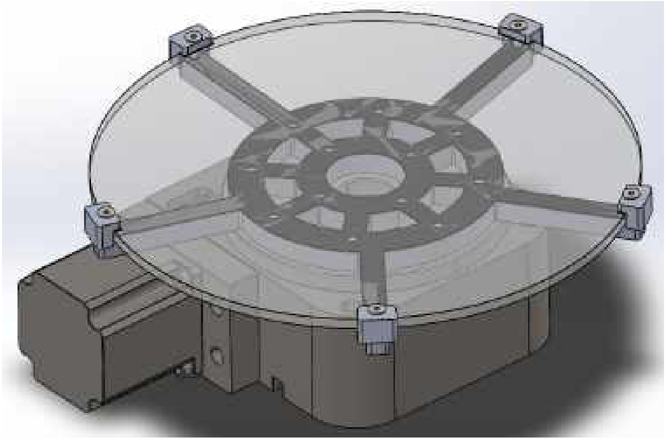


Figure 29: *Five prong design*

A quick mock-up was created to illustrate the core components of the printer. This design took inspiration from the GRR L320 and thus used Rexroth CKK LAs at a screw length of 500mm (Z-axis) and 300mm (X-axis)

Bosch Rexroth was only chosen for this initial design due to their products costing an unreasonable amount. The project Supervisor provided the .STP file for the ViscoTec vipro-HEAD 3/3 which can be seen in Figure 30.

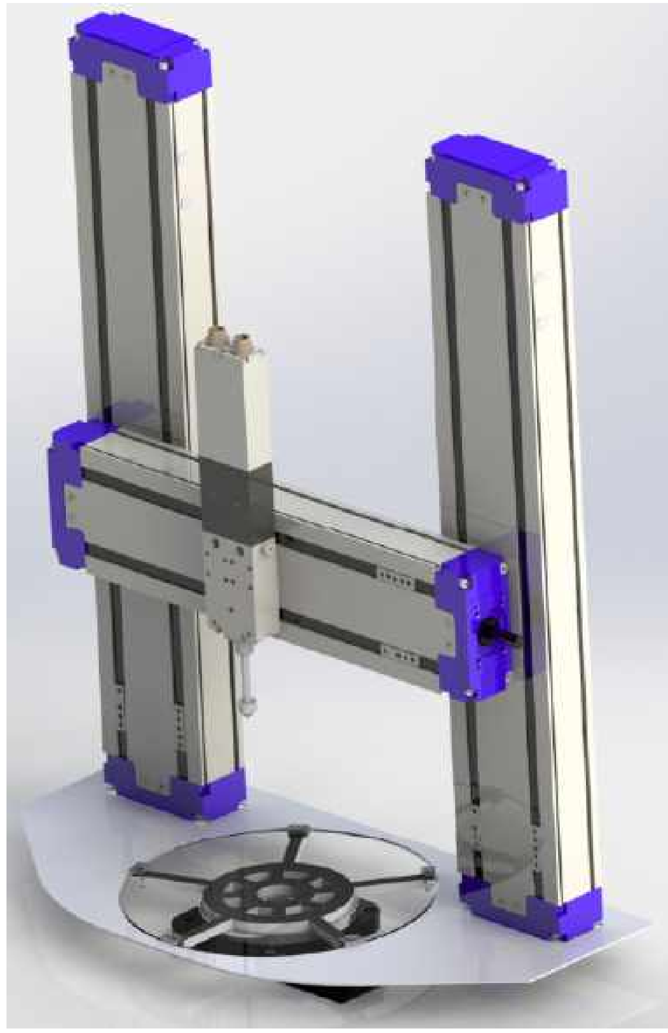


Figure 30.1: *Initial Bosch Rexroth build - full view*

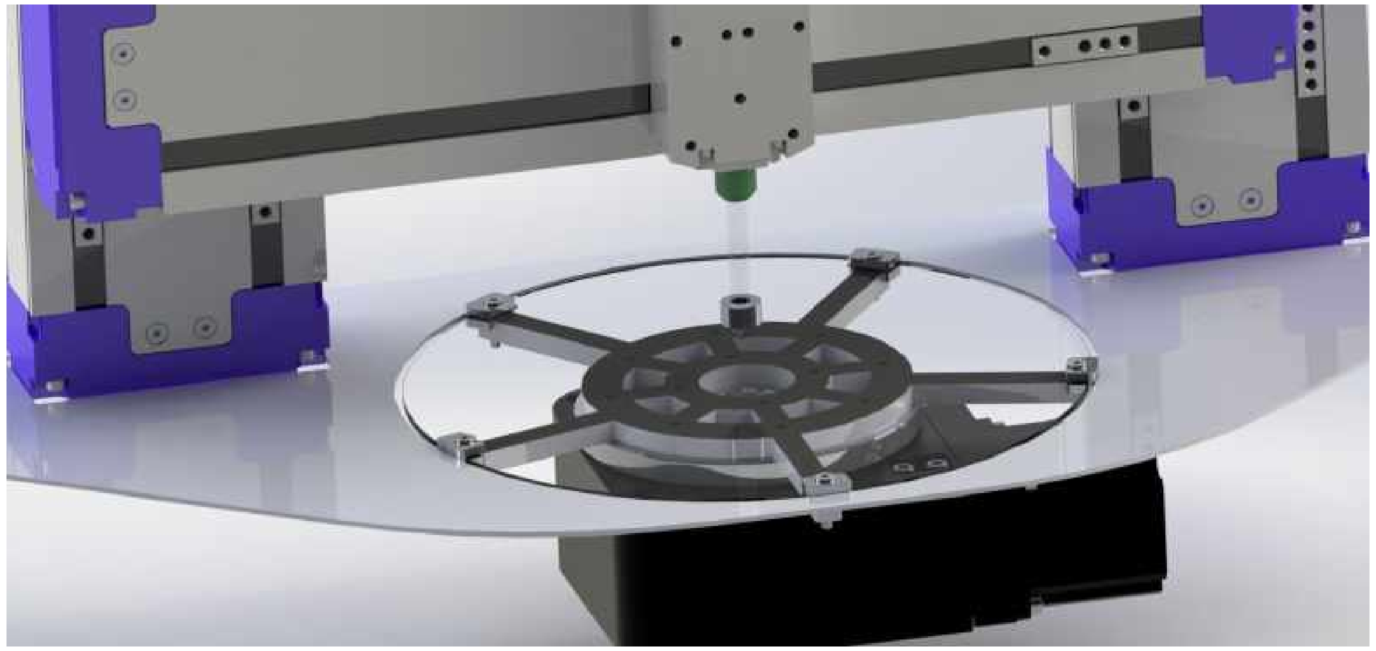


Figure 30.2: *Initial Bosch Rexroth build - bottom view*

7.2.1 LINEAR AXES - ROLLON

The second component to focus on was the linear axes movement systems. As mentioned in the research (3.3) the LAs were going to consist of a ball screw movement system with a servo motor with brake.

As the motors would add additional height if they were inline with the ball screw a wrap around kit/parallel kit (Rollon/Festo) was required. When enquiring about the product configuration this was raised as a necessity. For the Festo build (8.2.2) this meant that a reduction in motor power for the Z-axis LAs.

The designer was not supplied with any motors for the Rollon build and the only assistance received when choosing was not plentiful to ensure that the motors would be compatible with the linea actuators. Moreover, the motors that were compatible cost over £1,000 which is not cost effective for this product.

Furthermore, this build would have cost too much and the LAs used are over-engineered for this product. This lead to this iteration ceasing after communicating this design with the project supervisor.

(The build can be found to the right in Figures 31.1 – 31.4)

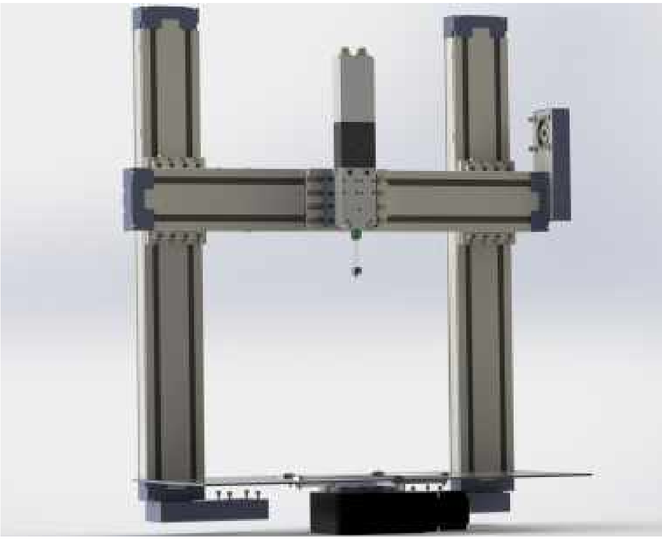


Figure 31.1: *Rollon build -- No motors*

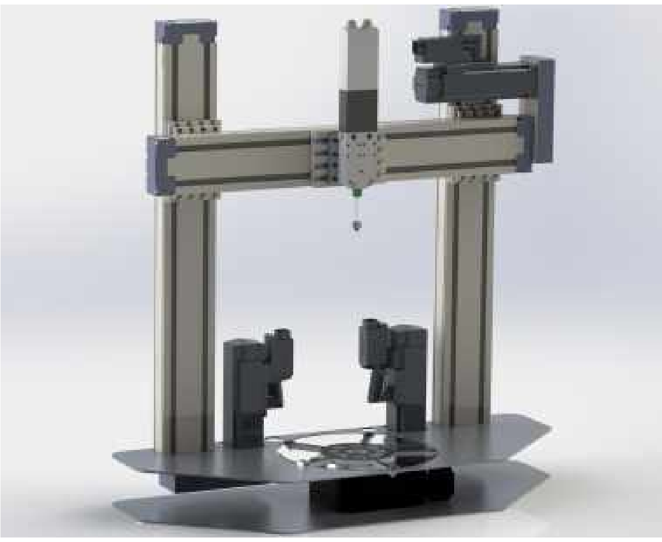


Figure 31.2: *Rollon build -- With motors*

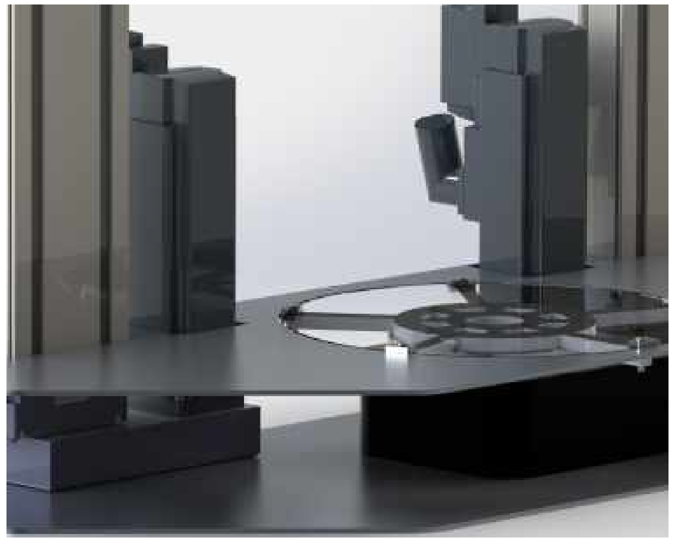


Figure 31.3: *Rollon build -- Close up*

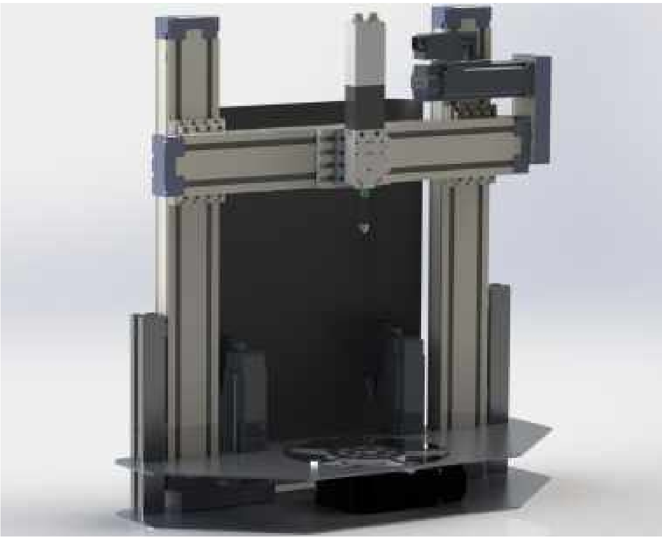


Figure 31.4: *Rollon build -- With a rear panel*

7.2.2 LINEAR AXES - FESTO

The Festo build is a lot more inline with the desired price for their linear actuators. The products cost less than £500 per LA. Furthermore, the overall form of their products is less which reduces the footprint of the final product. Before contacting Festo the Designer downloaded a model of their LA to test the fit within the machine [Fig.32.1].

The Author contacted Festo and after supplying them with the product configuration information (Appendix-9). A member of the Festo Team (who will be referred to as JS) supplied the product files to which the Designer then assembled in SolidWorks along with the vipro-HEAD 3/3 and a 7Oz plastic drip cup [Fig.32.2].

The advantage of using one supplier for the core components of the linear movement systems is that no additional work was required to find the correct motor and accessories (i.e. servo controllers, cables, etc.). Additionally, there is a possibility that a B2B relationship could develop where the products can be sold at a discounted price (which turned true as they reduced the price by 15% seein in Appendix-13).

In 8.3 (next page) the Z-axes LAs are positioned on top of the floor panel [Fig.33.2] with the clamps holding the Z-axis to the back of the machine. This was deemed a suitable design choice by JS at Festo. He mentioned, "*That looks ok. Your application is not too dynamic so it should be fine*". There is additional support as the LAs are positioned on top of the frame by the floor panel.

Figure 32.1: *Festo build -- Test fitting the product*

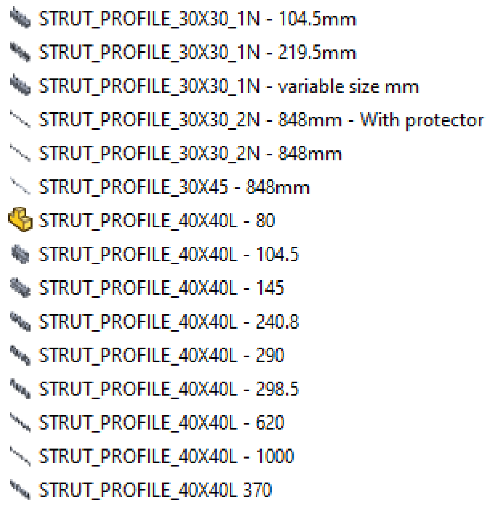
Figure 32.2: *Festo build -- Assembly of the downloaded files*

7.3 FRAMEWORK – BOSCH REXROTH

The development of the frame or skeleton of the 3D printer took the largest portion of 3D modelling time [Fig.33.2 - Fig.33.3]. This was down to the aesthetical choices chosen by the Designer. When designing and modelling the framework the aim was to use sizes that were round numbers (i.e. 1, 10, 100) with no decimal places. This was to make it easier for the production team at Rexroth. There were only a small number of profiles that did not follow the rule, 5/6 of the products are *x*.5 which is easily achievable for the production staff.

The 3D printer is made up of fifteen differently sized strut profiles [Fig.33.1]. The complete product is made up of twenty-nine profiles which are connected by:

- Twelve 45° connectors
- Thirty-one 90° 40x40 brackets
- Six 90° 40 80 Gussets



STRUT_PROFILE_30X30_1N - 104.5mm
STRUT_PROFILE_30X30_1N - 219.5mm
STRUT_PROFILE_30X30_1N - variable size mm
STRUT_PROFILE_30X30_2N - 848mm - With protector
STRUT_PROFILE_30X30_2N - 848mm
STRUT_PROFILE_30X45 - 848mm
STRUT_PROFILE_40X40L - 80
STRUT_PROFILE_40X40L - 104.5
STRUT_PROFILE_40X40L - 145
STRUT_PROFILE_40X40L - 240.8
STRUT_PROFILE_40X40L - 290
STRUT_PROFILE_40X40L - 298.5
STRUT_PROFILE_40X40L - 620
STRUT_PROFILE_40X40L - 1000
STRUT_PROFILE_40X40L 370

Figure 33.1: *Rexroth profile sizes*

This frame has been created with the intent of producing prints that are 500mm tall by Ø250mm. The frame of the printer has been designed to be customisable to user specification. If the customer wanted a product print height of 1000mm then an additional 500mm needs to be added to both the Festo Z-axis LAs and the vertical strut profiles. The same goes for the print bed diameter. The machine and components are adaptable to the users' specifications.

Figure 33.1: *Rexroth standard 40x40mm aluminium profile*

Figure 33.2: *Rexroth standard 40x40mm aluminium profile with rotary stage platform*

7.4 ROTARY STAGE – STANDA

During the building of the frame, the author discovered a better candidate for the rotary stage. The **STANDA 8MR170-190** which has a Ø190mm platform which meant that the Author could reduce the weight of the print bed holder along with removing over half the bolts and making the part cheaper to manufacture.

Seen in Figure 34.3, the print bed has modified print bed clamps [Fig.34.2] (the aluminium blocks around the circumference). The Designer has made the manufacturing a lot simpler and cheaper to produce as there are not any 'hard-to-reach' areas which would require repositioning of the artefact [Fig.34.1].

(See page 67 for Clamp engineering drawing)

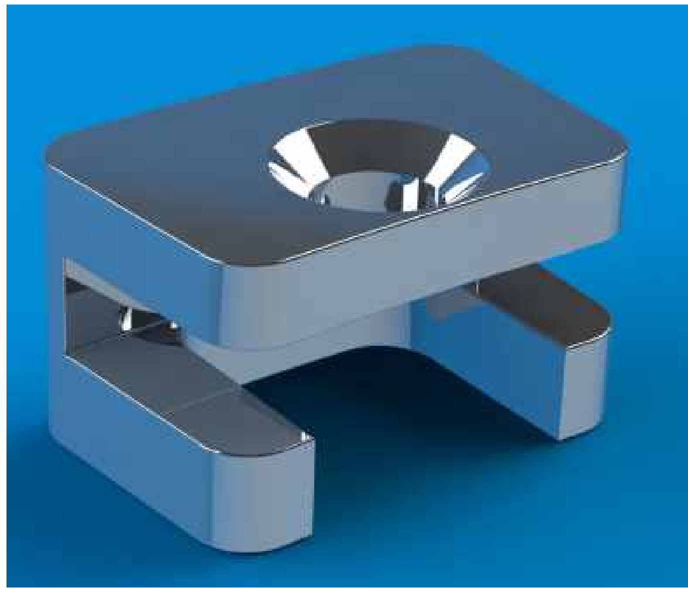


Figure 34.1: *Aluminiumprint bed holder - old*

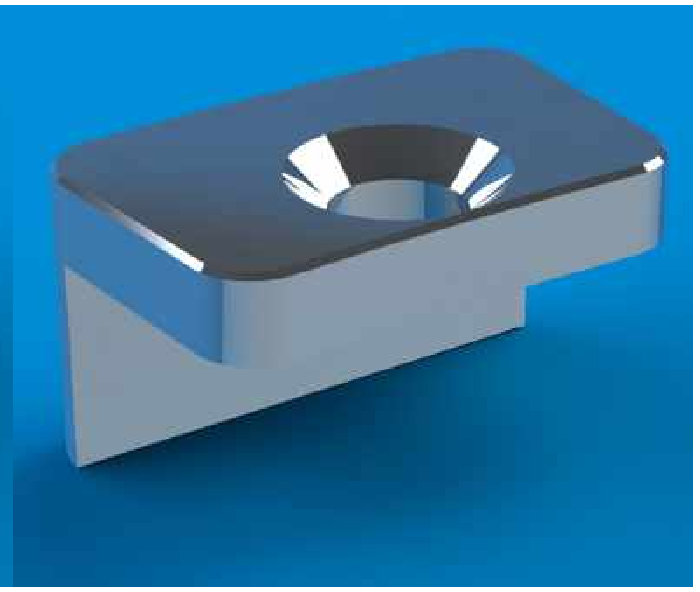


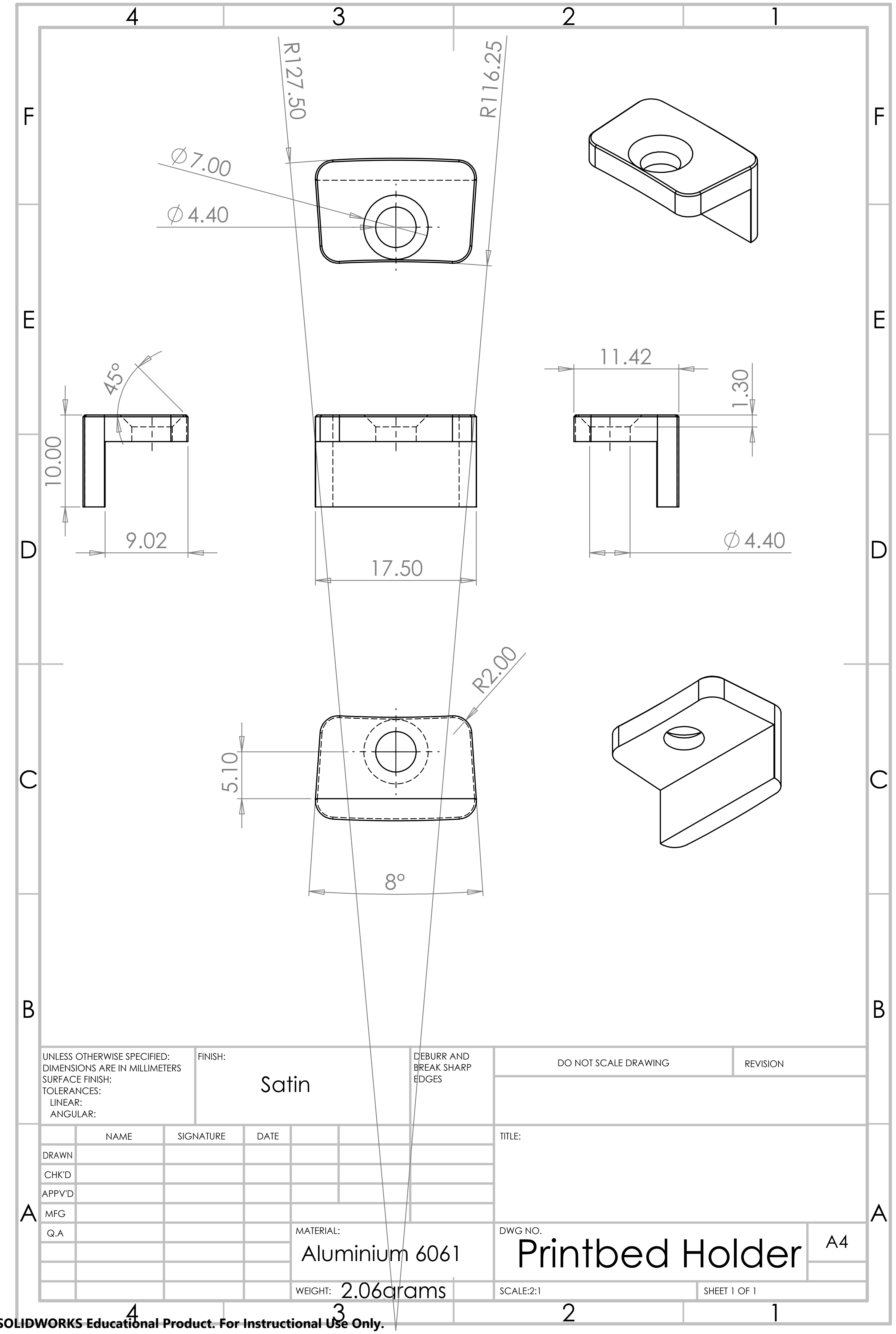
Figure 34.2: *Aluminiumprint bed holder - new*

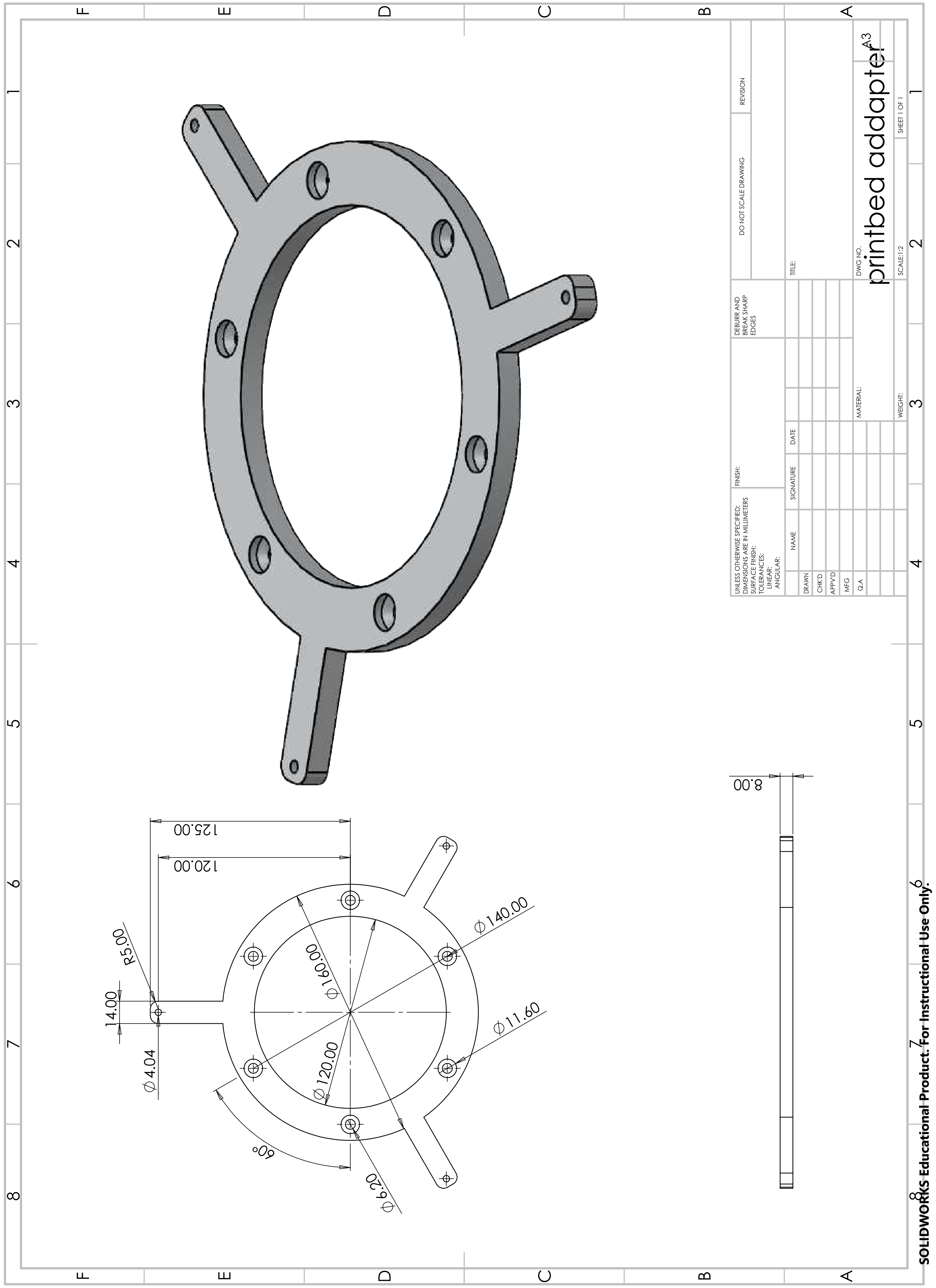
Figure 34.3: *Standa rotary stage with support plate*

The choice of this product also signified that the print bed holder can be changed back to the three-prong design. This change has the gains of better levelling adjustability and cheaper production.

(See page 68 for Print Bed Holder engineering drawing)

Figure 34.4: *Three-prong print bed holder*





7.5 CABLE MANAGEMENT – IGUS

Routing the cables effectively not only has aesthetic benefits but also functional too. Igus provide perfect cable routing products (Energy Chains (EC)) which the 3D printer takes advantage of. They are located on the rear (50mm), Z-axis (40mm), and X-axis LA (40mm). The chains are there to hold the servo and motor cables as well as the polyol and isocyanate liquid tubes. Fixing the Z-axis EC to the motor (via a connection piece) and the top support strut was considered a valid choice as vertical energy chains rarely have support structures [Fig35.1]. The X-axis EC needed additional support to ensure that it would not slide off. The Designer created two additional components and modified an existing Festo component (the glide) to ensure that the EC stays on the X-axis [Fig.35.2 & Fig.35.3].

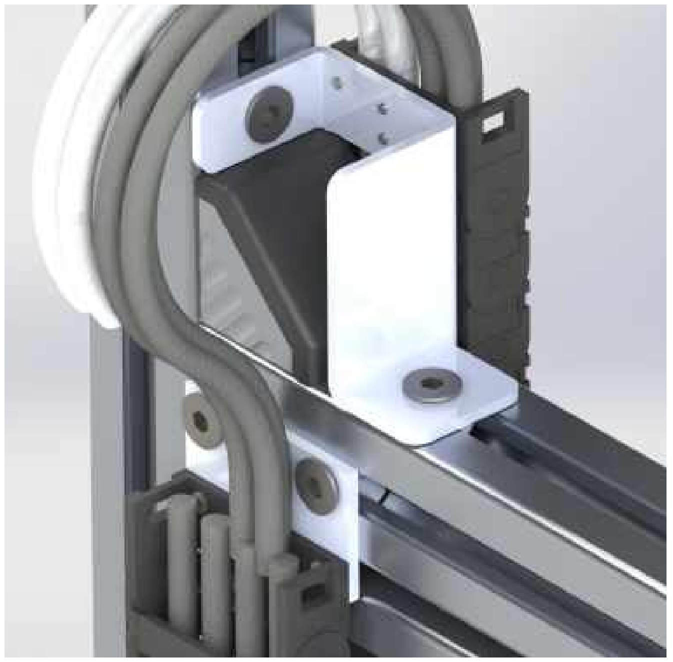


Figure 35.1: *Z-axis and rear EC attachment points*

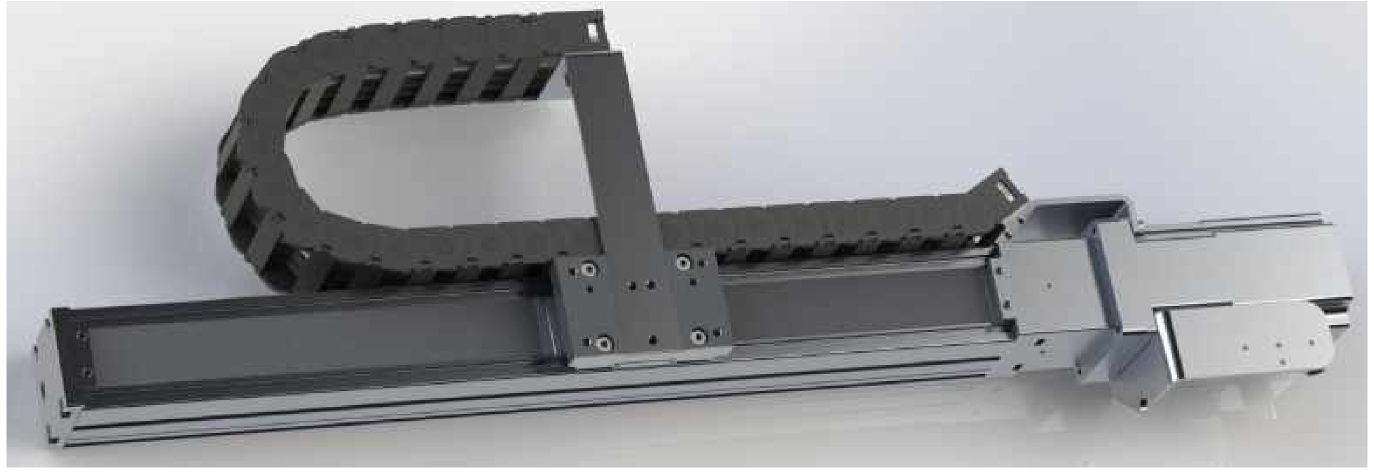


Figure 35.2: *X-axis - With attachment points*

The Festo glide has been modified to accommodate a strip of aluminium that the EC attaches to behind the vipro-HEAD 3/3. The glide has had holes drilled and tapped into it which the vipro-HEAD 3/3 attaches to through its mounting holes. The EC attachment artefact has had clearance holes drilled into it which allow the bolts that hold the material depositer to screw into the tapped holes of the linear glide [Fig.35.3].

The benefit of using an EC is that the chains move and can easily be swapped out if there was to be an issue with one of the links. This is due to the locking clip that Igus implement on their products.

Figure 35.3: *X-axis - Modified Festo glide*

On the rear of the product is a wider EC [Fig.35.4] as there is not a restriction in size. The larger size provides extra support and security as this area (the back of the machine) is accessible by the customer/engineers and could be hit by them as they maintain the machine or refilling the liquid containers.

Figure 35.4: *Rear of the 3D printer with EC, tubes and wires*

7.6 MOVEMENT & ACCESS

As this machine once set up would be hard to reposition. The products final resting place is intended for the table-top as this product is not ergonomic for standalone use. The Designer has chosen to put four roller wheels on the bottom of the machine [Fig.36.1] to aid repositioning of the product if needed. These wheels by Rexroth are Ø80mm with wheel locks so the machine will stay in place. The machine with the wheels on made the machine look unstable so the Designer also used four Rexroth levelling feet and positioned them two along the back and two on the 45° struts. This was to provide that added support which was taken away when the wheels were attached [Fig.36.2].

There needed to be a custom artefact made for the levelling feet to attach to the machine, as usual, they go into one of the open ends of aluminium tubing. However, due to the design of the lower frame, this was not an option. On the next page are engineering drawings for the product.

The next step is to close the print volume so particulates and contaminants do not enter. Seein in Figure 36.3 and 36.4 is the frame of the doors which are used to access the front of the machine. The doors consist of two parts, this was to reduce the area needed to open the doors. If the Designer chose to create the door as a solid unit then when opening the doors this would require a large area (up to 500mm of clearance on each side. Double hinging the door reduces the width to around 350mm (as long as the user opens the doors parallel to the front of the machine seen in Figure 36.4).

Further development 7.7 will describe how the opening width is confined.

The frame of the product is now complete and the following sub-chapters describe the aesthetical and other functional elements.

Figure 36.1: *Lower of the machine - Only wheels*

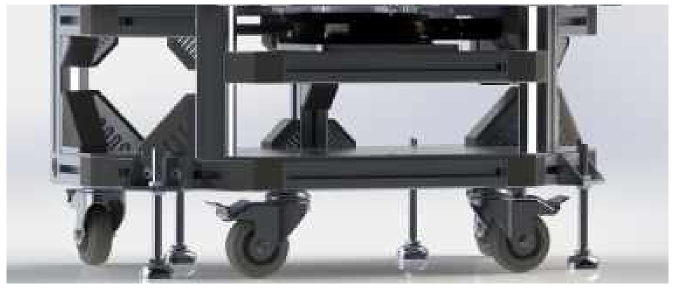
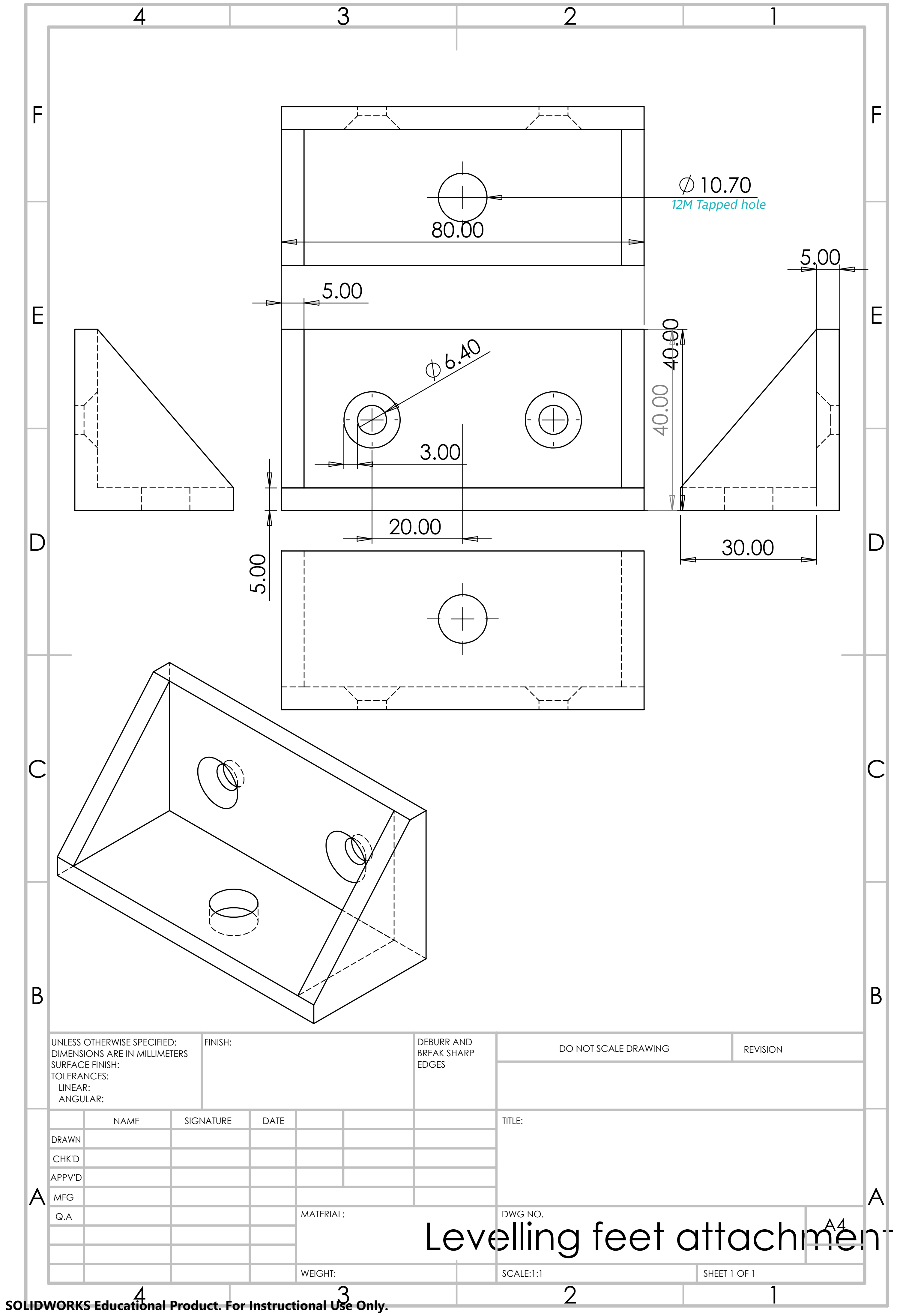


Figure 36.2: *Lower of the machine - With feet and wheels*

Figure 36.3: *Completed framework - Doors closed*

Figure 36.4: *Completed framework - Doors open*



7.7 ACCESS POINTS & ILLUMINATION

Aforementioned in 8.6 limiting how far the front doors can open was a challenge. The Author considered adding compression springs to force the doors closed however opted for a more suitable solution which also helps to provide safety was chosen. Finger guards (FGs), as seen in Figure 37.1, are there to protect an individual's fingers from getting trapped between door frames. There are many companies out there that will produce custom FGs but the best solution found was using rubber with adhesive strips (about 10mm wide) to attach the FGs to the aluminium profiles. Seen in Figure 37.2 the rubber strips stop anything getting trapped between the door segments and the hinge on the rear of the machine. The FGs act as a limiter for how far the doors can open.

To cover-up the lower area of the assembly which houses all the electronics the Designer wanted to make it easy to access from the front and the back of the machine. There were several solutions to this but ultimately found the simplest by using magnetic strips. These magnets made by Brugger Magnet (Fig.37.3) offer a simple and elegant solution as they are fitted to aluminium profiles and secured in place with a screw.

The next step was to create a way to hold neodymium magnets (chosen for their affordability and magnetic attraction) so that the panel will stay in place. The component had to be custom made (which can be found on the next page and in Figure 37.4) along with the covering panel. Removing and attaching the panel is made easy by the use of these magnetic strips and removes the need for screws and other attachment methods.

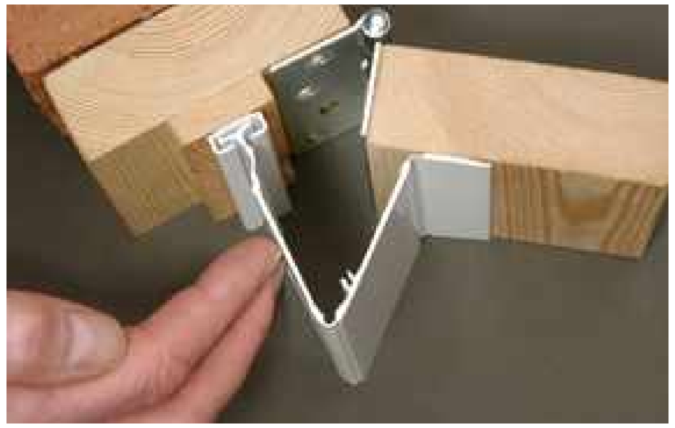
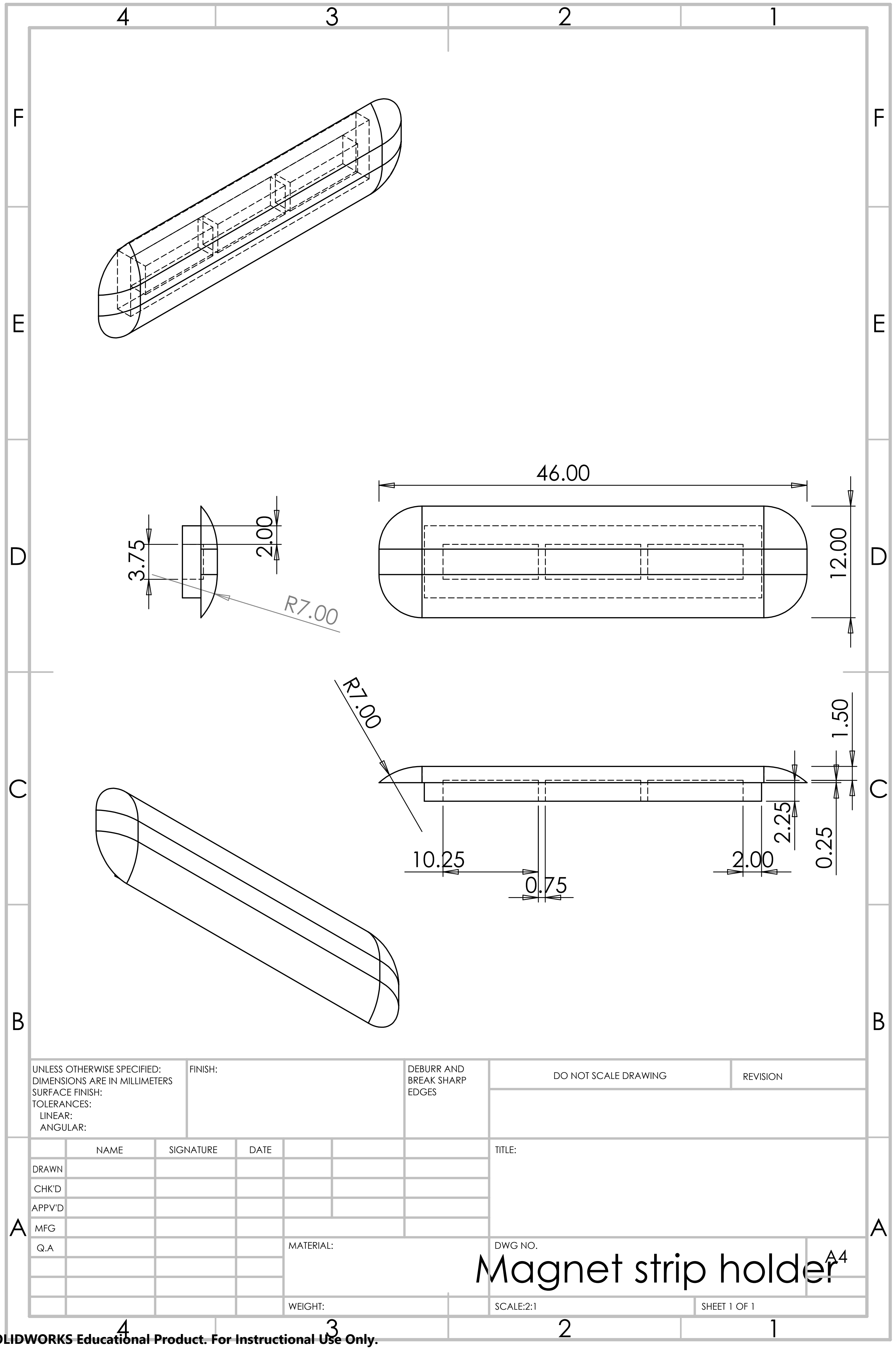


Figure 37.1: *Finger guard (Safety Assured, n.d.)*

Figure 37.2: *Finger guards on the machine*

Figure 37.3: *Magnets aluminium profile (Brugger Magnet, n.d.)*

Figure 37.4: *Covering up the internals at the bottom of the printer*



There is only one energy-efficient way to light the inside of the machine and that is using LEDs. Rexroth manufactures a clear 'Cover Profile' strip that goes between the profile gap. This adds a level of safety as it stops objects from going between the gap. Then using LED strip lights with an adhesive backing to them removes unnecessary fixings. The wires are then routed down to the electronics compartment (which is what the black panel covers) to be connected to a power block or circuit board.

The so far completed product can be found below (Fig.37.5).

Figure 37.5: *Front of the printer with doors open and LED strips*

NB *The image was rendered without the EC to illustrate how the cables and tubes are positioned in the machine*

7.8 ELECTRONICS & LIQUID STORAGE

The machine accommodates two different manufacturers. Festo for the axial movement and Standa for the rotating platform. Unfortunately, Festo did not provide a suitable rotating platform for the print bed which would have made this build easier for the team that have to code and make the electronics for the machine.

The servo drivers for the motors are located at the bottom of the machine in the electrical compartment. The Festo controllers are located on the left of the printer (right in Figure 38.1 & 38.2) and the Standa is located on the right (left in Figure 38.1 & 38.2). Both servo drivers can operate off the same G-code which is the most popular code to use for 3D printers which makes the coding simpler.

The servos have been mounted upon two telescopic slides which can be pulled out as seen in Figure 38.2 which allows for easier access to the internals of the product at the back of the machine. The servo drivers are attached to a custom sheet of aluminium which is attached to the slides *(see page 78 for the drawing)*.

The liquid containment has been an issue since the start of the project. How the material is dispensed has also been a troubling subject. The final design calls for a motor integral nut which attached at one end is a plunger to force the liquid out [Fig.38.3 & 38.4]. The chamber consists of an inlet and outlet pipe. The inlet can be refilled mid-print as the plunger retract; then once refilling has completed the plunger go back to pushing the liquid out. A warning appears on the hosting computer and users mobile when there is less than a determined amount of liquid (depending upon the printing settings i.e. 30-minutes of print liquid left) Each container for the table-top model holds 200ml of liquid.

A notification would also be sent to the individuals mobile device to ensure that someone refills the machine.

Figure 38.1: *Servo drivers - In*

Figure 38.2: *Servo drivers - Out*

Figure 38.3: *Material storage tank*

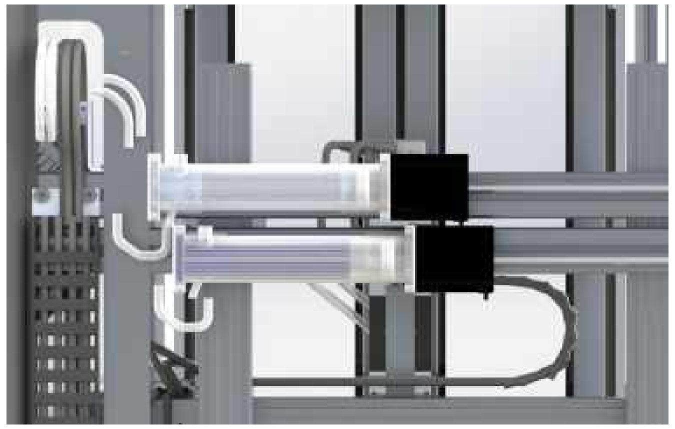


Figure 38.4: *Material storage on the back of the machine*

To check that the print bed is level a laser system is used. The laser measurer is located within the top horizontal strut at the front of the machine. The RX-500G Robust Photoelectric Sensor [Fig.38.5] from Panasonic uses the polished aluminium of the print bed clamps as the reflective surface to measure the distance. If the user over or under tightens a screw then the reading from that measurement point would be different as either the rubber layer has been compressed too much or too little. The user then uses a hex screwdriver to adjust the screws to the computers read-out until they are all the same level

The electrical assembly [Fig.38.6] consists of:

- Three Servo drives to control the Festo linea axes servo motors
- One Servo Drive for the Standa motorized rotational stage
- Mount for the PCB board *(Disclamer – The Author is not creating the electronics / PCB for this project as their expertise does not expand into this field so the final electronic set-up may vary or components may need revising to account for these changes).*

(PCB board by Thingster on GrabCAD (thingster, 2019))

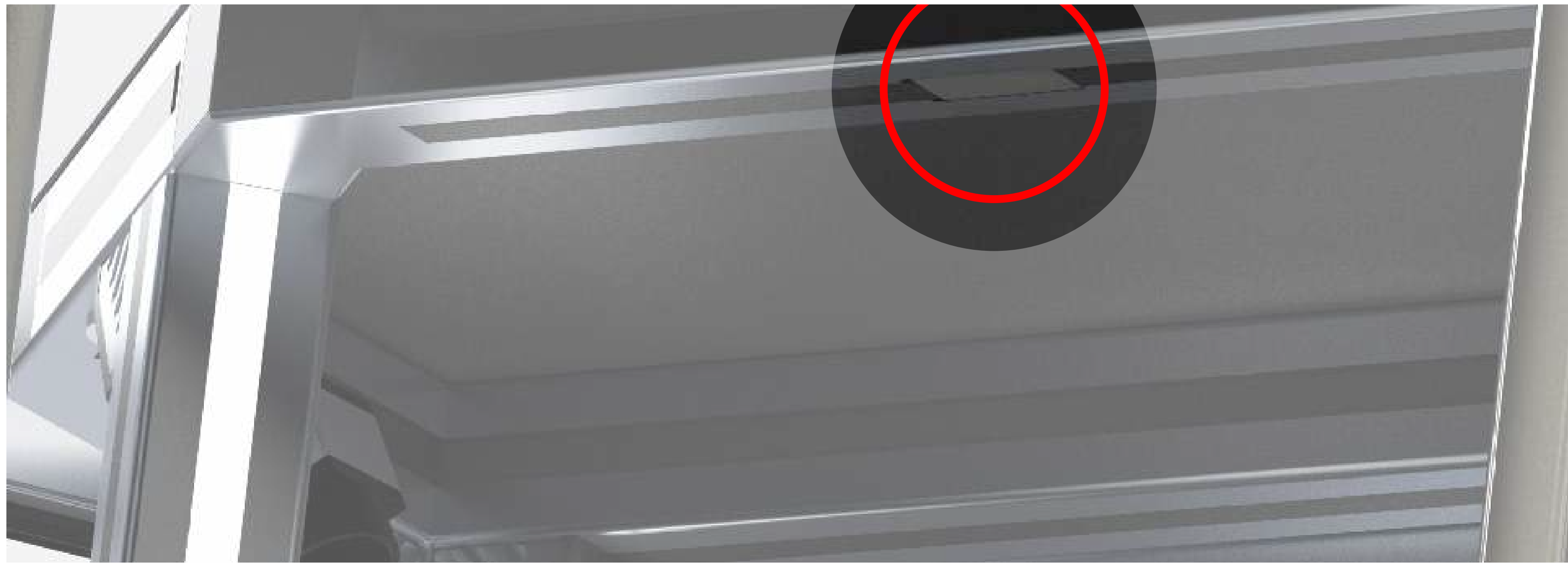


Figure 38.5: *Laser integrated into the aluminium strut*

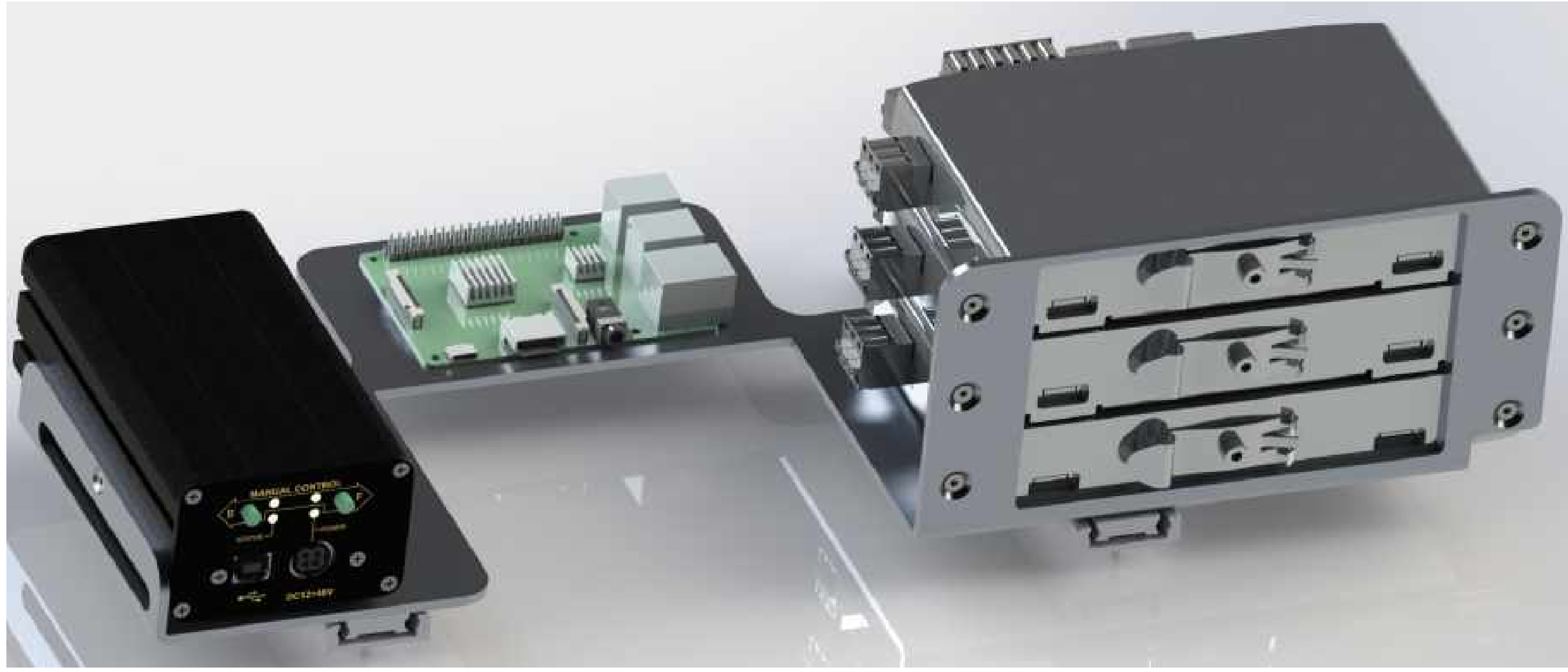
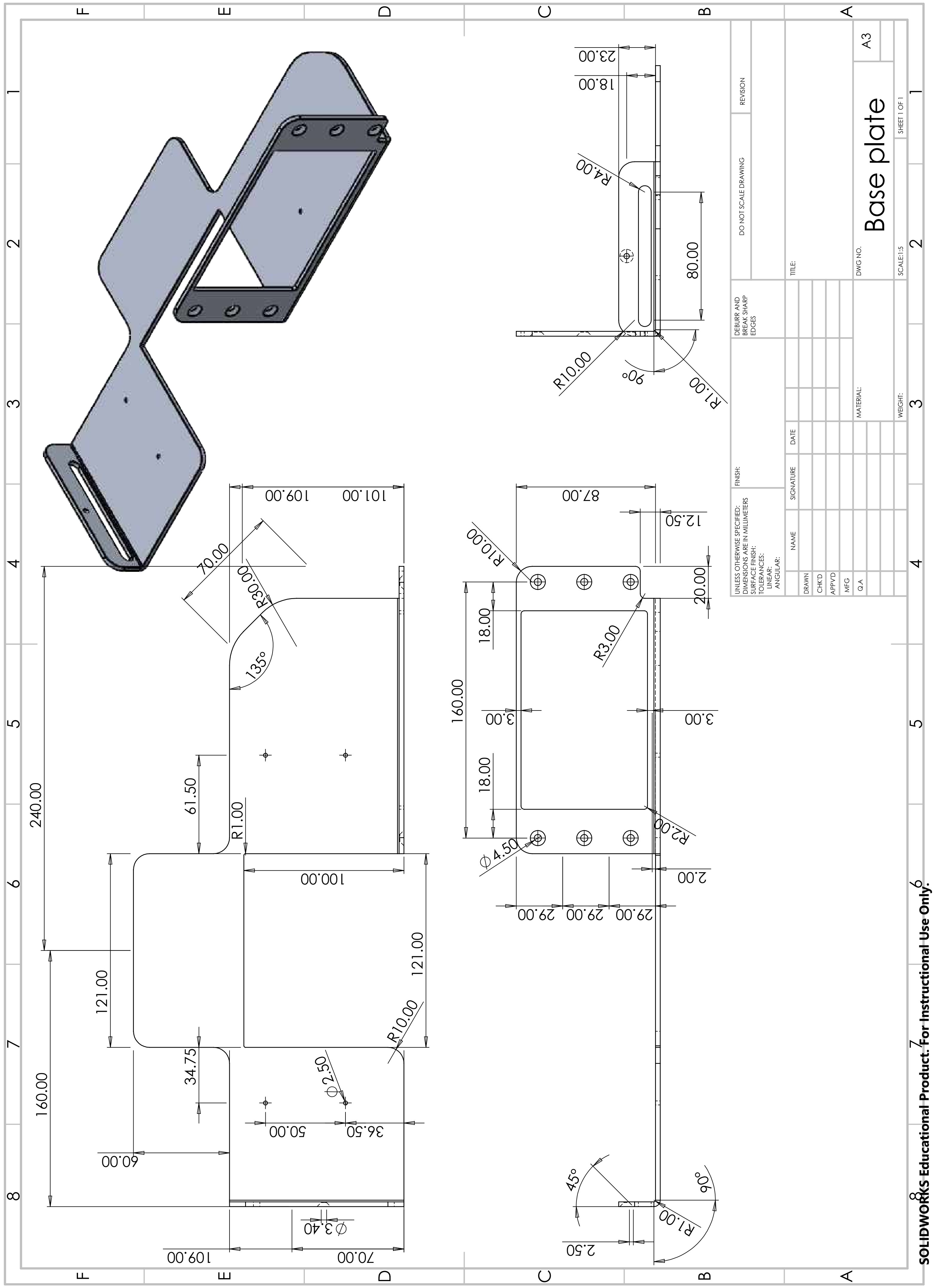
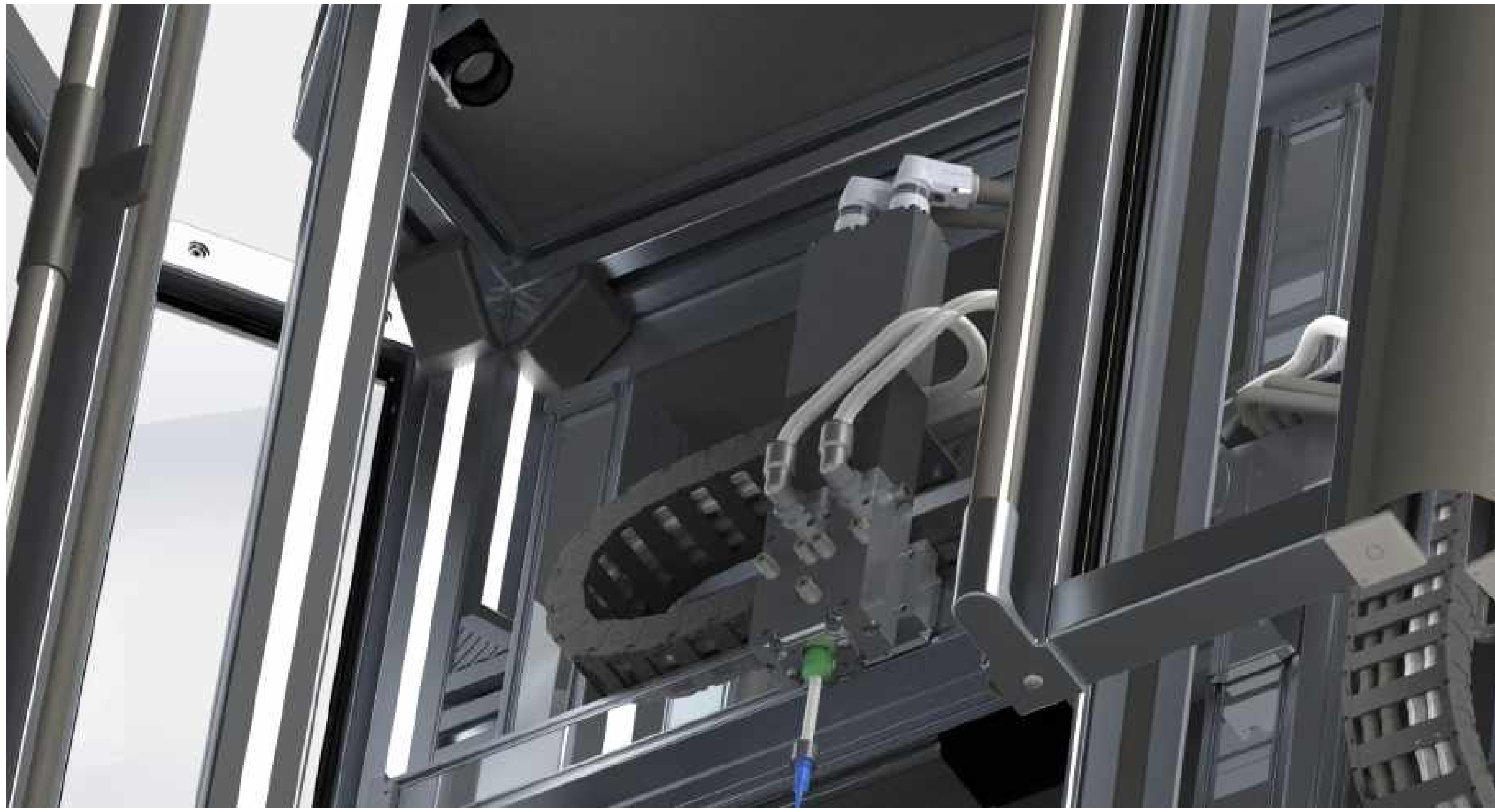
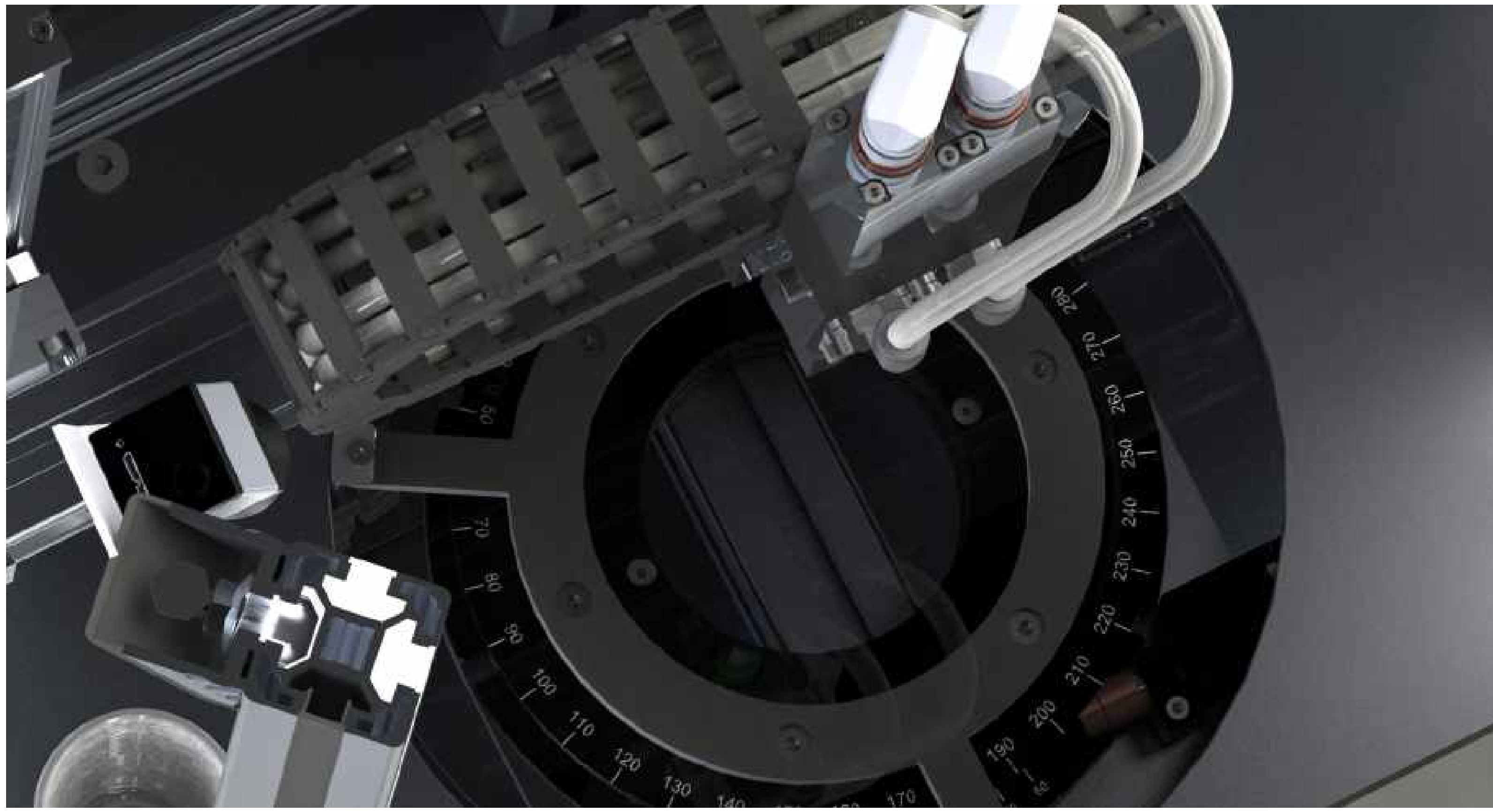


Figure 38.6: *Electrical assembly*



A point raised by the project supervisor was to come up with an idea for what to do with the dead space. A lot of 3D printers, cheap and expensive, make use of a camera. Festo provides cameras with different specifications. The practical application was to use a colour camera as the FlexTune™ material is coloured. If there is a problem with the printing application it may be useful to see if the colour of the deposited material has changed. The camera provides a constant video feed so users can remotely view the print to see if everything is going okay.





Festo Camera in the 3D printer

7.9 COVERS & HANDLE

The rear of the machine has exposed wires and an opening to the back of the printer. The Designer created two rear panel covers for the product [Fig.39.1 - 39.3]. The largest cover operates as an access point for everything at the back of the printer. This includes the servos, linear actuators, rotary stage, and liquid containers. The thin cover covers up the wires leading to the bottom of the machine and the tubes leading to the Z-axis energy chain.

This stage also includes ventilation holes cut into the sides of the front cover panel to allow air to freely pass-through the electronics compartment.

Both panels are held in place by M4 nuts which attache to M4 screws [Fig.39.3]. The screws are fused to the aluminium cover panel before the assembly of the machine. The largest panel is made from low/medium density PE and weighs 588g supported from four attachment points at the corners of the artefact. The thinner cover is made from the same material and weighs 98g supported for six attachment points along its perimeter.

Figure 39.1: *Rear of the 3D printer - Straight on*

Figure 39.2: *Rear of the 3D printer - Angled*

Figure 39.3: *Fixings attaching the covers to the printer*

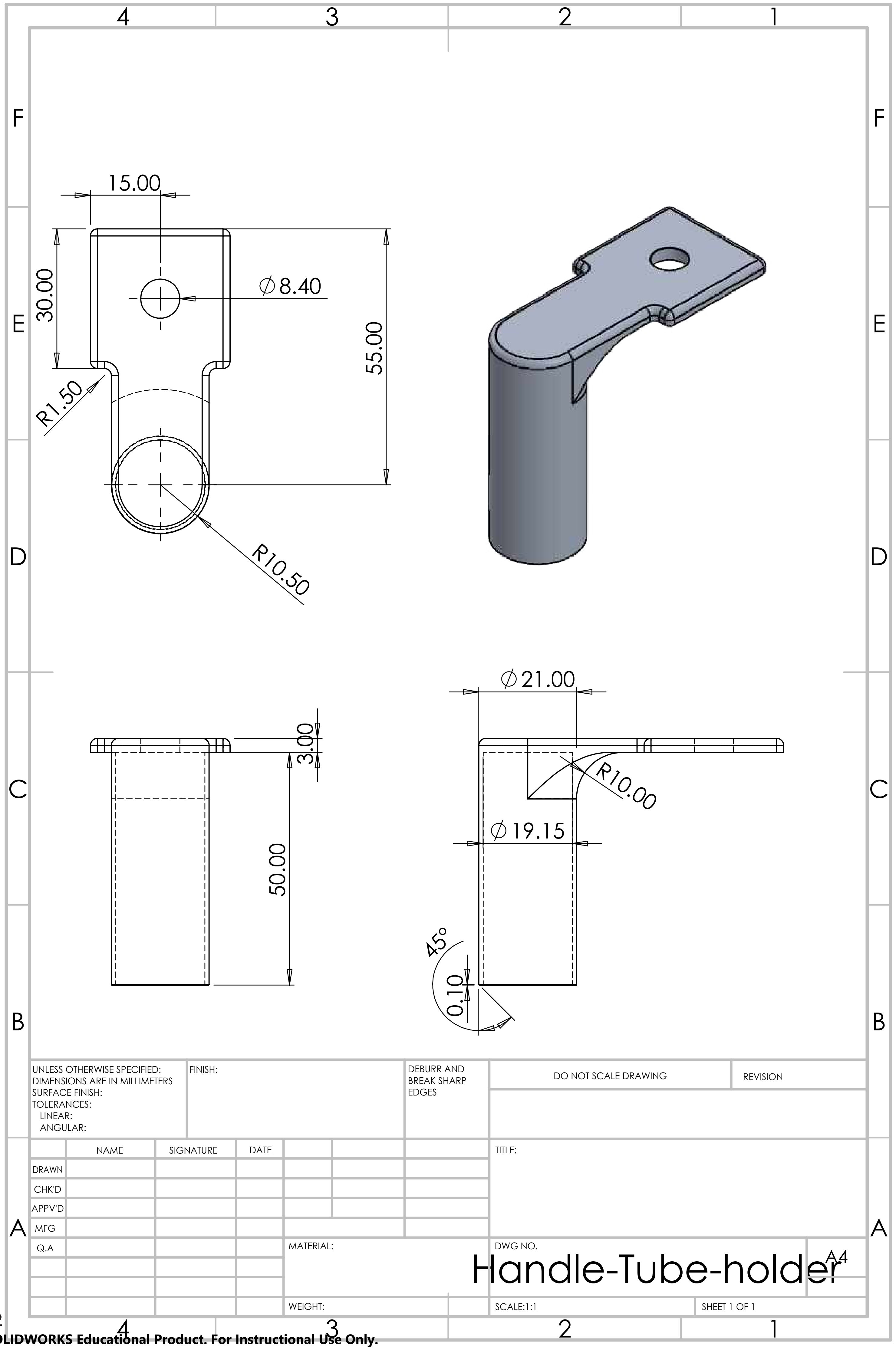
To open the doors the user grabs onto a unique locking handle. The handles comprise of a stainless steel tube which is fixed in place by two brackets (see drawing on next page). The handle on the right has a slot milled out for which the locking handle on the left can fit into it. This simple lock is enough to stop the doors unintentionally from opening.

The doors closed and open [Fig.40.1 - 40.2]. Close up of the locking handle in Figure 40.3.

Figure 40.1: *Doors closed - Handles locked*

Figure 40.2: *Doors Open - Handles unlocked*

Figure 40.3: *Close up of handles locked*



7.10 FINAL TOUCHES

The 3D printer has only one component left which is to cover-up the gaps between the aluminium extrusion. Rexroth provides covers for their aluminium profiles, the Author chose to use black cover strips to fit inline with the other plastic parts used. This option was further chosen because of the anodised strip provided by Rexroth is not for the profiles that are in this product.

Plastic strips to cover the gaps in the profile

VERSION - STANDALONE PRINTER

7.11 MAKING THE STANDALONE PRINTER

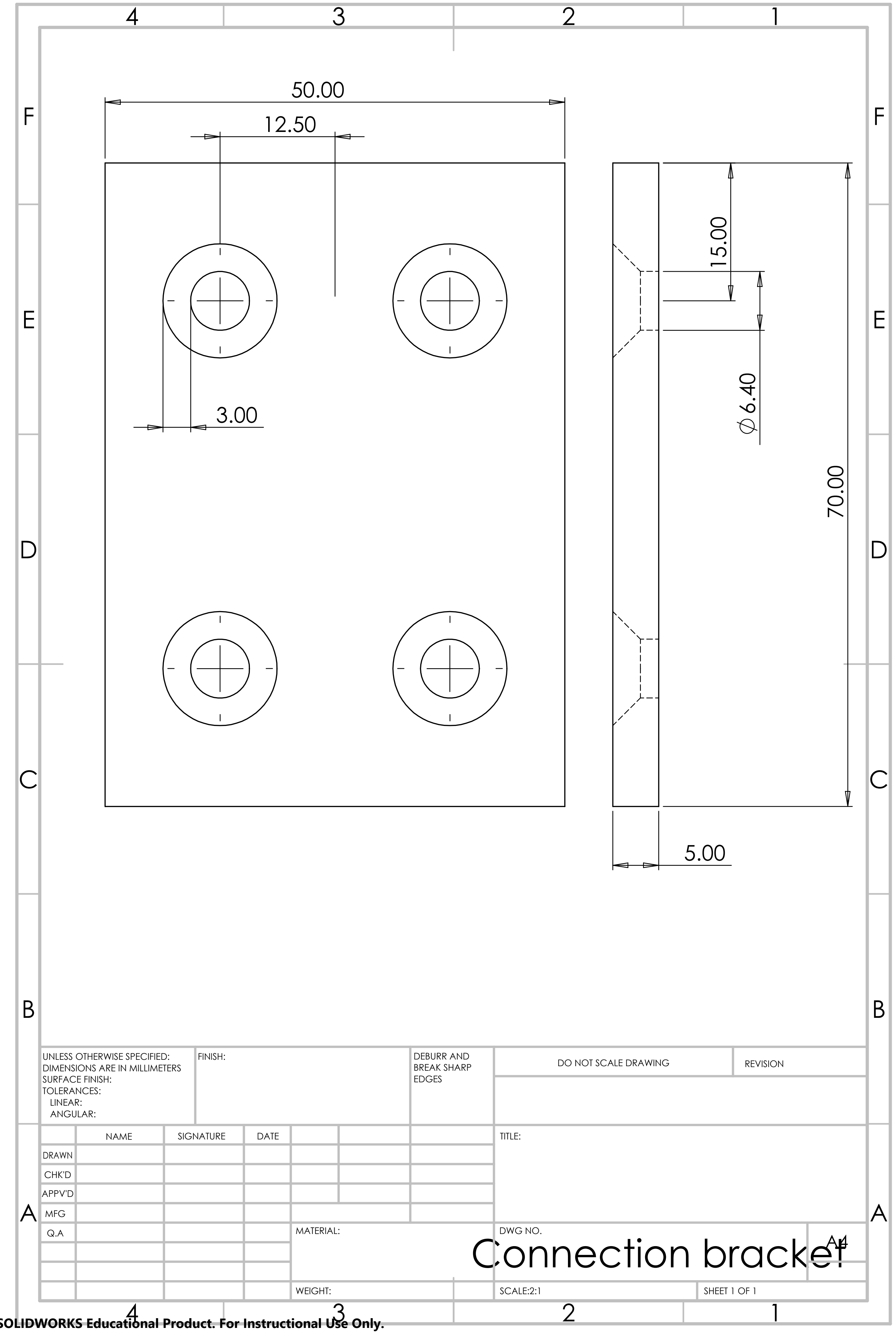
Figure 41.1: *Standalone framset*

The 3D printer's other configuration is its standalone version. This product uses almost all of the same components as it is Table-top counterpart except for a few component alterations. The standalone frameset [Fig.41.1] (now referred to as SFSET) is made in the same way that the core 3D printer is, using nearly all the same components except for the height of the vertical profiles which are now 488mm in length. Because there is now additional room the FlexTune™ containers (now holding 500ml each) have been moved to inside the SFSET Under the bottom liquid chamber is a drip tray as a safety measure to protect the electronics below [Fig.41.2]. The electrical assembly, as seen in 8.8, has also been moved to the bottom.

The access point for the printer has now been altered to address the addition of the SFSET. The rear still includes the e-chain cover but now includes a flat panel held in place by the four screws. The back of the STFET uses a cover with a hole for the electricals to feed in and out of at the bottom; whereas the front of the machine makes use of an extended component which covers up both the SFSET and core. The access panels are held in place by the magnets mentioned in 8.7.

To hold the core and SFSET together the Designer created an attachment bracket which can be found on the next page.

Figure 41.2: *Drip tray safety measure*



7.12 CONFIGURATION & SET-UP

The standalone 3D printer can come in two configurations:

- By itself – If the customer purchases a single unit then because of its short depth the product must be secured to a wall or another static object. The product has attachment brackets with a Ø10mm pin to hold and act as a pivoting point to access behind the machine (See Figure 42.1 and 42.2).
- As a pair – If the customer purchases two products then there is not a need to secure the machine to the wall. Instead, it is possible to connect them via a more secure attachment bracket [Fig.42.3]. Unlike the single unit, the machines cannot be moved to allow for access to the rear of the printer. However, as the front acces panels can be removed one machine can be maintained whilst the other is in operation [Fig.42.4].

The reason the front and rear panel is removable is so that if both machines are printing at the same time and the material needs refilling it can be done via the front access panel.

Figure 42.1: *Closed - Machine is fixed in place by the brackets*

Figure 42.2: *Accessable at the back - Maximum opening angle 60°*

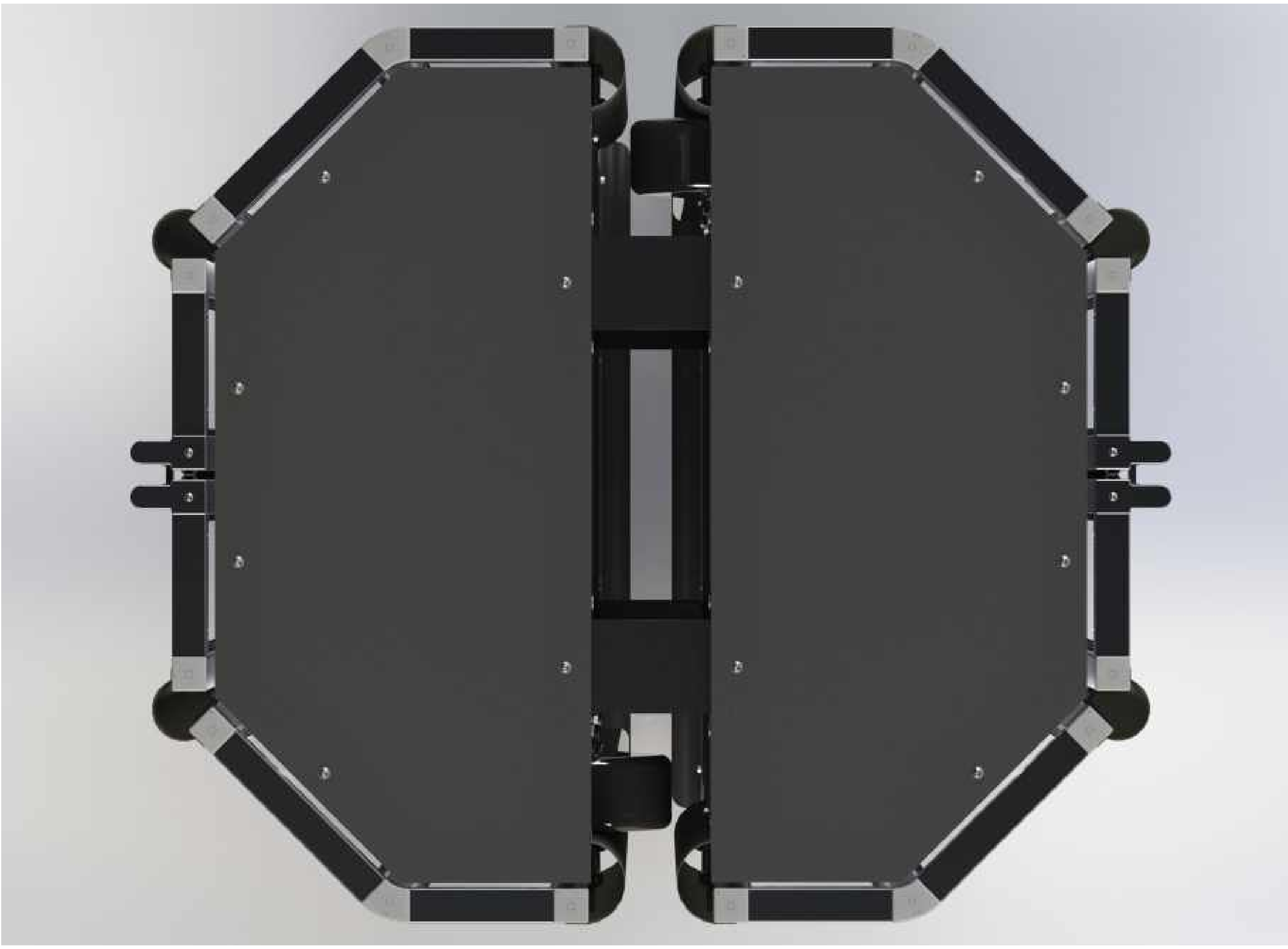


Figure 42.3.1: *Top view of both machines*

Figure 42.3.2: *Closed - Both machines are in opperation*

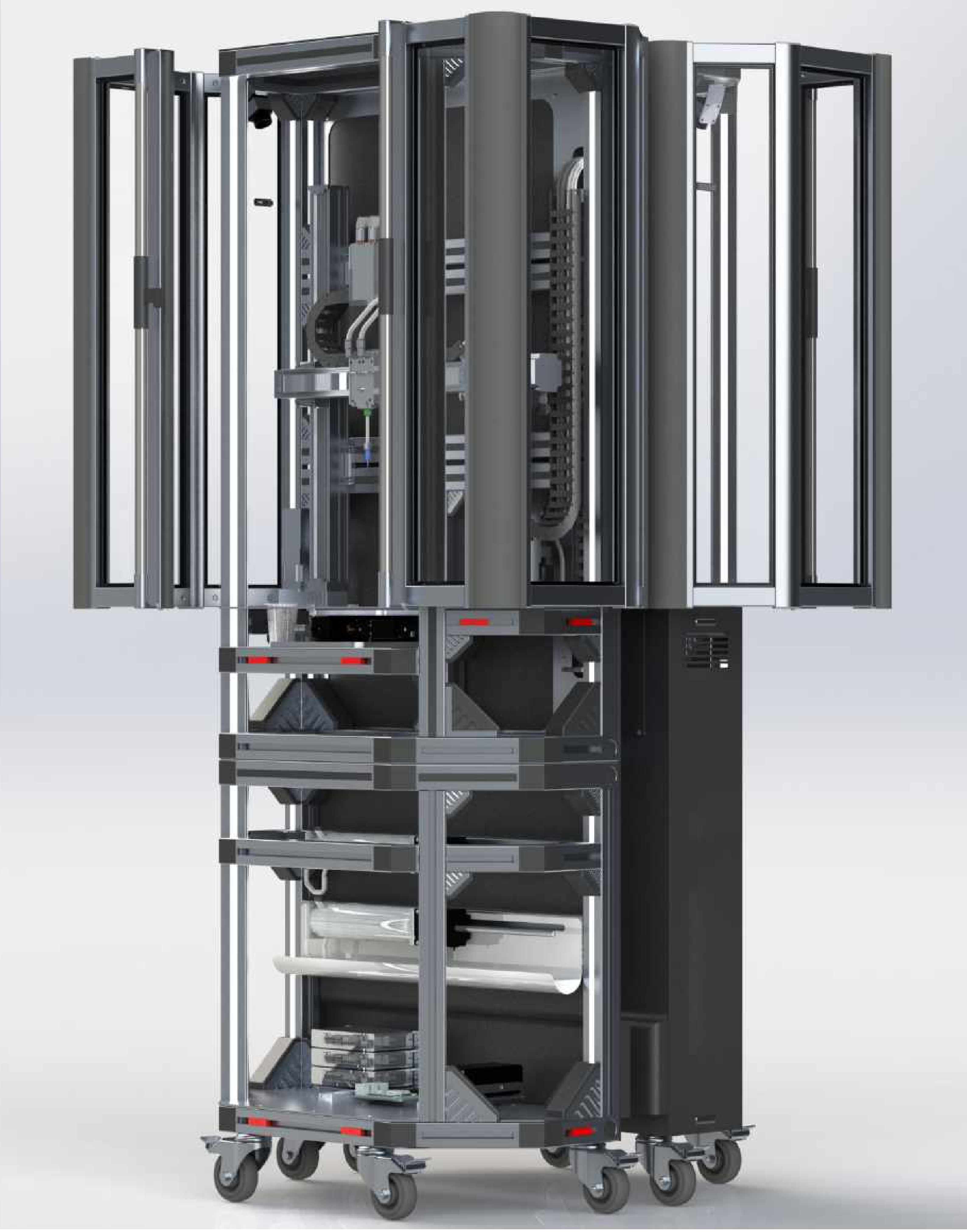


Figure 42.4: *Accessable at the back - Machine maintenance*

8 CONCLUSION

8.1 HOW TO USE THE PRINTER

The printer in either form functions in the same way. As mentioned in 9.1 the Standalone printer operates slightly different when accessing the rear of the product, however, the principle of what to do once the rear panel is off is the same. The process of setting up a print is fundamentally the same as any other printer that uses an external computer as a hosting system. Because this product does not have an integrated computer a hosting computer must be used to operate this machine.

The printer's software is still in development. C3D has proven that they can print in different ratios but unfortunately no publication or further research can determine what software they are using/developing.

Calibrating the printer consists of manual and automatic processes:

- Manual – The adjustment of the print bed involves using the laser readout and the user adjusting the bolts on the clamps. This either compresses or decompresses the rubber layer which acts as a compression spring.
- Automatic – The servo motors provided by Festo are capable of measuring power differences. When the cap of the static mixer touches the print bed and pushes into it this requires additional power which is a measurable factor. If the power required to move is greater than the normal then this is how the machine recognises it has touched the print bed and can determine the 'Z-axis zero'.

Maintaining the printer is carried out by a technician that checks the tubes for leaks and replaces parts where needed. As the LAs are ball screw this requires them to have routine lubricant checks and lubrication to be filtered through the product every-once-in-a-while.

On the next page is a user storyboard of the average use

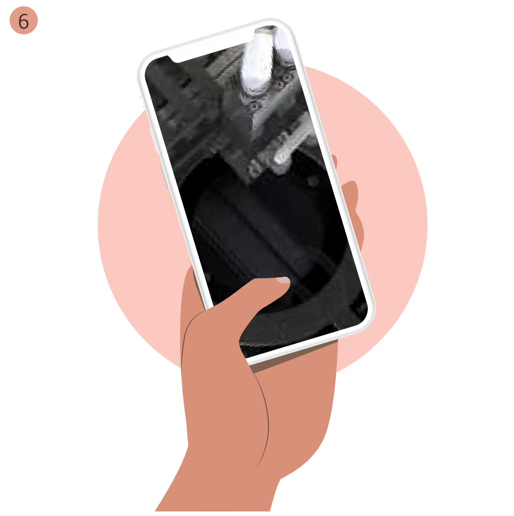
The Prosthetist finishes scanning the Amputee's stump

The scan gets edited and uploaded to the 3D printing software on the hosting computer for the printer

The Technician calibrates the machine following the instructions that are presented by the software

The doors then get closed

The file is sent to print, and estimated time and quantity of material is shown



The Technician can remotely check-up on the print via the camera using their phone

Once the print has finished the Technician gets a mobile alert

The print is then removed, and any clean-up is carried out

The Prosthetist then fits the prosthetic to the Amputee

Edited characters by and from Freepik

8.2 EVALUATION

The project has finished with a virtual product and several physical artefacts created during the ideation stage. This was far from the original idea but so is the final product. Looking at the first visual and physical prototypes it is so far from the final product which shows how the Designers mind has matured. The Designer is beyond happy to be presenting this manufacturing product as the solution to help create better prosthetics for LLA amputees.

8.3 FINAL PROPOSAL

The final deliverable for this project includes one product in two different configurations. The standalone unit would be the desired product to send out to customers, but the tabletop version was also created to offer a choice for those who have limited space or do not want to spend as much.

The product has been created in SolidWorks with rendering in both SolidWorks 2018 and KeyShot9. The product has been created virtually and no physical prototype has been produced because of the outbreak of COVID-19.

8.4 CONCLUSION

The Author has created a product that is designed to tackle the problem of mass prosthetic production for custom made prosthetic sockets. The project brought to light the current issues faced with lower limb prosthetic socket and uncovered the flaws in current manufacturing stages. The lack of innovation in this market is astonishing.

The manufacturing system developed by the Author produces custom-designed 3D printed prosthetic sockets within a day. This assists to speed up the process of prosthetic manufacturing for today, and tomorrows', market. There is a market gap for a manufacturing system dedicated to medical prosthetics production. The use of LAM (with FlexTune™) combined with Polar architecture addresses the specific issues faced when 3D manufacturing prosthetics; finally offering a solution in regards to slow production speeds and poor material choice.

Starting this dissertation brought to light the challenges that currently plague the manufacturing stages when creating a prosthetic socket. Even with medical and manufacturing advancements lower limb prosthetic sockets are still being made the same way they were last century. Though some companies have tried to progress this industry, ultimately they fail as they adapt current market 3D printers instead of developing a dedicated product. The possibility of 3D printing prosthetics has significant advantages for the company and amputee as time and money is saved by both parties. The opportunity to create a system capable of 3D printing prosthetic sockets will advance the market and assist in a better fitting, longer-lasting, and more comfortable products.

The final deliverable is a solution for manufacturing lower limb prosthetic sockets for a lower cost, with a massive reduction in time, and significantly higher customizability with a greater degree of finetuning. This leads to a prosthetic socket for a lower limb amputee that is functional and stable enough to compete with current market sockets, offering a new solution to a stagnant market

8.5 FUTURE DEVELOPMENT

The 'Ideal Outcome' would have a physical prototype to accompany this design report. However, because of an international crisis, this was not an option. Therefore, the next steps would be to create a physical prototype. Future development would be to create the motherboard/PCB along with further consideration for the wiring. Though there has been a lot of consideration given to how the wires and electrical systems would interact within the product the Author will need assistance in this area to get the final product ready.

Then once the product has been built the worlds first LAM 3D printed prosthetic socket can be shown to the world.

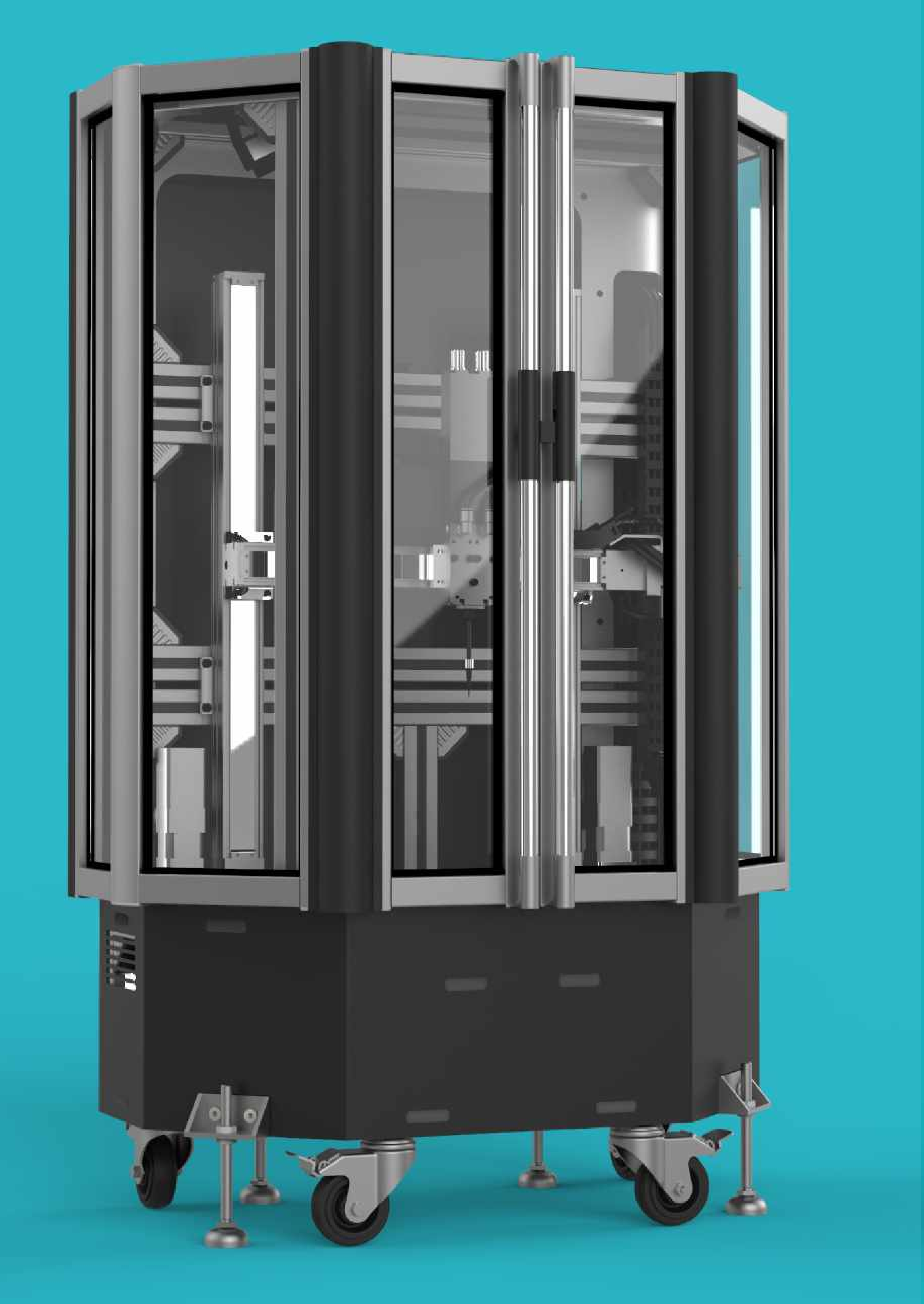
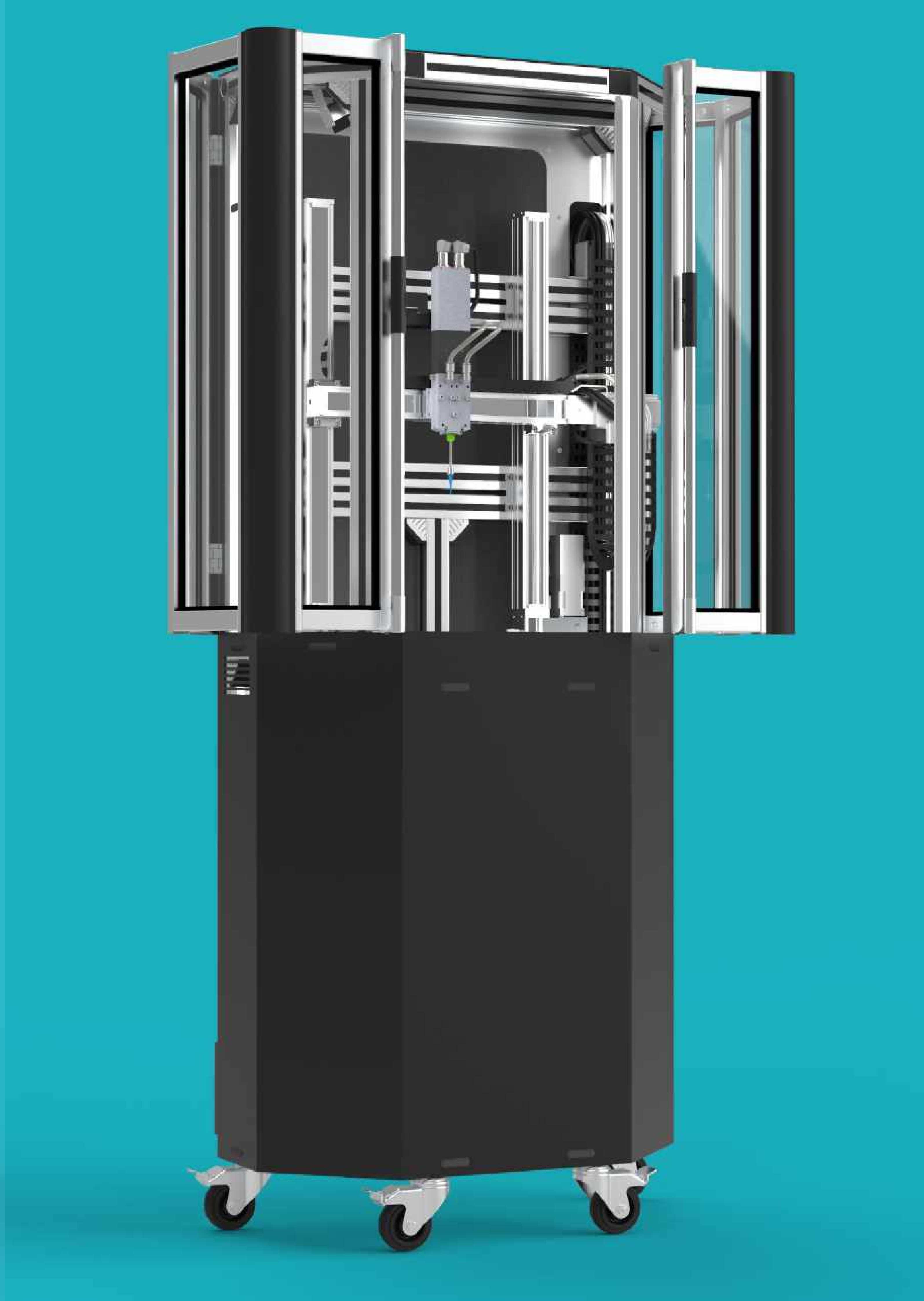
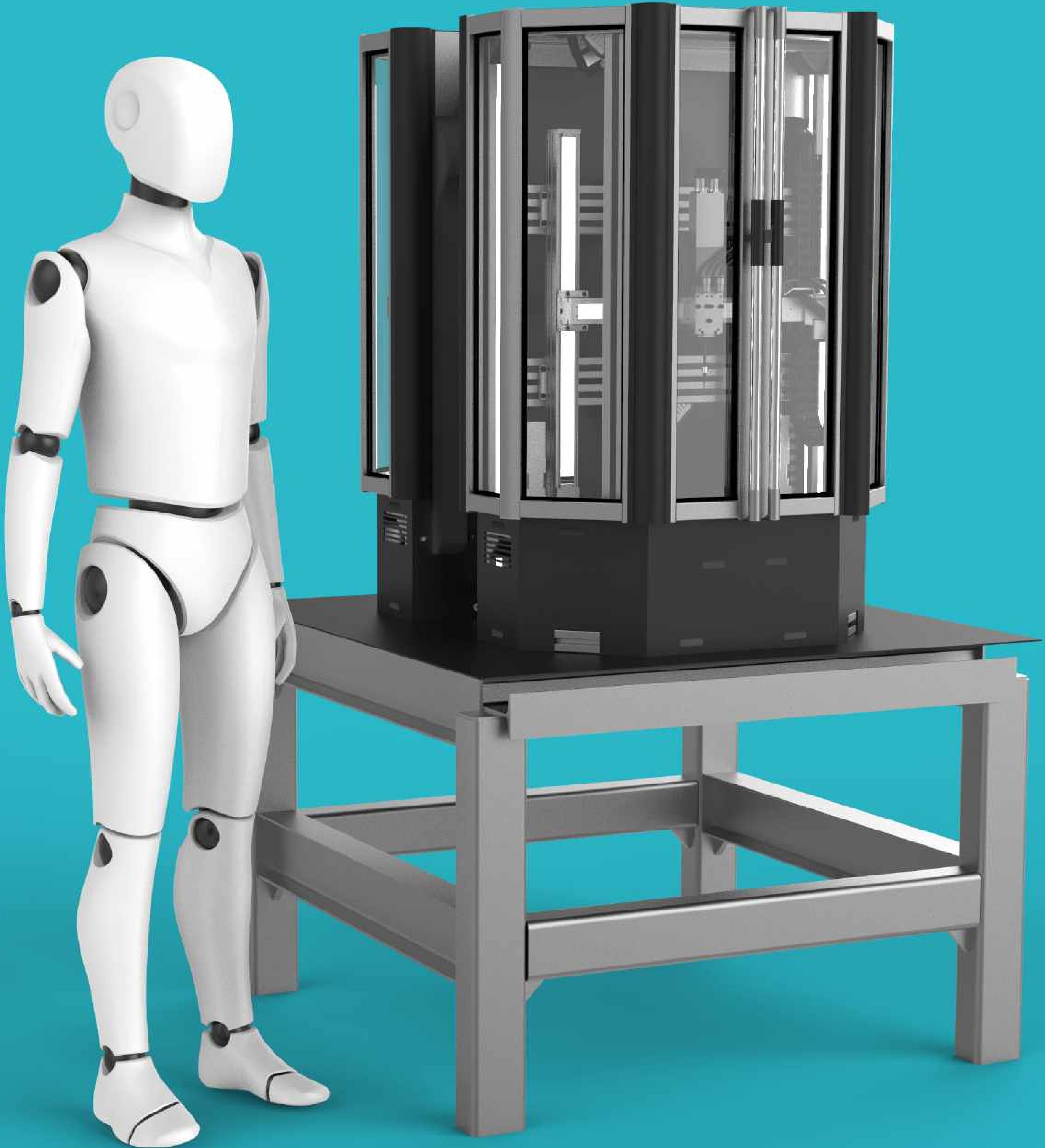
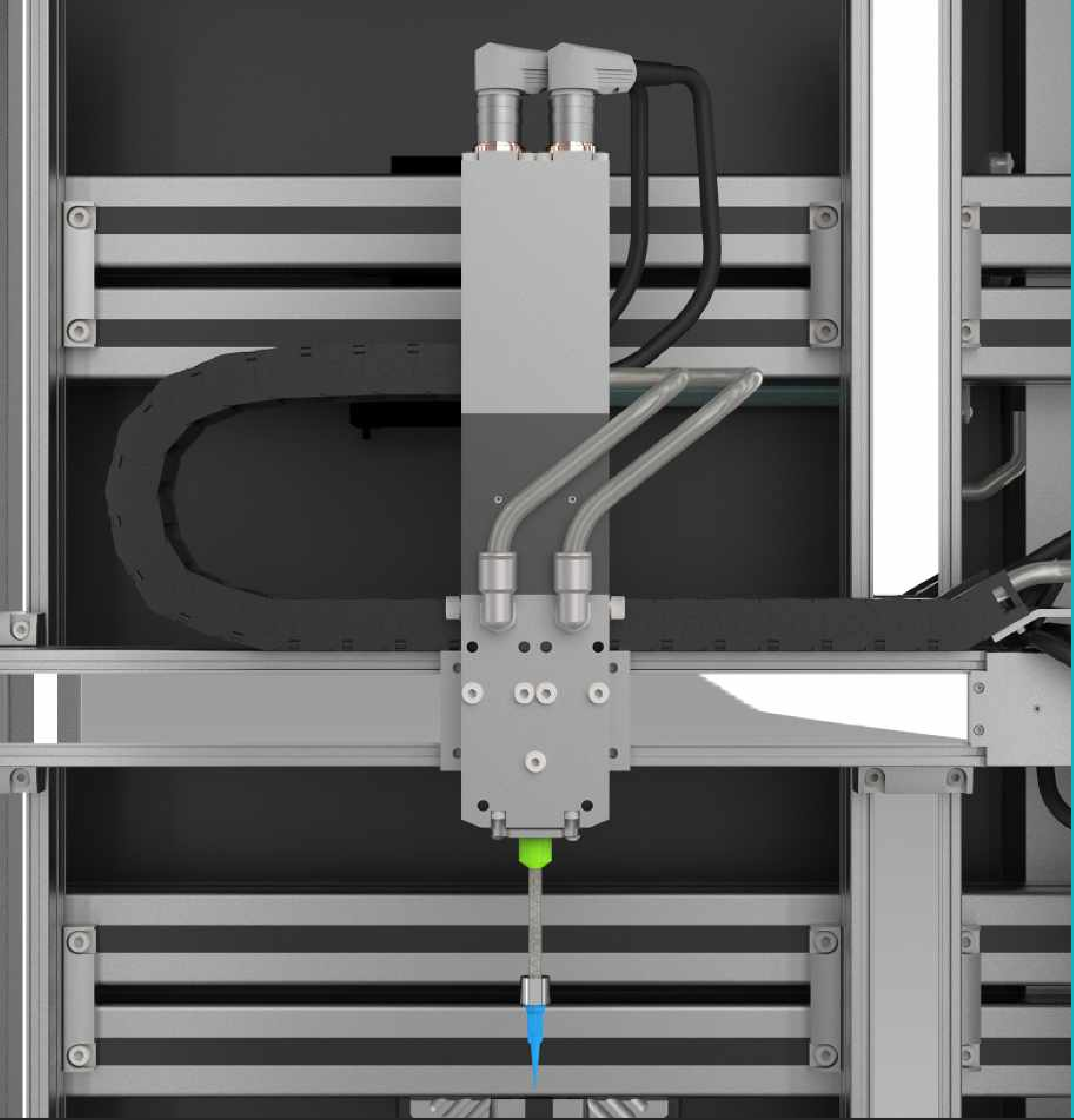
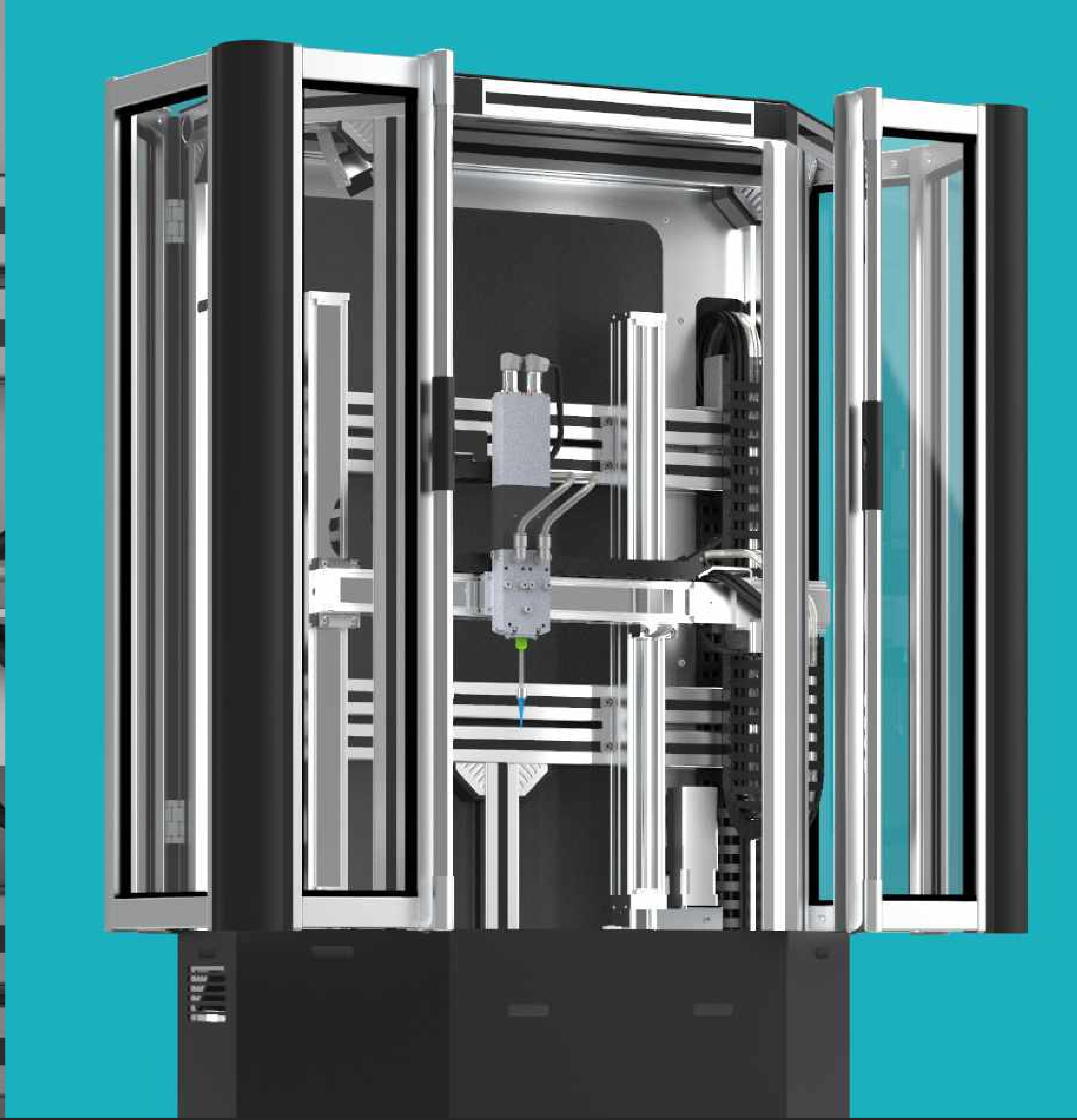



TABLE-TOP



STANDALONE





REFERENCES

3D Distributed, 2019. Renishaw Metal 3D Printer. [Online]
Available at: https://www.youtube.com/watch?v=Bf7KRxRVlyk
[Accessed 04 May 2020].

Access Prosthetics, 2017. 15 Limb Loss Statistics that May Surprise You. [Online]
Available at: https://accessprosthetics.com/15-limb-loss-statistics-may-surprise/
[Accessed 28 November 2019].

ALL3DP, 2019. 3D Printed Prosthetic Leg Made In 17 Days!. [Online]
Available at: https://all3dp.com/2/3d-printed-prosthetic-leg-most-promising-projects/
[Accessed 03 May 2020].

Amputee Coalition, 2015. Prosthetic FAQs for the New Amputee. [Online]
Available at: https://www.amputee-coalition.org/resources/prosthetic-faqs-for-the-new-amputee/
[Accessed 25 March 2020].

Baguley, R., 2015. Polar 3D — 3D Printer Review. [Online]
Available at: https://www.tomsguide.com/uk/us/polar-3d-printer,review-3206.html
[Accessed 04 May 2020].

BBC Click, 2016. BBC reporter and amputee tries out 3D printed legs - BBC Click. [Online]
Available at: https://www.youtube.com/watch?v=S7aKioxxSfk
[Accessed 23 March 2020].

DeLisa, J. A., 1998. Gait analysis in the science of rehabilitation. Department of Veterans Affairs.

Dimmock, D., n.d. dan dimmock 3mt71MKGjQ0 unsplash. [Online]
Available at: dan-dimmock-3mt71MKGjQ0-unsplash
[Accessed 28 April 2020].

Donnelly, L., 2019. Record numbers of amputations on NHS amid warnings 1 in 10 will soon suffer type two diabetes. [Online]
Available at: https://www.telegraph.co.uk/news/2019/04/02/record-numbers-amputations-nhs-amid-warnings-1-10-will-soon/
[Accessed 16 April 2020].

Drew, C., n.d. The Double Diamond: 15 years on. [Online]
Available at: https://www.designcouncil.org.uk/news-opinion/double-diamond-15-years
[Accessed 16 April 2020].

Footless Jo, 2019. 10 MORE Things I WISH Someone Said BEFORE Amputation!. [Online]
Available at: https://www.youtube.com/watch?v=4aBvTABWy1o&t=358s
[Accessed 04 May 2020].

Footless Jo, n.d. Footless Jo. [Online]
Available at: https://www.youtube.com/channel/UCvFroKGvBjvALxCTFzZXL5w
[Accessed 04 May 2020].

German RepRap, n.d. L320 3D printer. [Online]
Available at: https://www.germanreprap.com/printer/L320.aspx
[Accessed 27 November 2019].

Grobart, S., 2015. This Guy Has a Thought-Controlled Robotic Arm. [Online]
Available at: https://www.bloomberg.com/news/articles/2015-11-12/this-guy-has-a-thought-controlled-robotic-arm
[Accessed 05 May 2020].

Hapco incorporated, n.d. Hardness Chart. [Online]
Available at: https://hapcoincorporated.com/resources/hardness-comparison-chart/
[Accessed 23 March 2020].

HestonKent, 2014. Extruder slows down while printing small cylindrical objects. [Online]
Available at: http://www.soliforum.com/topic/7353/extruder-slows-down-while-printing-small-cylindrical-objects/
[Accessed 04 May 2020].

Kapp, S. & Miller, J., 2009. Lower Limb Prosthetics. Care of the Combat Amputee, p. 554.

Kenney Orthopedics, n.d. Moving from a Temporary to a Definitive Prosthesis. [Online]
Available at: https://www.kenneyorthopedics.com/about/news/view/416/moving-from-a-temporary-to-a-definitive-prosthesis
[Accessed 25 March 2020].

Made in Brunel, 2020. photos. [Online]
Available at: https://www.facebook.com/madeinbrunel/photos/a.1487931551273235/3005440429522332/?type=3&theater
[Accessed 28 April 2020].

Ottobock, n.d. Ipso Cast. [Online]
Available at: https://pe.ottobock.com/en/743G15.html
[Accessed 2 December 2019].

Part On, n.d. 40 x 40mm Light Aluminium Strut Profile Bosch Rexroth 3842 993 120. [Online]
Available at: https://www.part-on.co.uk/product/40-x-40mm-aluminium-profile-bosch-rexroth/
[Accessed 24 March 2020].

Photos Startup Stock, n.d. man wearing black and white stripe shirt looking at white 212286. [Online]
Available at: https://www.pexels.com/photo/man-wearing-black-and-white-stripe-shirt-looking-at-white-printer-papers-on-the-wall-212286/
[Accessed 28 April 2020].

Physiopedia, 2020. Lower Limb Prosthetic Sockets and Suspension Systems. [Online]
Available at: https://www.physio-pedia.com/Lower_Limb_Prosthetic_Sockets_and_Suspension_Systems
[Accessed 25 March 2020].

Pooja, D. G. & Sangeeta, L., 2013. Prevalence and aetiology of amputation in Kolkata, India: A retrospective analysis. Hong Kong Physiotherapy Journal, 31(1), p. 38.

Potok, B., 2018. I'm on My Fourth Check Socket - Is this normal?. [Online]
Available at: https://amputeestore.com/blogs/amputee-life/prosthetic-test-sockets-how-many-is-normal
[Accessed 25 March 2020].

Prosthetic & Orthotic Care, n.d. Prosthetic Timeline. [Online]
Available at: http://www.pandocare.com/prosthetic-timeline/
[Accessed 2 Devember 2019].

Prosthetic Design Inc., 2018. 3d printed socket faq's. [Online]
Available at: https://prostheticdesign.com/index.php?route=journal2/blog/post&journal_blog_post_id=6
[Accessed 04 May 2020].

Rader, M. T., n.d. matthew t rader zq4UnZoy5AQ unsplash. [Online]
Available at: https://unsplash.com/photos/zq4UnZoy5AQ
[Accessed 28 April 2020].

Ridderflex, n.d. Polyurethane rubber or plastic: terms are often mixed up - Ridderflex. [Online]
Available at: https://www.ridderflex.com/polyurethane-rubber-or-plastic-terms-are-often-mixed-up/
[Accessed 13 November 2019].

Rogers, B. et al., 2007. Advanced Trans-Tibial Socket Fabrication Using Selective Laser Sintering. Prosthetics and Orthotics Internationa, 31(1), p. 93.

Sbriglia, L. R. et al., 2016. Embedding Sensors in FDM Plastic Parts During Additive Manufacturing. Topics in Modal Analysis & Testing, Volume 10, pp. 205-214.

Templin, J., 2018. The US government just gave someone a $120-million robotic arm to use for a year. [Online]
Available at: https://qz.com/1194939/the-us-government-just-gave-someone-a-120-million-robotic-arm-to-use-for-a-year/
[Accessed 04 May 2020].

The Dow Chemical Company, 2018. SILASTIC™ 3D 3335 Liquid Silicone Rubber Technical Data Sheet. [Online]
Available at: https://www.dow.com/en-us/document-viewer.html?ramdomVar=8093021025852275507&docPath=/content/dam/dcc/documents/en-us/productdatasheet/45/45-15/45-1580-01-silastic-3d-3335-lsr.pdf
[Accessed 24 March 2020].

Tolchard, L., 2019. Increasing Comfort for Transtibial Amputees with Improvements to Prosthetic Design and Function Through 3D Manufacturing Method. Interim Report, 1(1).

ViscoTec, n.d. PRINT HEADS FOR VISCOUS FLUIDS & PASTES IN ADDITIVE MANUFACTURING. In: Materials. Töging am Inn: s.n., pp. 6-7.

Zastrozhnov, A., n.d. Wooden figure of man with artificial prosthetic leg. Amputee and disability concept.. [Online]
Available at: https://www.shutterstock.com/image-photo/wooden-figure-man-artificial-prosthetic-leg-1442825048
[Accessed 20 January 2020].

ZMorph Multitool 3D Printer, n.d. zmorph multitool 3d printer UqCCSbAIaDU unsplash. [Online]
Available at: https://unsplash.com/photos/UqCCSbAIaDU
[Accessed 28 April 2020].

APPENDIX

APPENDIX-1

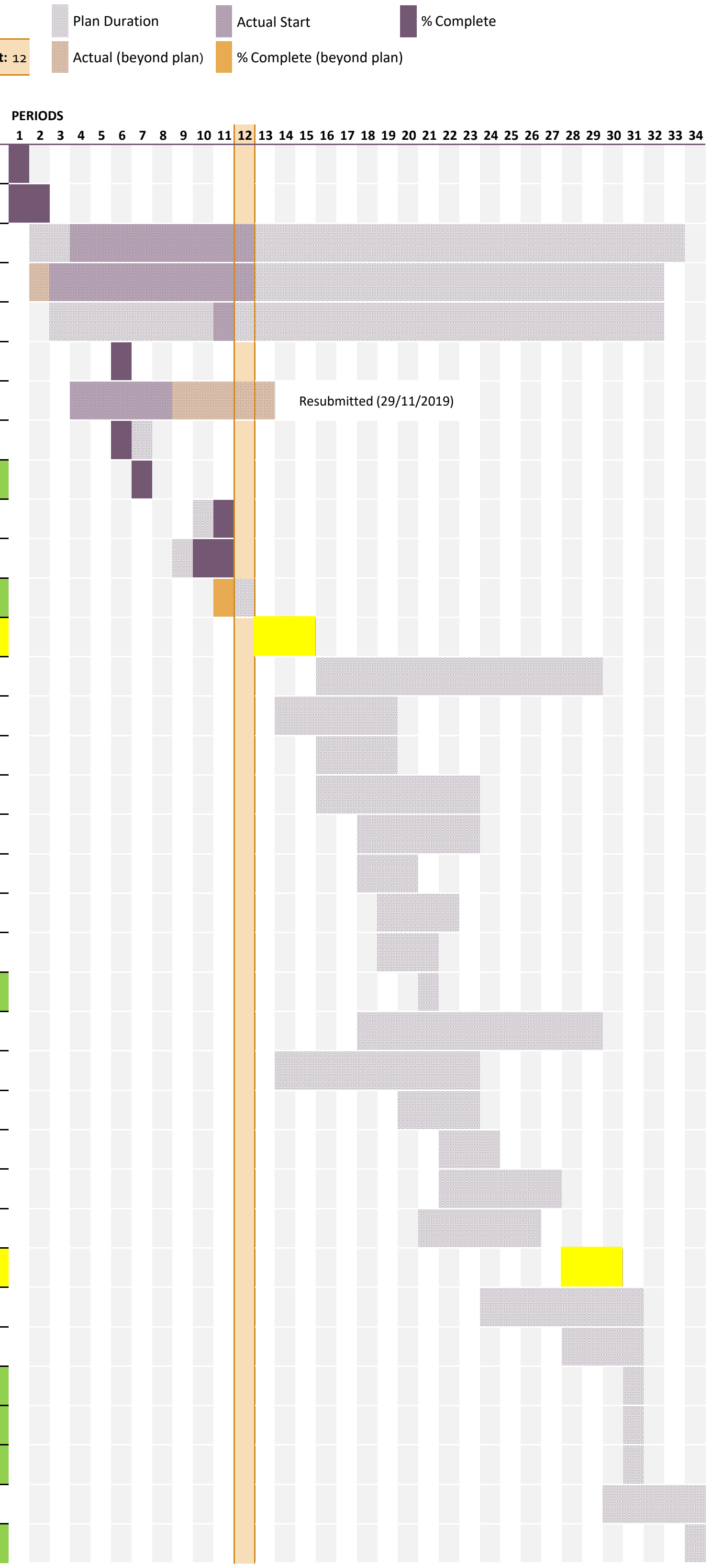
ORIGINAL GANTT CHART

Project Planner

Select a period to highlight at right. A legend describing the charting follows.

Period Highlight: 12

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Statement of Intent Submission	1	1	1	1	100%
Project Planning	1	2	1	2	100%
Meetings with Major Tutor	2	32	4	9	0%
Seconday Research	3	30	2	11	0%
Primary Research	3	30	11	1	0%
Risk Assessment	6	1	6	1	100%
Ethics Form	4	5	4	10	0%
Viva Boards Preperation	6	2	6	1	100%
Viva Presentation	7	1	7	1	100%
Initial Design Specification	10	2	11	1	100%
Intrum Report Preperation	9	3	10	2	100%
Intrum Report Hand-in	12	1	11	1	100%
Christmas Break	13	3	13	3	
Extruder Development	16	14	0	0	0%
Ideation	14	6	0	0	0%
Beta Prototype	16	4	0	0	0%
Testing	16	8	0	0	0%
Concept Development	18	6	0	0	0%
Design Specification Review	18	3	0	0	0%
Gama Prototype	19	4	0	0	0%
Preperation for IRE Board	19	3	0	0	0%
IRE Board	21	1	0	0	0%
Delta 3D printer development	18	12	0	0	0%
Ideation	14	10	0	0	0%
Beta Prototype	20	4	0	0	0%
Concept Development	22	3	0	0	0%
Testing	22	6	0	0	0%
Gama Prototype	21	6	0	0	0%
Easter Break	28	3	28	3	
Alpha Prototype	24	8	0	0	0%
Preperation for Final Design Package	28	4	0	0	0%
Submission of Final Design Package	31	1	0	0	0%
DIMP Business Model	31	1	0	0	0%
Final Report	31	1	0	0	0%
Preperation for Final Viva Presentation	30	5	0	0	0%
Final Viva Presentation	34	1	0	0	0%



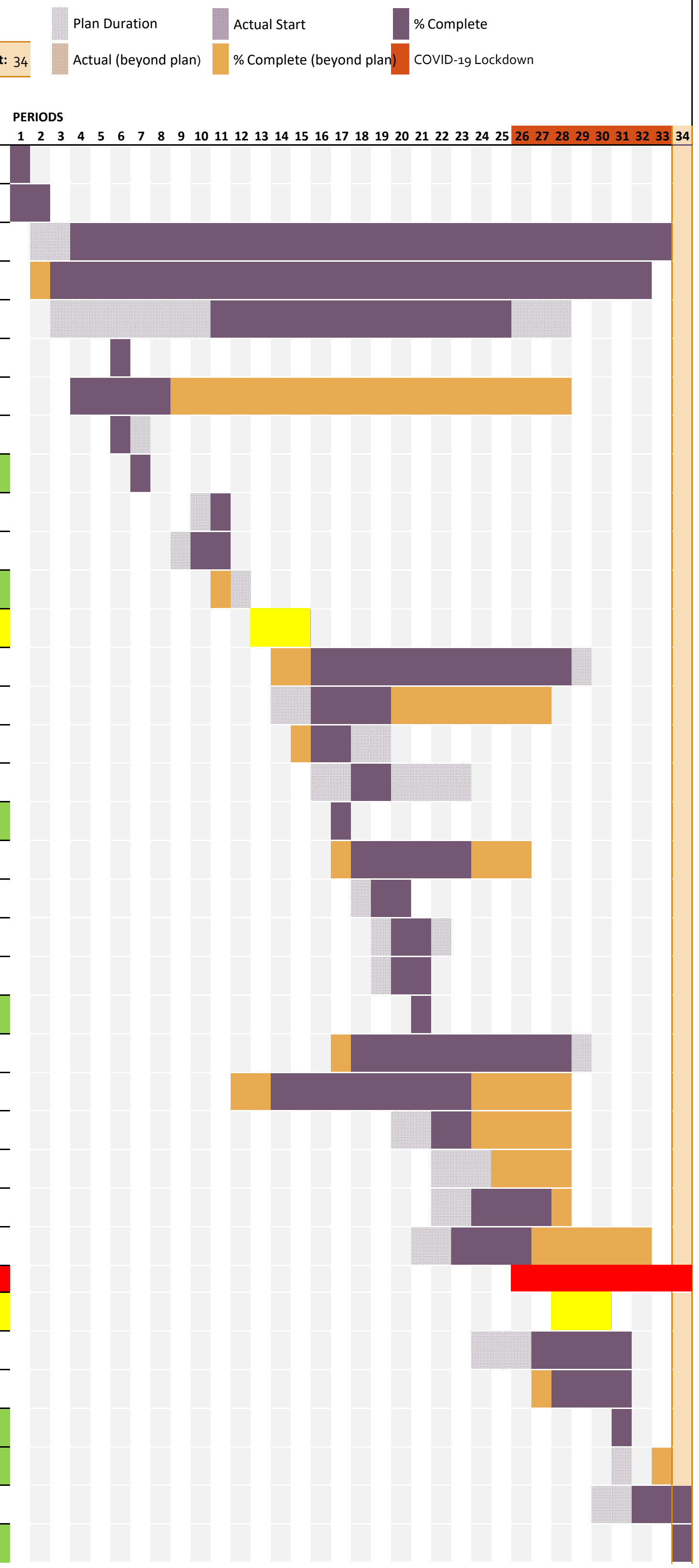
REVISED GANTT CHART

Project Planner

Major Project - Polar 3D Printer

Period Highlight: 34

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Statement of Intent Submission	1	1	1	1	100%
Project Planning	1	2	1	2	100%
Meetings with Major Tutor	2	32	4	30	100%
Seconday Research	3	30	2	31	100%
Primary Research	3	26	11	15	100%
Risk Assessment	6	1	6	1	100%
Ethics Form	4	5	4	25	100%
Viva Boards Preperation	6	2	6	1	100%
Viva Presentation	7	1	7	1	100%
Initial Design Specification	10	2	11	1	100%
Intrum Report Preperation	9	3	10	2	100%
Intrum Report Hand-in	12	1	11	1	100%
Christmas Break	13	3	13	3	
Mechanics Development	16	14	14	15	100%
Ideation	14	6	16	12	100%
Beta Prototype V1 (Digital)	16	4	15	3	100%
Testing	16	8	18	2	100%
DIMP Business Model	17	1	17	1	100%
Concept Development	18	6	17	10	100%
Design Specification	18	3	19	2	100%
Gama Prototype V1 (Physical)	19	4	20	2	100%
Preperation for IRE Board	19	3	20	2	100%
IRE Board	21	1	21	1	100%
Polar 3D printer development	18	12	17	12	100%
Ideation	14	10	12	17	100%
Beta Prototype V2 (Digital)	20	4	22	7	100%
Concept Development	22	3	25	4	100%
Digital Testing	22	6	24	5	100%
Gama Prototype V2 (Digital)	21	6	23	10	100%
COVID 19	26				
Easter Break	28	3	28	3	
Alpha Prototype (Digital)	24	8	27	5	100%
Preperation for Final Design	28	4	27	5	100%
Submission of Final Design	31	1	31	1	100%
Final Report	31	1	33	1	100%
Preperation for Final Viva	30	5	32	3	100%
Final Viva Presentation	34	1	34	1	100%



Red marks subjects that were affected by COVID-19

APPENDIX-2

RE: Subject: Get in touch

GM **Gergana** [redacted]
02/12/2019 09:37

To: Luke Tolchard (Student)

Hi Luke,

Unfortunately, a lot of the info requested could be considered IP for us but I can say that we have designed our own cloud software platform, specifically for creating above-knee and below-knee prosthetic sockets for 3D printing, with upcoming projects to include upper-limb applications.

The socket is being scanned by 3rd party scanners, exporting a .stl file which is then imported within our software. The prosthetist will make an alignment of the socket in the 3d environment using special tools, will attach a connector and rectify the socket surface depending on the patient's medical needs. The file then is being sent to us, we check the structural integrity, add certain variable thickness as required and send for printing and delivery.

We are currently printing using MJF technology, with the expertise of FDM and SLS in the past. We are also now experimenting with TPU materials for soft inner sockets as the latest and most promising in the field.

Bear in mind that one of the issues in the industry has been acquiring regulations for the sockets and deciding on the legal responsibilities as these are considered medical devices, therefore carrying strict regulatory burden. A lot has been done lately in the experimental sense worldwide but we are aiming to ensure industrial approaches and standards, certifying sockets as medical devices under ISO. In that way the industry gains more confidence when working with new technologies which turns to be a key element in this conservative community.

In that sense, developing a 3D printer sounds challenging and yet intriguing so good luck and I hope that we have been helpful.

Keep us posted with new updates on the process,
Gergana

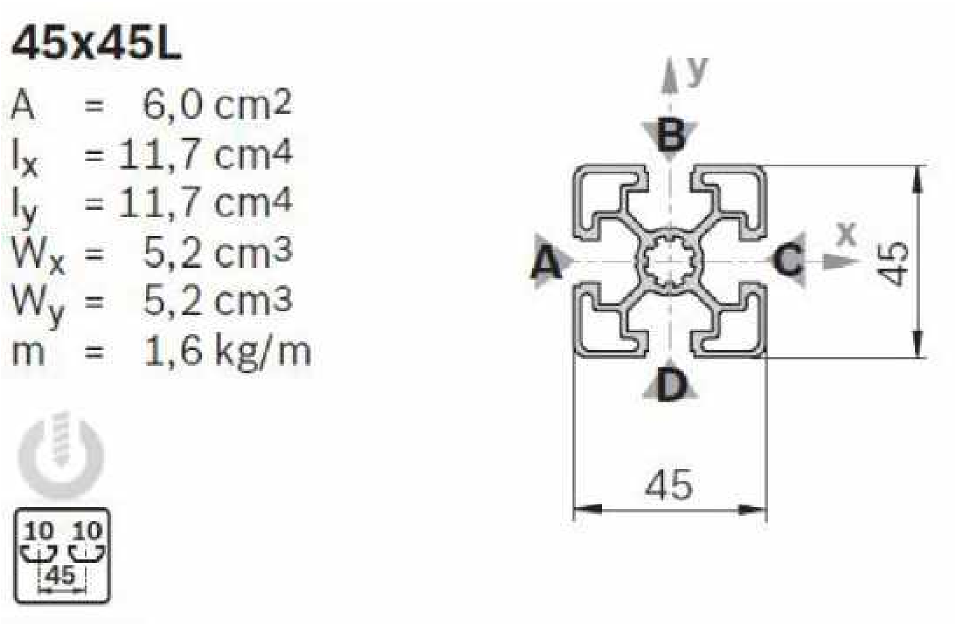
This e-mail describes what ProsFit use in their creation of products

APPENDIX-3

All Motion units are by Bosch Rexroth:

1. Print Bed (Z) - Compact Modules with toothed belt drive - CKR
2. Two Parallel Linear Actuators (Y) - Closed-type drive units with ball screw drive - AGK
3. Extruder (X) - Compact Modules with toothed belt drive - CKR

German RepRap L320 top half EDITED (German RepRap, n.d.)



40 x 40mm Light Aluminium Strut Profile Bosch Rexroth (Part On, n.d.)

APPENDIX-4

Shore A and D hardness comparison (Hapco incorporated, n.d.)

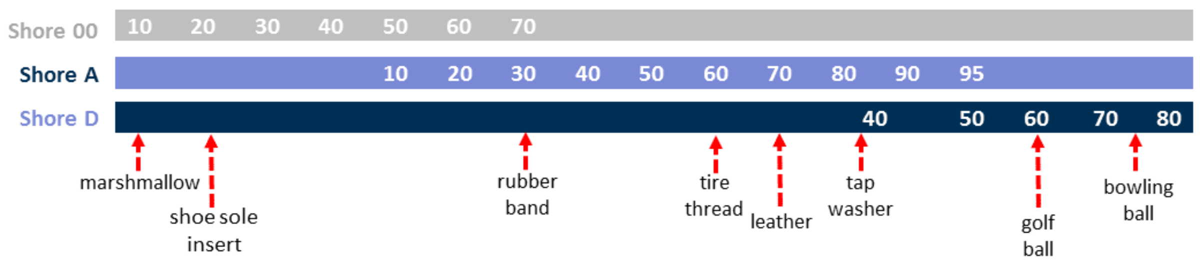


Figure 7 *Shore hardness levels of PU (Ridderflex, n.d.)*

APPENDIX-6

MATERIALS

1-COMPONENT MATERIALS

A selection of possible materials:

- UV adhesives
- Epoxy resins
- Acrylate
- Silicone
- Grease
- Inks
- Waxes
- Abrasive pastes
- Bio-technichal suspensions
- Advanced, high-performance and technical ceramics
- ...

2-COMPONENT MATERIALS

A selection of possible materials:

- Silicone
- Epoxy resins
- Polyurethane
- Acrylate
- Polyester resins
- ...

The viscous fluids are cross-linked and give the component the properties that they need for production.

CURING METHODS

UV, humidity, heat and a combination of these.

Page 6 of the ViscoTex brochure – Materials (ViscoTec, n.d.)

APPENDIX-7

2-COMPONENT PRINT HEAD

MOTOR

- Control via 3D print signals
- Compact design with parallel arrangement of the individual motors

MATERIAL SUPPLY & BLEEDING SCREW

- Easy product handling
- Optional bleeding screw for uncomplicated bleeding

ENDLESS PISTON PRINCIPLE

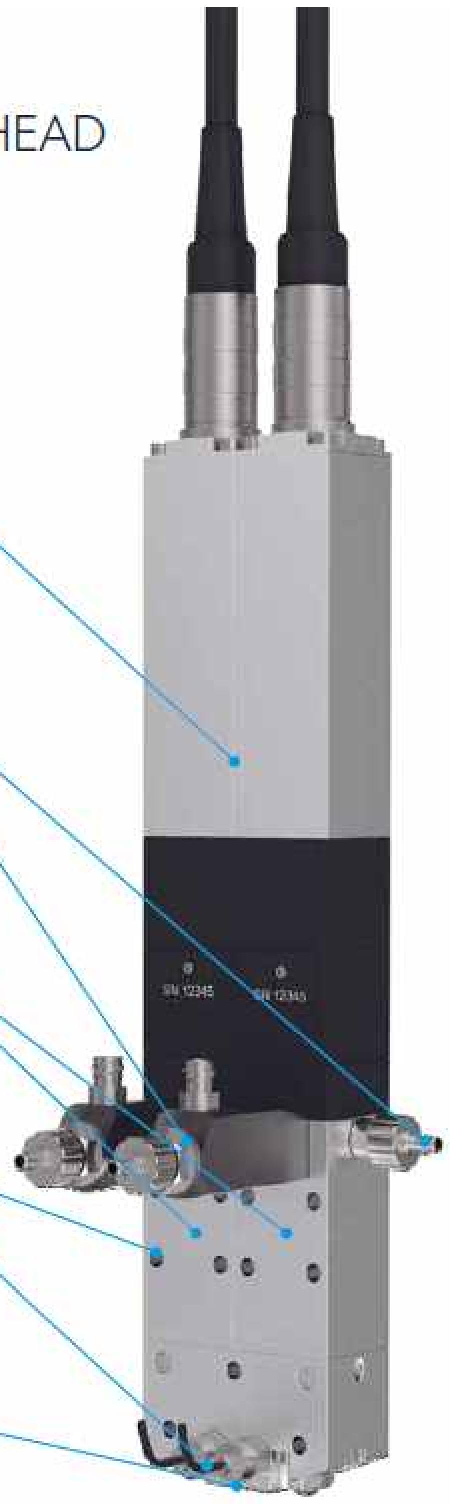
- Continuous dispensing
- For almost all viscous 2-component fluids and pastes

MONITORING & CONNECTION

- Optional monitoring via pressure sensor (material inlet and outlet)
- Different opportunities to connect print head with 3D printer

STATIC MIXER

- A wide range of different static mixers
- Optimum mixing of 2-component fluids and pastes



Page 5 of the ViscoTex brochure – 2-Component Print Head (ViscoTec, n.d.)

APPENDIX-8

List of companies that were contacted and their responses (if they responded):

ROTATIONAL PRINT PLATFORM:

- Applegate
- Automotion Components
- Laser Support Services Ltd
- Standa

Inbox | Sent

Sort By: Date, most recent first

Search for: Go!

Graham [redacted], Laser Support Services Ltd.
Re. Re. Re. ST-8MR170-190 - Motorized Rotary Stages

Graham [redacted], Laser Support Services Ltd.
Re. ST-8MR170-190 - Motorized Rotary Stages

Re. Re. Re. ST-8MR170-190 - Motorized Rotary Stages
Graham [redacted], Laser Support Services Ltd.

Reply

OK Luke.

I will send you a quotation for a rotary stage, a controller and a power supply, this will come with its own software but will have, labview, matlab C vis basic drivers.

Can you send me an email please to g.rogers@laser-support.co.uk, I will send you the quotation direct

Regards,

Graham [redacted] Laser Support Services Ltd.

The content of this message is the sole responsibility of the sender and no part of this message should be considered attributable to Applegate, which acts as facilitator only for the communication.

On , Luke Tolchard wrote:

This isnt a replacement,

I was looking to use one of your rotating systems in the product I'm building.

Is this not possible?

I need a rotating platform for my product and something like the one below works really well in this application

Regards,

Luke Tolchard

The content of this message is the sole responsibility of the sender and no part of this

Re: Activation code

SW [redacted]
02/03/2020 09:51

To: Luke Tolchard (Student)

Dear Luke,

Thank you for your email.

Your claim code is [redacted]

I trust this information is helpful.

If you require further assistance please do not hesitate to contact us.

Kind regards

Luke

Luke [redacted]
Automotion Components Sales Team
Email: [redacted]
Web: www.automotioncomponents.co.uk
Tel: 0333 207 4498
Automotion Components Ltd, Alexia House,Glenmore Business Park,
Portfield Works, Chichester, W. Sussex, PO19 7BJ

The information in this e-mail and in any attachments is confidential and is intended solely for the attention and use of the named addressee(s). It might contain privileged information. If it has come to you in error and you are not the intended recipient you must not disclose, copy, use or disseminate any information contained therein, please delete it and contact us without delay so that we may take whatever action we consider appropriate. Although this e-mail and any attachments are believed to be free from any virus it remains the responsibility of the recipient to ensure that this e-mail and any attachment is virus free and no responsibility is accepted by us in this regard. Company Reg. No: 2761902 VAT Reg. No: 566 9902 88

Activate

Re: ST-8MR170-190 - Motorized Rotary Stages

G

g.[redacted] <g.[redacted]@laser-support.co.uk>
02/04/2020 16:51

To: Luke Tolchard (Student)

[redacted]Luke.pdf
5.77 KB

Hi Luke

Thank you for your email.

I have attached our quotation to supply you with a rotary stage, controller and power supply.

If you require any additional information, please do not hesitate to contact me

Best regards

Grahame [redacted]
laser Support Services Ltd

[redacted]

Re: Product Enquiry - Motorized Rotation Stage

GM

Giedrius [redacted]
07/04/2020 11:15

To: Luke Tolchard (Student)

Pro...
64.81 KB

Dear Mr. Tolchard,

Thank you for your web-request and interest in our products. Apologies for delayed response.
I am sending you Pro-Forma Invoice / Quotation No. [redacted], please find it attached.
Both stages are quoted, I have also included controller and power supply that fits for both options.

Now, can I ask to clarify, in what orientation are you planing to use this stage? Will you use stage in horizontal or in vertical position?
Will the load be centered on rotation axis or will center of mass be offside the rotation axis.
8MR190-90 series stage is better suited to handle higher loads then 8MR170-190 series.
8MR170-190 stage is fitter with motorized actuator screw, which means it is spring loaded (to return stage carrier back when actuator screw is going back).
I have quoted both stages with 8SMC5-USB-B8-1 controller and power supply.
Our 8SMC5-USB series controller can drive stepper/dc/servo motors.
For all of our motorized stages we do provide motor profiles, but if you know motor parameters, you can easily prepare motor profile yourself.
We do offer XiLab software, but our controller is compatible with : C++, C#, .NET, Delphi, Visual Basic, gcc, Xcode, Matlab, Java, LabVIEW, Python
Here you can read more about Example of motor connection:
https://doc.xisupport.com/en/8smc5-usb/8SMCn-USB/Quick_start_guide/Example_of_a_motor_connection.html
Here you can read more about setting motor profile:
https://doc.xisupport.com/en/8smc5-usb/8SMCn-USB/Quick_start_guide/Manual_profile_setting.html

Our Software support could help to answer questions you would have when setting everything.

I have included 3 axis controller version for price reference, if you are interested. Same power supply applies for this controller.

We do have everything on stack and can dispatch in 1 day after receiving order.

If you have any questions, please feel free to contact me.

Looking forward to hearing from you.

Sincerely,

Giedrius [redacted]
Sales Engineer

STANDA
E-mail: [redacted]

LINEAR AXES:

- Barch
- Bosch Rexroth
- Festo
- IsoTech
- Macron
- Rollon

Re:RE: Re:RE: Re:RE: Mr. Luke Tolchard, details of XYZ gantry

A Alice [redacted]
24/03/2020 09:45

To: Luke Tolchard (Student)

X40-10_L500.STEP
17.45 MB

Hello Luke,

Please try this one.

———

BARCH

Best regards,

Alice [redacted]

Sales Manager

Homepage: www.barchmotion.com

BARCH Stuttgart: +49 [redacted] BARCH Hong Kong: +852 [redacted] BARCH China: +86 [redacted]

[redacted] Linear Motion - Products needed for project

DS DCGB Customer Services [redacted]
20/02/2020 17:16

To: Luke Tolchard (Student)

[redacted]

Linear Motion - Products needed for project

Hi Luke
Without more application details such as speed and precision it is difficult to make an exact recommendation but I would suggest looking initially at our CKK range of ballscrew driven compact modules
Initially I would look at the CKK90 for the base axis and the CKK70 for the upper axis
More information is available at:
https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-axes-and-electromechanical-cylinders/linear-axes/connection-technologies

These can be easily combined to make XY systems and we have a range of connection kits which use our easy to combine interface which ensures that they are locked in position
More details from
https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-axes-and-electromechanical-cylinders/linear-axes/connection-technologies

If you need any further assistance with selection, sizing etc then please let me know

With kind regards,
Edmonds [redacted]

Should you wish to send further email communication on this matter please refer to case number [redacted] in the subject line.

Bosch Rexroth Ltd
Customer & Sales Support
[redacted]
www.boschrexroth.co.uk
boschrexroth.co.uk/eshop

RE: Festo Contact information

SJ [redacted] Joshua [redacted]
01/04/2020 11:08

To: Luke Tolchard (Student)

Hello Luke,

I trust you are well.

Please change the field separator to a semicolon.

Import

Back | Create New Net Price List | Start Import

Field separator ;
String delimiter "

Festo part number are in column no. -
Quantities are in column no. -
My own part numbers are in column no. (option) -
Identcode 1 are in column no. (option) -
Identcode 2 are in column no. (option) -
x-Stroke values are in column no. (option) -
Save settings

	Position	Part No.	Qty.	Your part no.	Identcode 1	Identcode 2	x-Stroke	Basketname
☑	"Posi	Part No.		Your part no.	Identcode 1	Identcode 2	x-Stroke	
☑	1	8061486	1					
☑	2	4597016	3					
☑	3	1370475	1					
☑	4	8084005	3					
☑	5	1450737	3					
☑	6	1451675	3					
☑	7	8081885	3					
☑	8	8061488	2					
☑	9	1370477	2					
☑	10	8066714	2					

Back | Create New Net Price List | Start Import

Kind Regards

Joshua [redacted]

FESTO

FW: Isotech, Inc Contact Form

DC Dave [redacted]
18/03/2020 19:42

To: Luke Tolchard (Student)

Product-Idea.pdf
382.66 KB

Hi Luke,

Are you looking for the hardware only and you will be doing your own motors and controls?

Or are you looking for a full turnkey solution – hardware, motor, drive, cables, Electrical Design, panel fabrication, software development?

Is this a one time project or will this go into production?

Thank you!
Dave [redacted]
Isotech, Inc.
[redacted]
Fax: [redacted]
New Address
[redacted]
www.IsotechInc.com
[redacted]

RE: Brunel University London RFQ

MG

Michael [redacted]

23/03/2020 21:31

To: Luke Tolchard (Student)

MCS-R15-500-500-S300_B.zip
3.92 MB

See attached revised model

MACRON

Michael [redacted]
National Sales Manager
[redacted]
www.macrondynamics.com

R: 3D Printer - Call on Friday 28th

AA

ABT Application [redacted]

18/03/2020 10:21

To: Luke Tolchard (Student) [redacted]

Save all attachments

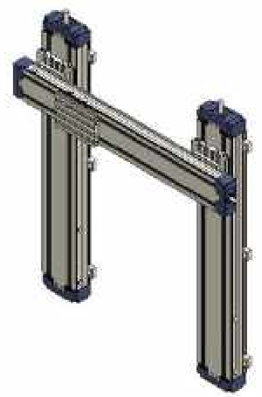
LY00544.zip 1.54 MB | Y-Axis.pdf 455.27 KB | Z-Axis.pdf 459.03 KB

Hello Luke,

After realizing that the two parallel units will be mounted vertically I had to revise the sizing. 2 x TH 90 SP4 will not have a sufficient lifetime of the ball screws (about 20'000 km) and I would **suggest to use 2 x TH 110 SP4 instead.**

Z-Axis (Vertical): **2 x TH 110 SP4** (Ø16mm, 10mm lead) – (500mm of stroke and 500mm of central distance)
Y-Axis (Horizontal): **TH 90 SP4** (Ø12mm, 5mm lead) - (250mm of stroke, 220mm of extra stroke)

Enclosed you can find the updated report for the two axes and the updated 3D model in STEP format.



- We always suggest to fix the profiles on a rigid structure by means of fixing brackets. In this case I considered a total number of 12 x TH 110 fixing brackets (Rollon code 1002970) which require M6 screws
- You can find some commonly used wrap-around kits with TH 90 and TH 110 in our catalogue on page PS-20 to have an idea about the interface dimensions (shaft diameter, centering diameter and bolt circle) of the commonly used servomotors on these units.

APPENDIX-9

Details about the manufacturing system and the mechanical requirements/set-up

3D Printer

1. Application

The product in development is a 3D printer. There are 2 Z-axis and 1 XY-axis linear actuators - 2 Vertical (Z-axis) linear actuators work in parallel to move 1 Horizontal (XY-axis) linear actuator a distance of 0mm to 500mm (stroke length = 500mm).

2. Product environment

The product is intended for medical applications. The product will be situated in clean rooms but the 3D manufactured product cannot risk any contamination – This is of the utmost importance, keeping the work area clean.

3. How many systems?

This initial product would be a prototype but if everything goes to plan and this product gets greenlit then we would assume anywhere around 100 – 500 units over several years. Accurate numbers are unknown.

4. The 1.3kg at 320mm – is this the COG

The extruder would be resting at it's 'Zero' (0) position which would be away from the centre of the print bed (Refer to the Blue line in the first email). So, the machines resting position would be its most common position.

I'm not certain what the products Centre of Gravity is but it wouldn't be directly in the centre, it would bias to one side.

5. What speeds are involved?

Print speed	**10 - 150 mm/s**
Travel speed	**10 - 300 mm/s**

6. What degree of accuracy is needed?

The degree of accuracy needs to be high but doesn't require Nanometre precision. Its needs high repeatability as this machine is being designed for custom made medical devices (prosthetics and orthotics). Accuracy is needed so the **accuracy of +/- 0.2mm.**

The layer height of a typical 3D print is measured in millimetres (<1mm layer height) so each 'step' of the Z-axis must be accurate when moving small distances.

7. What max speed?

Ref. '5. What speeds are involved'

8. Maximum acceleration?

Moving Speeds/Acceleration: 0 – 300mm/s in under 5-seconds but greater than 3-seconds

3D Printer

Speed difference	
Initial speed	0 m/s
Final speed	0.3 m/s
Time	5 sec
Acceleration	0.06 m/s^2

Speed difference	
Initial speed	0 m/s
Final speed	0.3 m/s
Time	3 sec
Acceleration	0.1 m/s^2

Printing Speeds/Acceleration: 0 – 150mm/s in under 4-seconds but greater than 1-second

Speed difference	
Initial speed	0 m/s
Final speed	0.15 m/s
Time	4 sec
Acceleration	0.0375 m/s^2

Speed difference	
Initial speed	0 m/s
Final speed	0.15 m/s
Time	1 sec
Acceleration	0.15 m/s^2

9. Price?

The product would range from £30k - £55k (€33k - €67k)

Provide suitable components that keep this product price in mind. The extruder costs £12k so the solution you provide must be secure enough so that this product is safe.

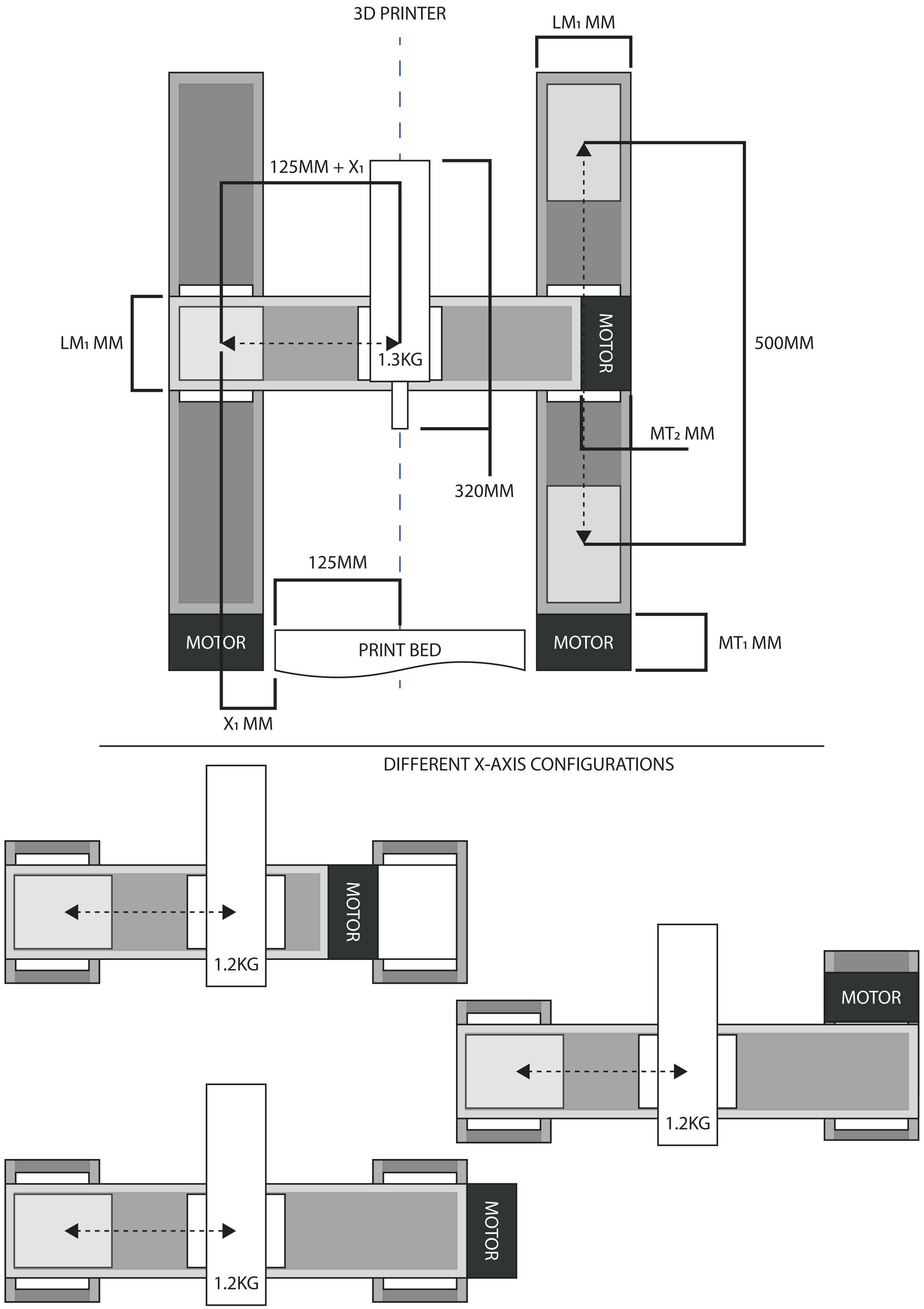
(Could you provide a cost break of all the components needed? i.e. Axes; Servo; Power supply; etc. So, I can pass this onto the project supervisor).

10. Scalability

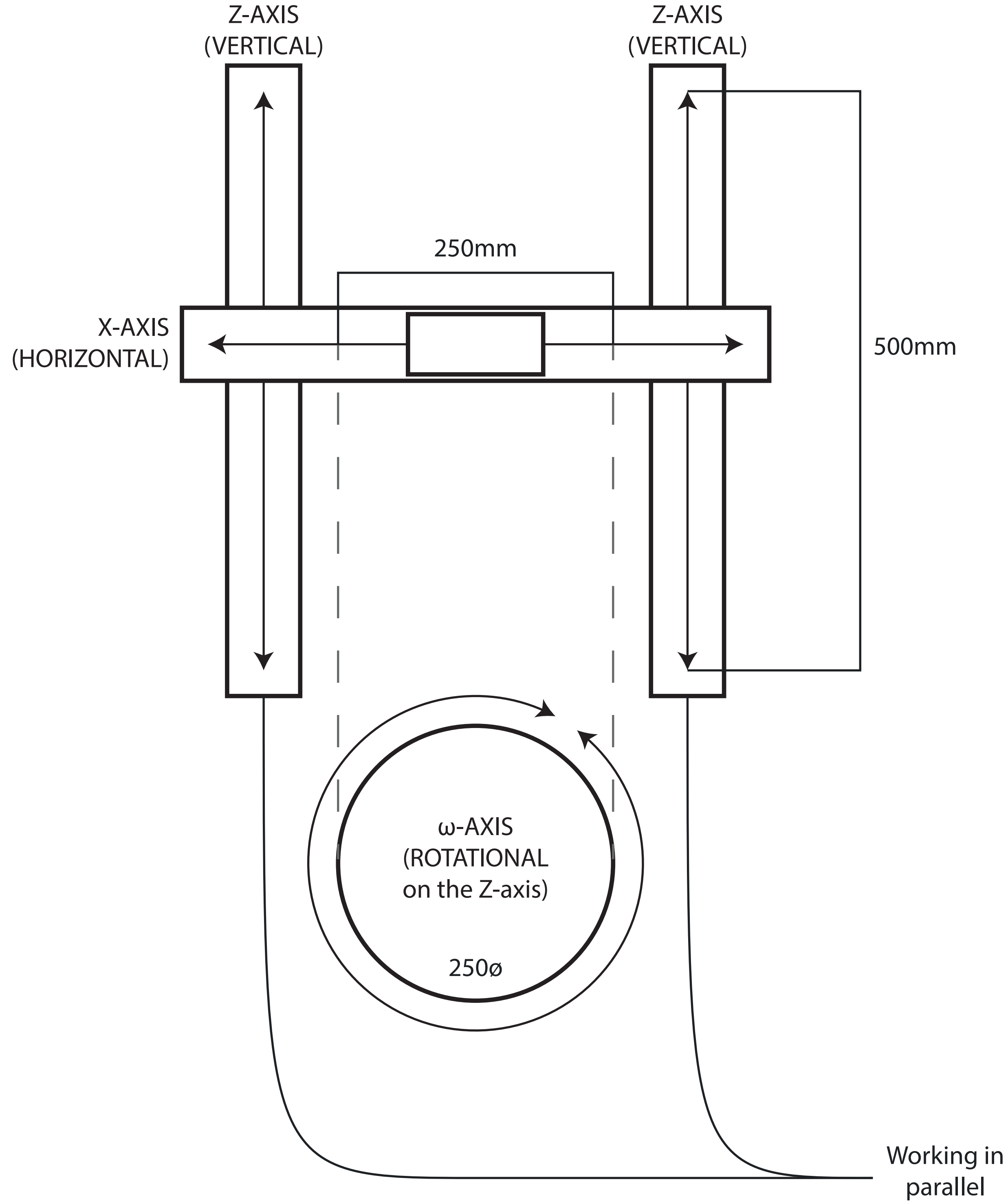
The product is intended so that the customer can choose what print height they would like. This could make for the Vertical linear actuators to have a stroke length of 250mm or 1000mm.

11. Maintenance

There will be technicians available on call, however, lower maintenance would be more desirable but isn't much of a concern. We just want the best product for the out system.



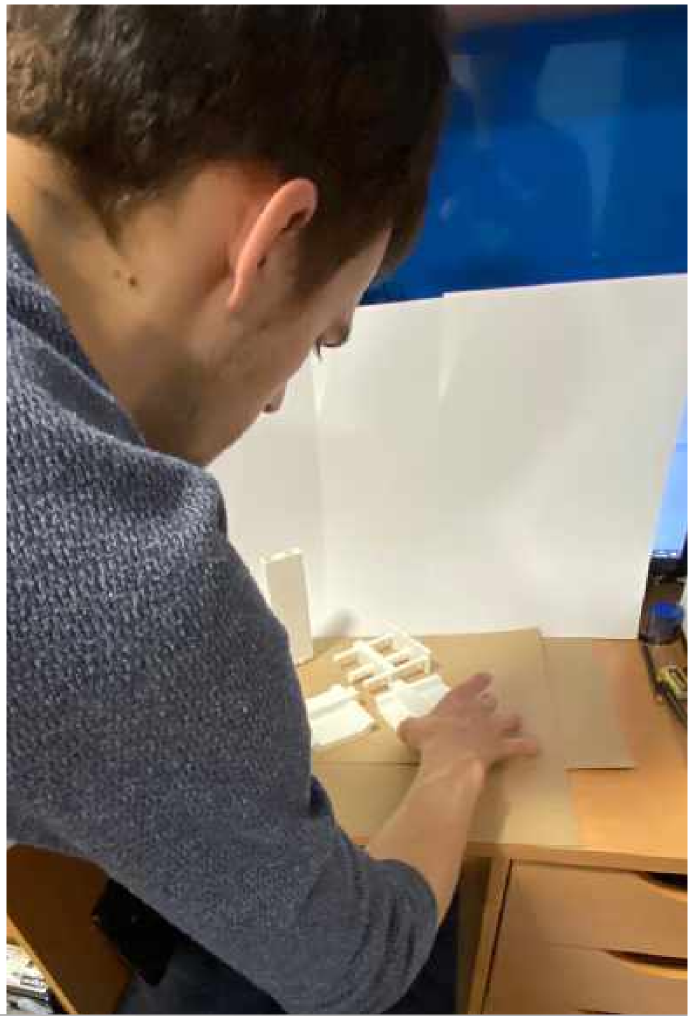
The product configuration

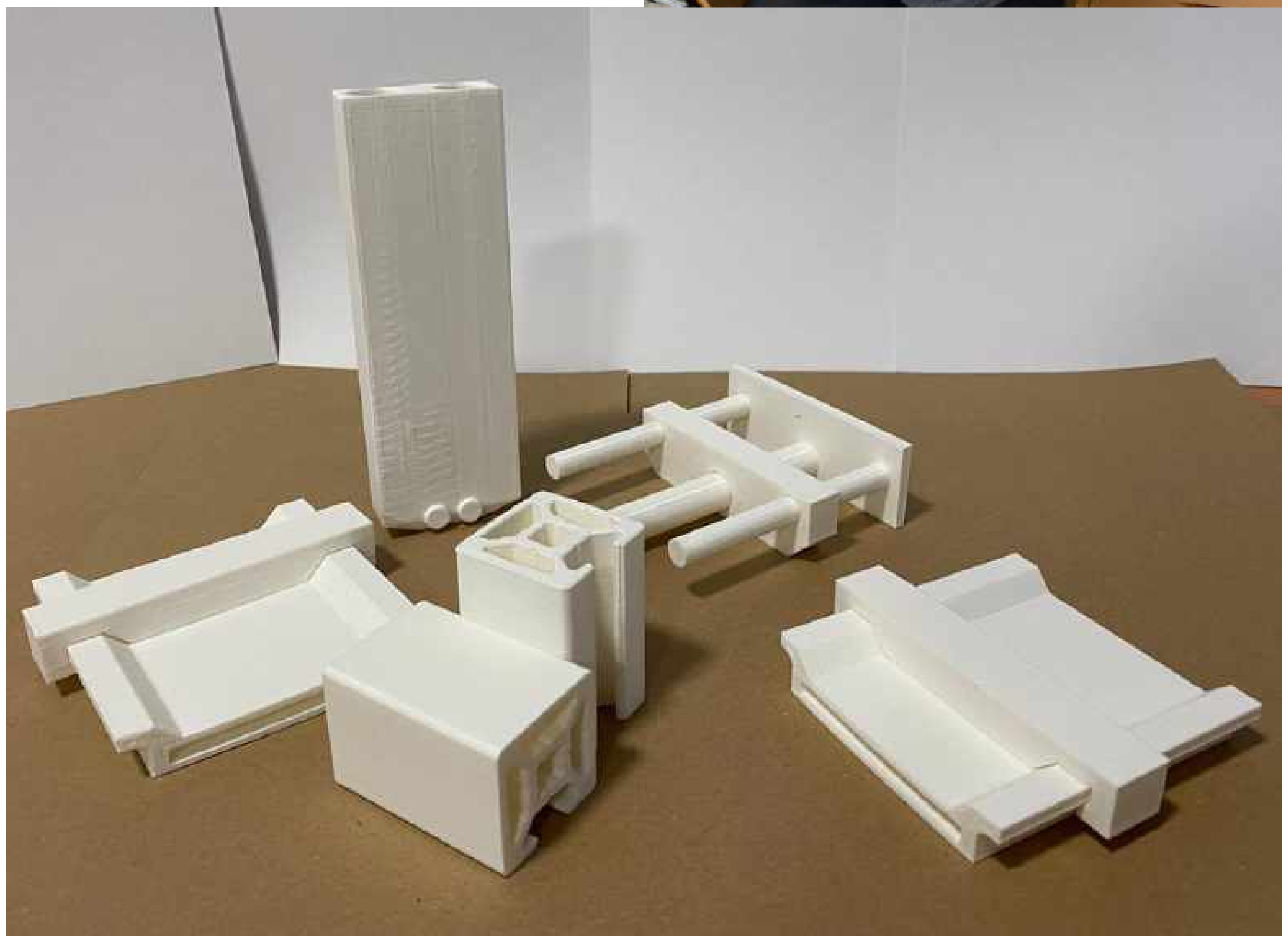


Axes configuration

APPENDIX-10

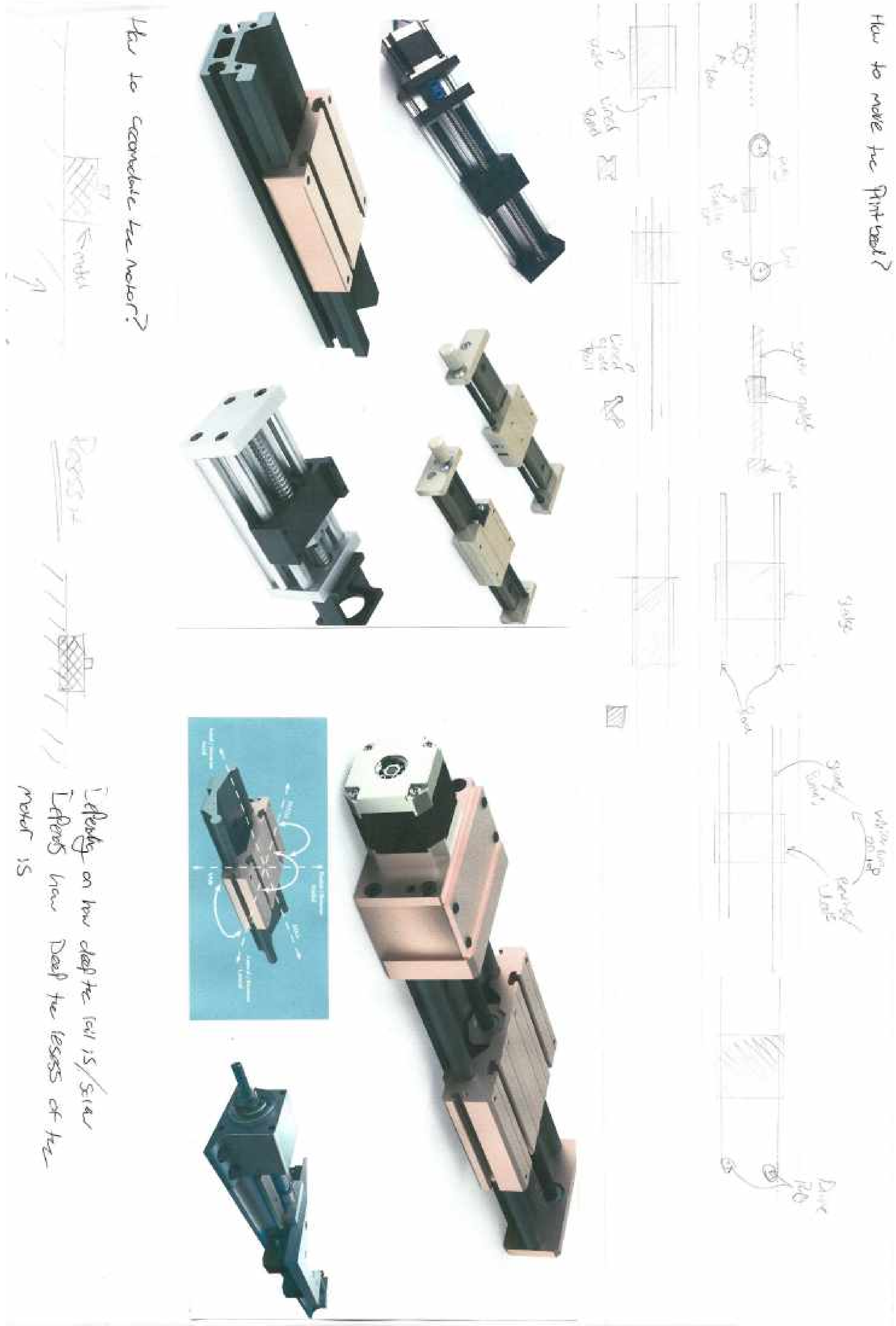
The Author setting up some 3D printed components for a photoshoot. This was to better visualise the size and mechanics of these basic parts





3D printed models so that the Author could understand the different components better understand them

APPENDIX-11



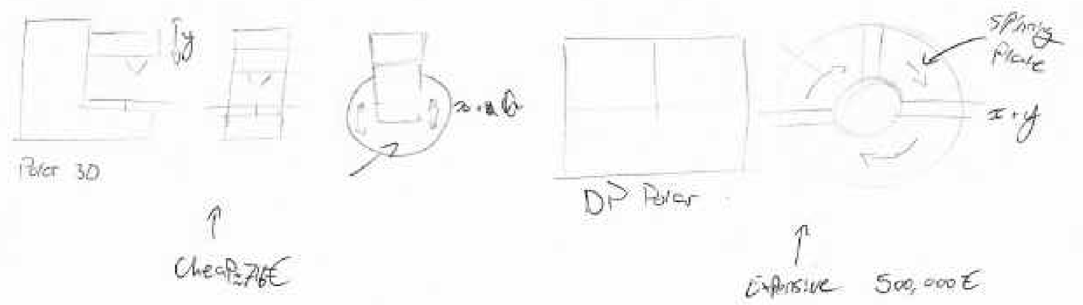
Development pages for initial product ideations

APPENDIX-12

Prosthetic Dimensions h = 400mm
⌀ = 150mm

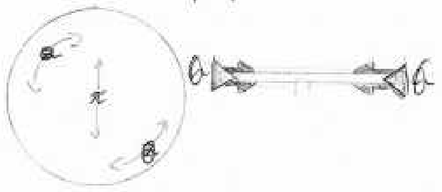
500mm
+ 100mm for special cases to be accomodated.
250 mm

≈ 7.07 ×10⁶ cm³



These machines both perform the same function of a Rotating Print bed and an Extruder above. Polar 3D uses Polar coordinates to move the Print bed. DP Polars Print bed wouldn't be the desired solution for 3D Printing Prosthetics.

The Print bed must:



Core of the Printer:

- Print head/bed needs to move y axis ↕
- Print head/bed needs to move x axis ⟷
- Print bed needs to move θ axis

◦ Print bed needs to Rotate but be supported on very outer edge

Point of Rotation

Needs to be heavy enough to resist this torque

What are the solutions?

◦ Viscotec Printhead weight = 1.2kg (1200g)

Added Need Support if it's on an unsupported arm (only mounted on one side

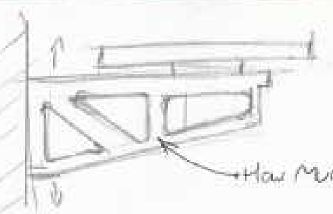
Point of Rotation

Different mounting methods?

◦ How to move the Print bed in x axis?
If the Product moves on the Print bed (out of alignment) then it's a Failed Print.
If it's a narrow Pin holding the Printbed, the movement could shake the Print bed

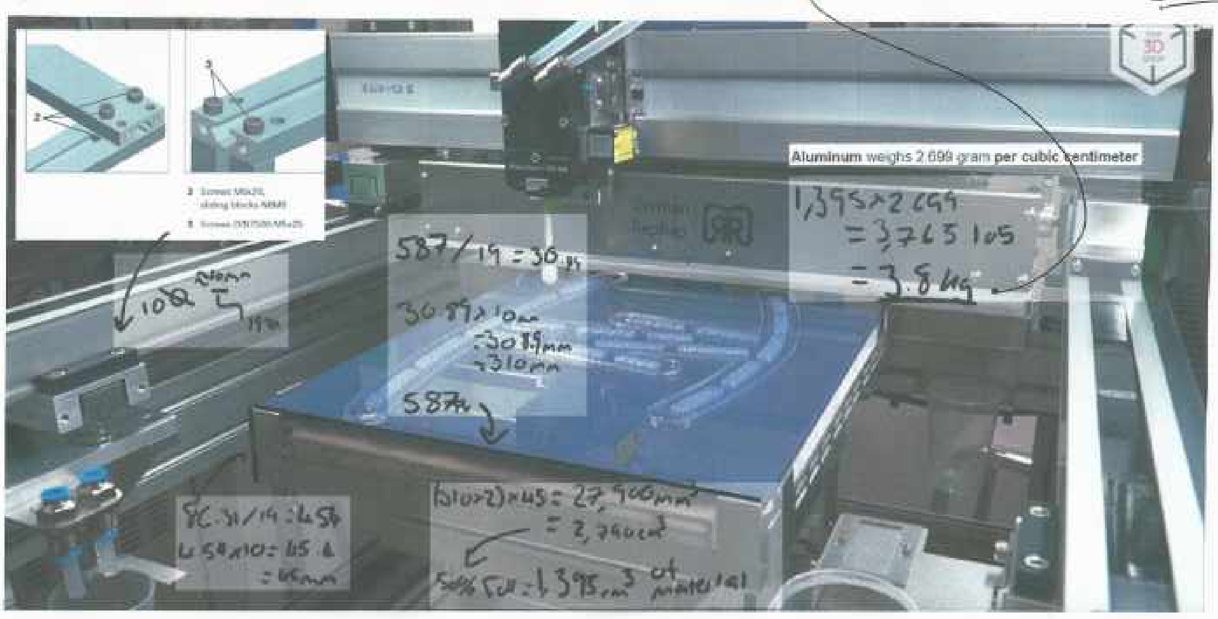
Needs to have a solid base and movement, how?

Example - German RepRap L320

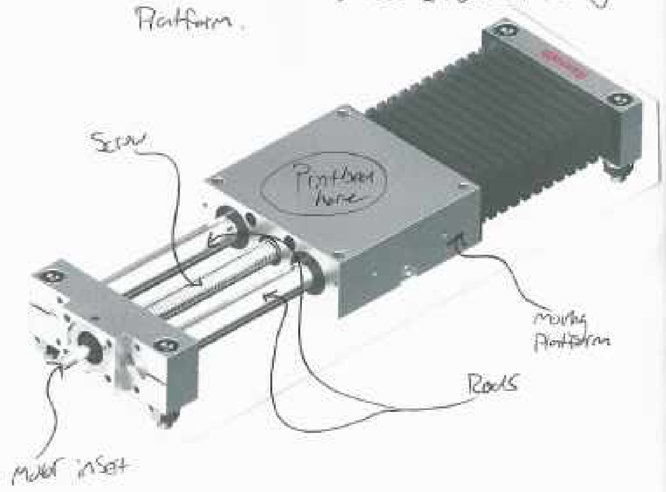


How much is this supporting?

From doing some guessing and rough calculation, I'm assuming that the structure is supporting ≈ 3.8kg



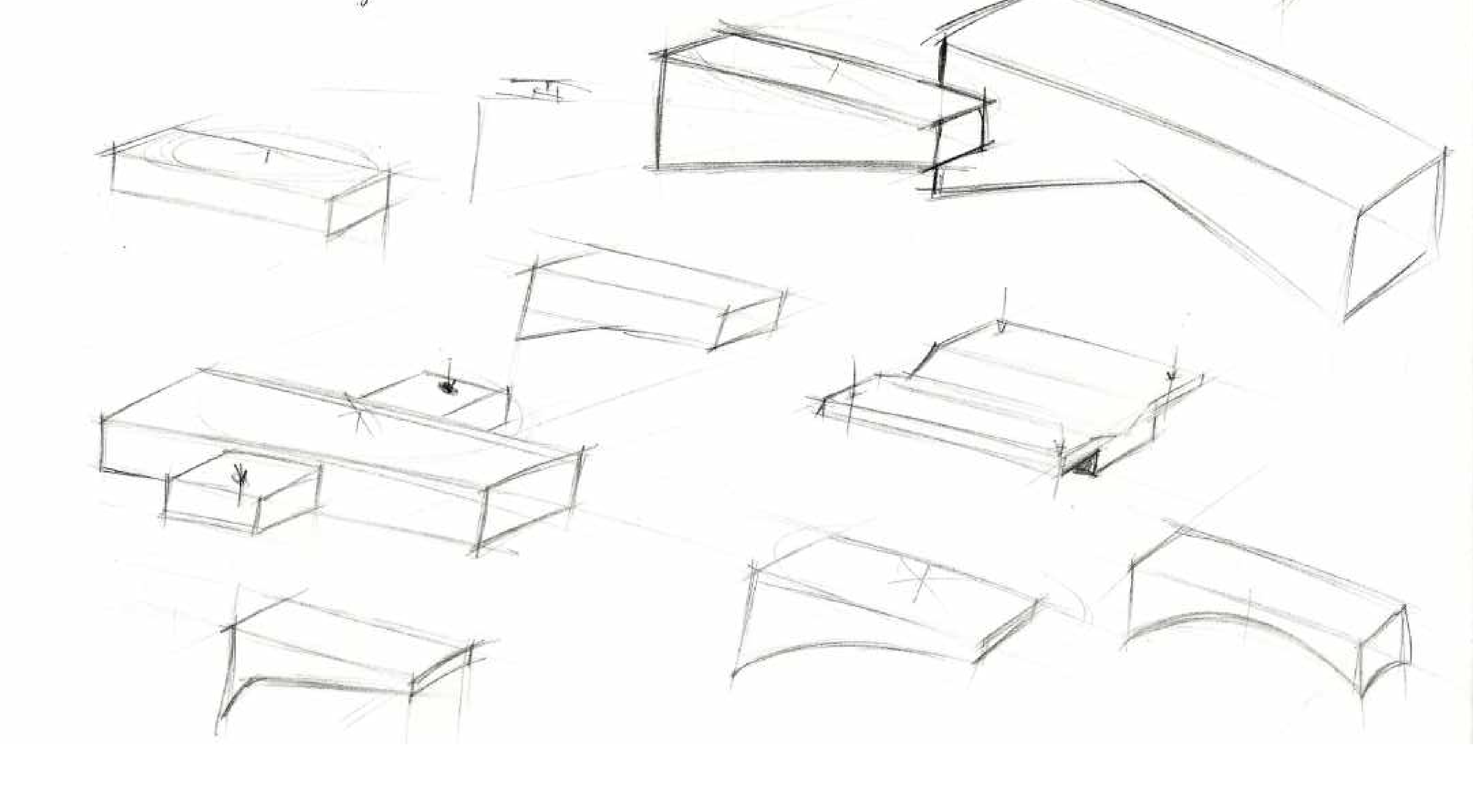
→ The movement method I want to use for my Printhead mover would weigh over 2kg (I'm assuming). Using this structure, or one very similar would Provide the strength of a Vertical Moving Platform.



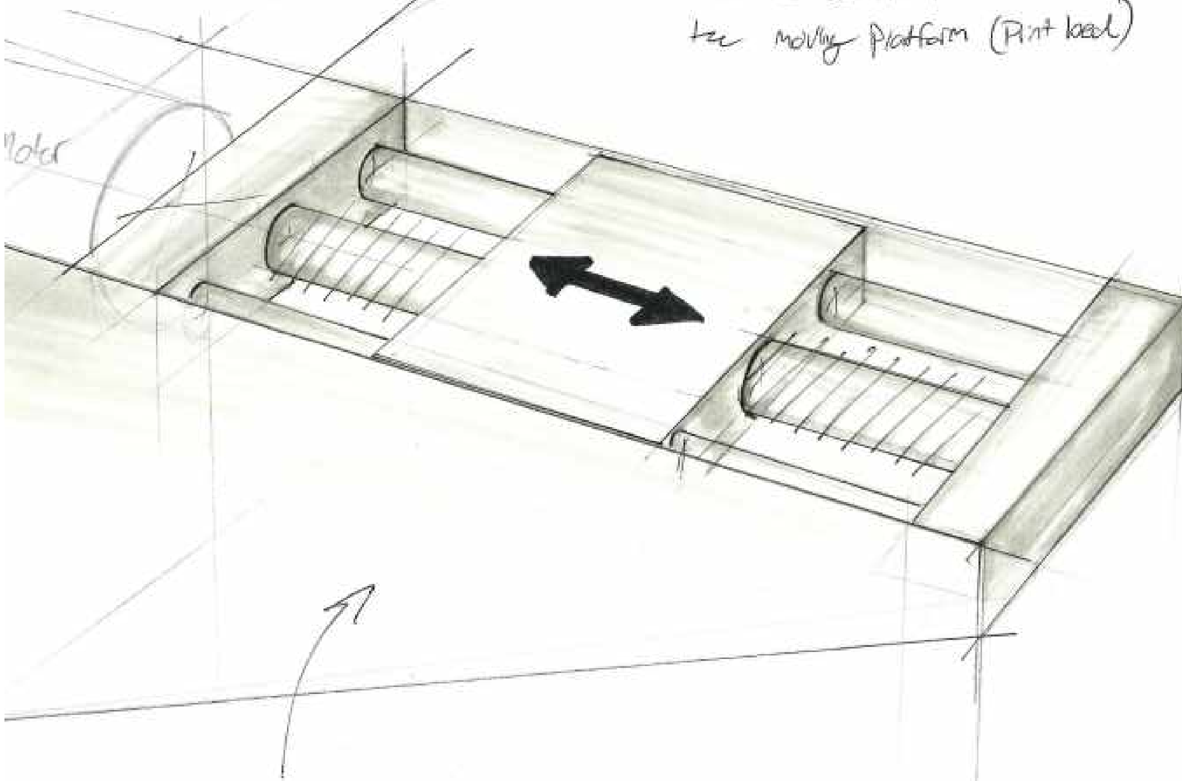
How to achieve y-axis movement?

What will reduce the vibration from the Printhead/Printbed/Extruder?
- Having them Separated

Separate the Extruder from any movement - extruder stays centre
extruder bed to move x+y



The essential movement of the moving platform (Print bed)

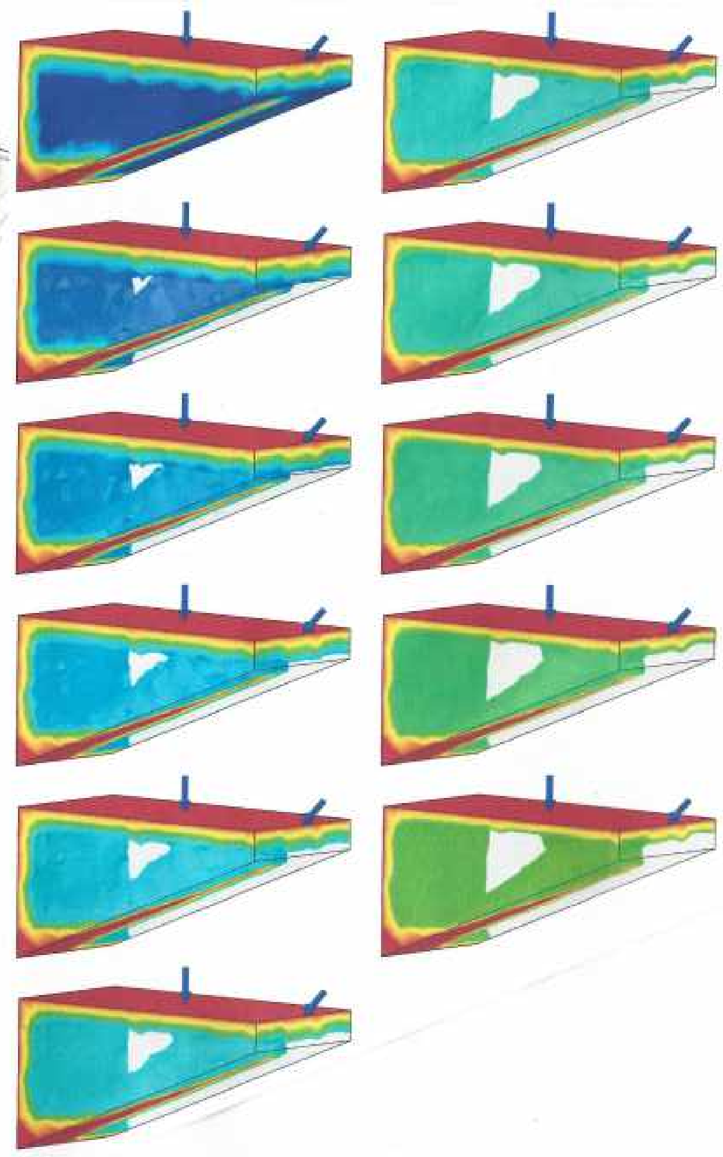


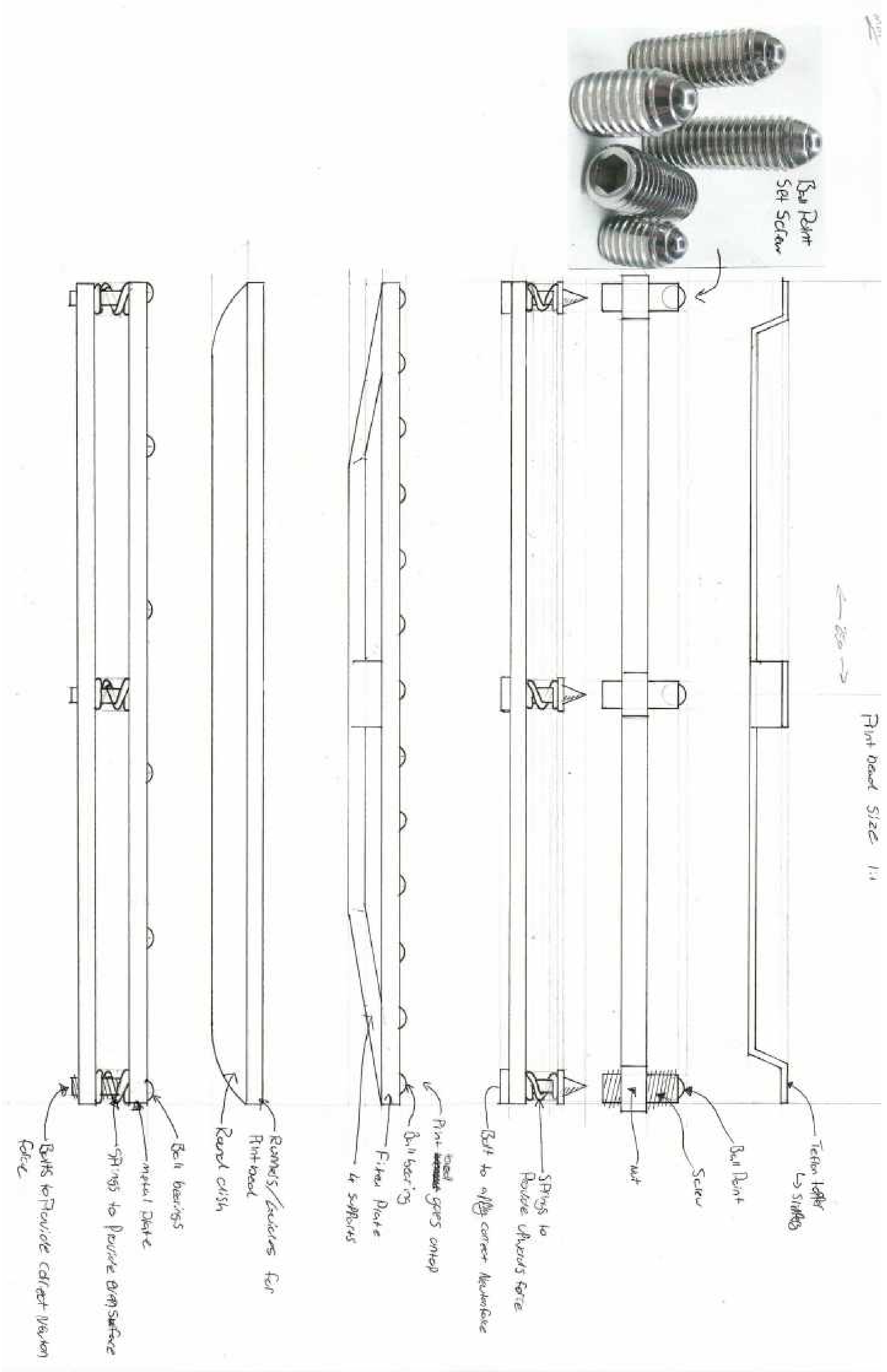
Weight can be saved

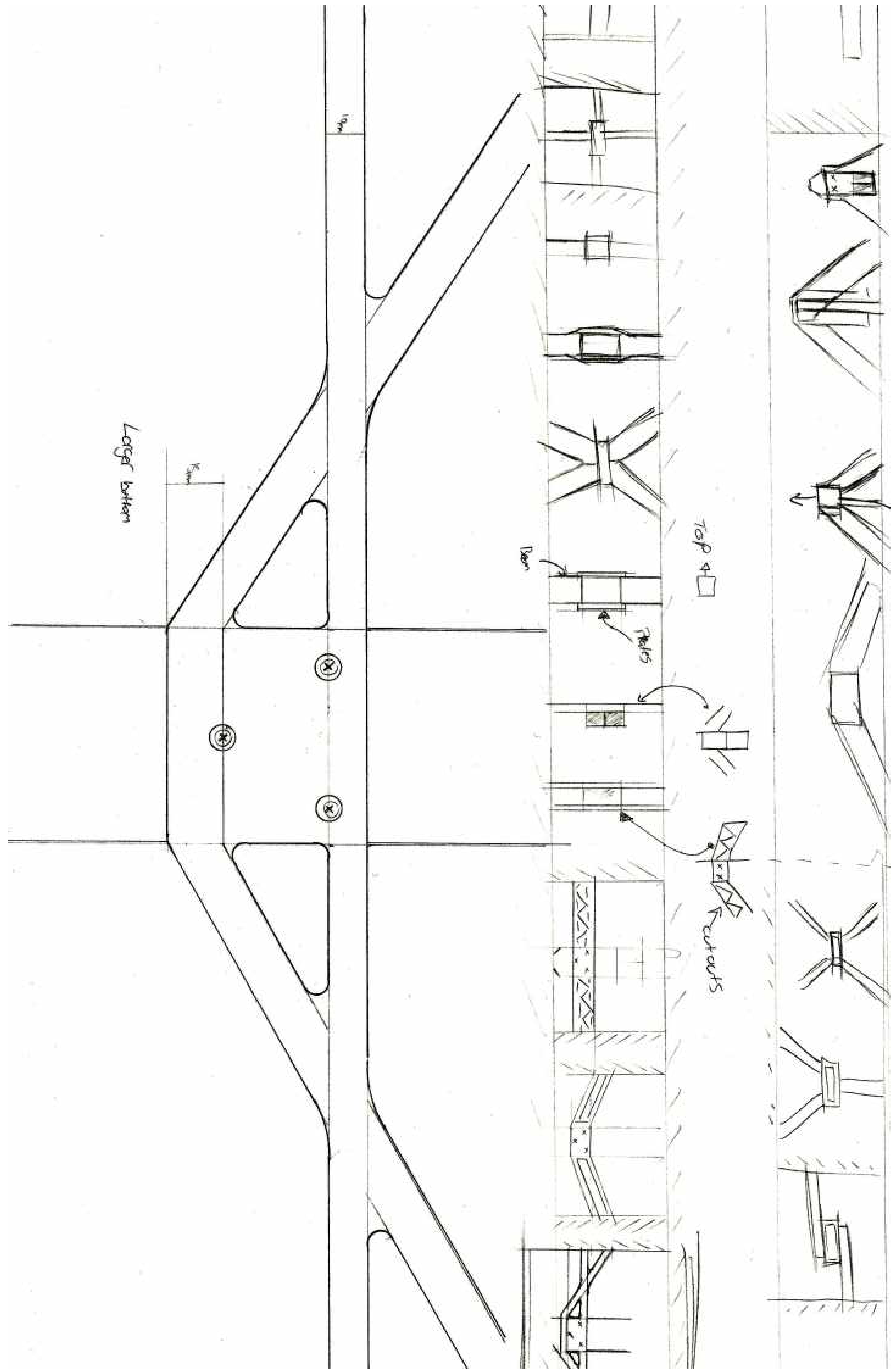
→ Optimise Shape

Through a more defined model I can create a component which is strong, lighter than original design, and less cumbersome to make.

Example of shape optimisation ↓




Ball Point
Set Screw
Print bead size 1:1
Ball Point
Screw
Nut
Ball bearings
Fixed plate
Ball bearings
Metal plate
Round edges


Larger bottom
Top
Side
Cutouts

APPENDIX-13

The cost of the raw materials and components comes to £27.818.19
This does not include:

- Manufacturing costs
- Storage and warehouse
- Workforce, and
- Other amenities

Included in this costing sheet are components that would go towards multiple builds. For example, Thompson Linear, choosing to purchase ten motors as opposed to one reduces the price per unit. The same example for Festo's 'Plastic Tubing PLN-8X1,25-NT', to purchase this component it comes in roles which would then be cut by the production workforce to the required length.

Costing for product (excluding manufacturing and workforce)

Company	Product	Name / Code	Amount	Price	Total	Link	Additional	Sub Total	£xxx.xx
ViscoTec	Extruder (LAM)	vipro-HEAD 3/3	1	£12,000.00	£12,000.00	https://		Sub Total	£12,000.00
Standa	Rotary Platform	8MR170-190	1	£1,650.96	£1,650.96	http://w			
	Motorised Stage Controller	8SMC5-USB-B8-1	1	£795.92	£795.92	http://w	Quotation from - Laser Support Service - https://www.laser-support.co.uk/	Sub Total	£2,715.59
	Power supply 36volt dc	PS36-4.4-4	1	£243.71	£243.71	http://w			
	Delivery				£25.00				
Festo	X-axis - Spindle axis ELGC-BS-KF-45-300-10P	8061486	1	£482.10	£482.10		15% off has been included		
	Z-axis - Spindle axis ELGC-BS-KF-45-500-10P	8061488	2	£512.71	£1,025.42				
	X-axis - Stepper motor EMMS-ST-57-S-SE-G2	1370475	1	£231.98	£231.98				
	Z-axis - Stepper motor EMMS-ST-42-S-SEB-G2	1370473	2	£454.83	£909.65				
	Parallel kit EAMM-U-45-V32-42A-63	4280674	2	£95.79	£191.57	https://	Use the		
	Adapter kit EHAA-D-L2-45-L2-45	8066714	2	£15.08	£30.16	www.f	search		
	Profile mounting EAHF-L2-45-P-D3	4759739	4	£15.08	£60.32	esto.co	feature		
	Axial kit EAMM-A-V32-57A	4597016	1	£53.22	£53.22	m/cms	on their		
	servo drive CMMT-ST-C8-1C-EC-S0	8084005	3	£331.70	£995.09	/en-	website.	Sub Total	£6,014.18
	Assortment of plugs NEKM-C-22	8081885	3	£21.11	£63.32	gb_gb/i	Copy		
	Motor cable NEBM-S1W9-E-2.5-Q5-LE6	1450737	3	£57.47	£172.42	ndex.ht	and		
	Encoder cable NEBM-M12W8-E-2.5-LE8	1451675	3	£51.08	£153.25	m	paste		
	Push-in L-fitting NPQH-L-G18-Q8-P10	578282	2	£5.10	£10.20		the code		
	Camera heads SBPB-R9C-U3-1E1A-C	8066471	1	£1,624.08	£1,624.08				
	Plastic tubing PLN-8X1,25-NT	193405	1	£3.60	£3.60		8mm OD 6mm ID - 1 - 50m lengths		
	Delivery				£7.80				
Bosch Rexroth	Strut profile 40x40L - 80mm		12	£5.16	£61.92				
	Strut profile 40x40L - 104.5mm		4	£6.68	£26.72				
	Strut profile 40x40L - 145mm		8	£6.68	£53.44				
	Strut profile 40x40L - 240.8mm		2	£8.20	£16.40				
	Strut profile 40x40L - 290mm	3842993120	2	£8.20	£16.40				
	Strut profile 40x40L - 298.5mm		6	£8.20	£49.20				
	Strut profile 40x40L - 370mm		1	£9.72	£9.72				
	Strut profile 40x40L - 488mm		4	£11.24	£44.96				
	Strut profile 40x40L - 620mm		9	£18.84	£169.56	https://			
	Strut profile 40x40L - 1000mm		4	£14.28	£57.12	www.b			
	Strut profile 30x30_1N - 104.5mm		4	£5.60	£22.40	oschrex			
	Strut profile 30x30_1N - 122mm	3842992397	4	£5.60	£22.40	roth.co			
	Strut profile 30x30_1N - 179.5m		4	£5.60	£22.40	m/en/x			
	Strut profile 30x30_2N - 848 mm	3842992399	8	£15.89	£127.12	c/prod			
	Strut profile 30x45° - 848mm	3842993011	2	£18.11	£36.22	ucts/pr			
	Adbdeckkappe_30x45°	3842551010	4	£12.02	£48.08	oduct-			
	Cap_30x30_no_hole	3842548744	12	£0.77	£9.24	groups/		Sub Total	£2,095.92
	Mounting rim profile PP, N8 - 104.5mm		4	£5.46	£21.84	assemb			
	Mounting rim profile PP, N8 - 122mm	3842518347	4	£0.00	£0.00	ly-			
	Mounting rim profile PP, N8 - 179.5mm		4	£0.00	£0.00	technol			
	Mounting rim profile PP, N8 - 788mm		12	£0.00	£0.00	ogy/ba			
	Sealing_Profile_N8 - 848mm	3842516598	2	£50.20	£100.40	sic-			
	Hinge, aluminum P1=30 P2=40	3842544528	8	£19.46	£155.68	mecha			
	T-nut 10 mm slot steel; galvanized M6 1)	3842530285	100	£0.46	£46.00	nic-	(packs of 10)		
	Connector 45° 40x40 set (standard)	3842532205	24	£13.12	£314.88	elemen			
	CUBIC CONNECTOR 40X40	3842549868	8	£9.54	£76.32	ts	40/3;SET		
	Bracket 40x40 set (standard)	3842529383	47	£4.35	£204.45		2xFS5		
	Cover cap for bracket 40/40, black	3842548855	47	£0.91	£42.77				
	Angle 40x80 set (standard)	3842529386	12	£9.67	£116.04		4xFS7		
	Cover cap for bracket 45/180, black	3842548857	12	£2.51	£30.12				
	Levelling foot M12x160	3842536470	4	£8.62	£34.48				
	LR with lock, solid rubber, F600	3842547836	4	£24.79	£99.16		Wheels		
	Cover profile, N10 H-PVC, colourless	3842191182	8	£3.68	£29.44		Needs LEDs behind it		
	Cover profile, N10 H-PVC, black	3842548877	8	£3.88	£31.04		46 Individual parts = 8 meters		
Igus	System E2 micro Series E2.15	E2_15_40_3 E2_150_40_2_6 E2_150_40_3_5 E2_15_50_1 E2_150_50_2_3 E2_150_50_5_1			£72.02	https://www.igus.co.uk/info/medium-load	For all the 3 different e-chains the total is	Sub Total	£78.02
	Delivery				£6.00				
Thomson Linear	Nut integral to motor	MLN23B39-M08040S30500N-C7A0-XXX - Motorized, NE	10	£198.00	£1,980.00	https://	Lead time 5-7weeks (more price options)	Sub Total	£1,980.00
Chambrelan	Telescopic Slide	D402	2	£6.80	£13.60	https://	Minimum order of £50 // No delivery chare over £50	Sub Total	£13.60
	Delivery	No delivery charge over £50			£0.00				
	COUNTERSUNK_HEAD_SCREW - hex	M6 10mm	100	£0.46	£46.00				
	ISO 10642 - M3 x 8 - 8N		100	£0.46	£46.00				
	ISO 14579 M4x10(F)		100	£0.46	£46.00		A rought price per unit has given going off of Bosch Rexroth's T-Nut	Sub Total	£276.00
	ISO-4762 M2_5x8		100	£0.46	£46.00				
	ISO-4762 M3x10		100	£0.46	£46.00				
	ISO-4762 M4x16		100	£0.46	£46.00				
Brugger Magnet system	Magnet assembly to be clipped into aluminium prof	MS041NdRe04K-09	1000	1.70 €	£1,479.00	https://	Other quantities are available (100 units = €230 / 500 units = €900 / 2500 units = €4050)	Sub Total	£1,499.00
	Delivery				£20.00				
Flecfire LEDs	3020 Super Bright Strips	UB-IS-62K-12V-10FT (Priced per reel (10ft))	3	$145.00	£352.35	https://	UltraBright™ Industrial Series LED Strip Light	Sub Total	£422.18
	Delivery				£69.83				
Metals Warehouse	Aluminium	1000mm x 1000mm x 2mm	5	£38.70	£193.49	https://		Sub Total	£398.37
	Aluminium	1000mm x 1000mm x 3mm	3	£68.29	£204.88				
Sheet Plastic	Plastic window	2mm Anti Reflective Acrylic Sheet 1500 X 1000	3	£57.00	£171.00				
	Black plastic	2mm Black Acrylic Sheet Cut To Size (1000 x 1000	3	£31.68	£95.04	https://	Custom sizes	Sub Total	£274.33
	Delivery				£8.29				
	Plastic Cup	7Oz for drip cup	1	£1.00	£1.00		Come in packs from local shop		
	10 x 3.5 x 2.25mm thick N45 Neodymium Magnet -	MOD9-10	1	£20.00	£20.00	https://	Come In packs can are north or south	Sub Total	£51.00
	Handle	Stainless round tube	2	£15.00	£30.00	https://	Minimum order of £25		

Grand Total £27,818.19

APPENDIX-14

INITIAL DESIGN SPECIFICATION

1. **TARGET MARKET:**
    1.1. Those who have interest in producing prosthetic sockets;
    1.2. 3D printing firms;
    1.3. Organisations and businesses who produce prosthetics:
        1.3.1. Chromatic 3D;
        1.3.2. German RepRap;
        1.3.3. ProsFit;
        1.3.4. Ottobock;
        1.3.5. WillowWood;
    1.4. National Health Service (NHS);
    1.5. Prosthetists;

2. **AESTHETICS:**
    2.1. Modern and future-safe design;
    2.2. Industrial;

3. **PRODUCT ENVIRONMENT:**
    3.1. In clean environments inside;
    3.2. Good circulation of air;
    3.3. Away from flammable materials;

4. **LIFECYCLE & SUSTAINABILITY:**
    4.1. This product is designed to last for 10-years with moderate to high use;
    4.2. Since materials are 3D printed low waste is produced;
    4.3. Higher efficiency than other competing printing methods and styles;

5. **TIMESCALE:**
    5.1. The deliverables must be completed by 22/April/2020;

6. **COST & PRICE:**
    6.1. Between £20,000 and £50,000 [See Appendix A-7];
    6.2. Purchased by companies and individuals;
    6.3. Able to purchase additional materials;
    6.4. Replicable components available for purchase;

7. **HEALTH & SAFETY:**
    7.1. Heating elements must be protected and shielded away from external environment;
    7.2. Electrical components must be shielded from the outer environment;
    7.3. Material can pose a hazard to health if spillages occur;
    7.4. The materials containers must be able to cope in undesirable situations with minimum damage caused to the container;
    7.5. Visual display elements will be put in place to address any faults or potential hazards that the printer could cause;
    7.6 Sufficent training is needed before the opperation of the 3D printer;

8. **FUNCTIONAL PERFORMANCE:**
    8.1. The printer must be able to print to the maximum sizes of human prosthetic sockets;
    8.2. No vabration to translate into the extrusion and therefore product;
    8.3. Able to provide sufficent access to repaire and clean the printer;
    8.4. A system to detect faults before they get serious;
    8.5. Understand without human intervention when an issue has occurred;
    8.6. Accurately dispense the correct amount of material;
    8.7. Perform reliably;
    8.8. Users must be able to interact with the machine without confusion;
    8.9. The rotary table must be able to revolve in both clockwise and anti-clockwise directions;
    8.10. The printing platform must be able to navigate the *X* and *Y*-axis in relation to the printhead;
    8.11. The printhead liner axes must be able to navigate the *Z*-axis;

9. **FEATURES:**
    9.1. Liquid deposition;
    9.2. 3D printing;
    9.3. Material mixing;
    9.4. File transfer via USB and Cable;
    9.5. Polar rotation of the printing table;

10. **SIZE & WEIGHT:**
    10.1. Large enough to print 1 prosthetic socket with room for more;
    10.2. Weight/centre of mass must be towards the bottom third of the printer;

11. **PRODUCT LIFESPAN:**
    11.1. To last for several years without the need for replacing minor components;
    11.2. Whole product to last for minimum of 10-years;
    11.3. Major components to last for minimum of 1-year of constant use;
    11.4. Obsolescence through dated technology not through fault of machine;

12. **INTERFACE REQUIREMENTS:**
    12.1. Feature a screen and interface that the user can interact with;
    12.2. Area to refill or replace empty containers of liquid;

13. **INFORMATION & INSTRUCTIONS:**
    13.1. On screen information to assist with successful printing;
    13.2 Instruction guide on how-to use the machine;

14. **MATERIALS:**
    14.1. Resilient materials able to cope with repeated use;
    14.2. Will not flex under weigh;
    14.3. Surface for printing must be smooth and easy to keep clean;
    14.4. Non-rust materials;

15. **MAINTENANCE:**
    15.1. The product is expected to be serviced by a technician;

16. **POWER SUPPLY:**
    16.1. Able to run off any mains electricity;
    16.2. Transformer / power supply unit to be incorporated in the product;

REVISED / FINAL DESIGN SPECIFICATION

1. TARGET MARKET:
   1.1. Those who have interest in producing prosthetic sockets;
   1.2. 3D printing firms;
   1.3. Organisations and businesses who produce prosthetics:
      1.3.1. Chromatic 3D;
      1.3.2. German RepRap;
      1.3.3. ProsFit;
      1.3.4. Ottobock;
      1.3.5. WillowWood;
   1.4. National Health Service (NHS);
   1.5. Prosthetists;

2. AESTHETICS:
   2.1. Modern and future-safe design;
   2.2. Industrial;

3. PRODUCT ENVIRONMENT:
   3.1. In clean environments inside;
   3.2. Good circulation of air;
   3.3. Away from flammable materials;

4. LIFECYCLE & SUSTAINABILITY:
   4.1. This product is designed to last for 10-years with moderate to high use;
   4.2. Since materials are 3D printed low waste is produced;
   4.3. Higher efficiency than other competing printing methods and styles;
   4.4. Creating longer lasting products so there will be resources used over time;

5. TIMESCALE:
   5.1. The deliverables must be completed by 06/May/2020;

6. COST & PRICE:
   6.1. Between £35,000 and £50,000 [See Appendix A-7 of Mid-term Interim Report];
   6.2. Purchased by companies and individuals;
   6.3. Able to purchase additional materials;
   6.4. Replicable components available for purchase;

7. HEALTH & SAFETY:
   7.1. Heating elements must be protected and shielded away from external environment;
   7.2. Electrical components must be shielded from the outer environment;
   7.3. Material can pose a hazard to health and environment if spillages occur;
   7.4. The materials containers must be able to cope in undesirable situations with minimum damage caused to the container;
   7.5. Visual display elements will be put in place to address any faults or potential hazards that the printer could cause;
   7.6 Sufficent training is needed before the opperation of the 3D printer;

8. FUNCTIONAL PERFORMANCE:
   8.1. The printer must be able to print to the maximum sizes of human prosthetic sockets;
   8.2. No vabration to translate into the extrusion and therefore product;
   8.3. Able to provide sufficent access to repaire and clean the printer;
   8.4. A system to detect faults before they get serious;
   8.5. Understand without human intervention when an issue has occurred;
   8.6. Accurately dispense the correct amount of material;
   8.7. Perform reliably;
   8.8. Users must be able to interact with the machine without confusion;
   8.9. The rotary table must be able to revolve in both clockwise and anti-clockwise directions;
   8.10. The printing platform must be able to navigate the X and Y-axis in relation to the printhead;
   8.11. The printhead liner axes must be able to navigate the Z-axis;

9. FEATURES:
   9.1. Liquid deposition;
   9.2. 3D printing;
   9.3. Material mixing;
   9.4. File transfer via USB and Cable;
   9.5. Polar rotation of the printing table;
   9.6. External computer is needed for the 3D printer;

10. SIZE & WEIGHT:
   10.1. Large enough to print 1 prosthetic socket with room for additional components based on the artefacts' size;
   10.2. Weight/centre of mass must be towards the bottom third of the printer;
   10.3. Smaller dimensions than competing products; without limiting print size;

11. PRODUCT LIFESPAN:
   11.1. To last for several years without the need for replacing minor components;
   11.2. Whole product to last for minimum of 10-years;
   11.3. Major components to last for minimum of 1-year of constant use;
   11.4. Obsolescence through dated technology not through fault of machine;

12. INTERFACE REQUIREMENTS:
   12.1. Require a hosting computer to communicate witht the machine;
   12.2. Area to refill or replace empty containers of liquid;
   12.3. Area access electronic compoenents;
   12.4. Easy access to the print area;

13. INFORMATION & INSTRUCTIONS:
   13.1. On screen information to assist with successful printing;
   13.2 Instruction guide on how-to use the machine;

14. MATERIALS:
   14.1. Resilient materials able to cope with repeated use;
   14.2. Will not flex under weigh;
   14.3. Surface for printing must be smooth and easy to keep clean;
   14.4. Non-rust materials;

15. MAINTENANCE:
   15.1. The product is expected to be serviced by a technician;
   15.1. Use of standardised components to help with replacement of components;

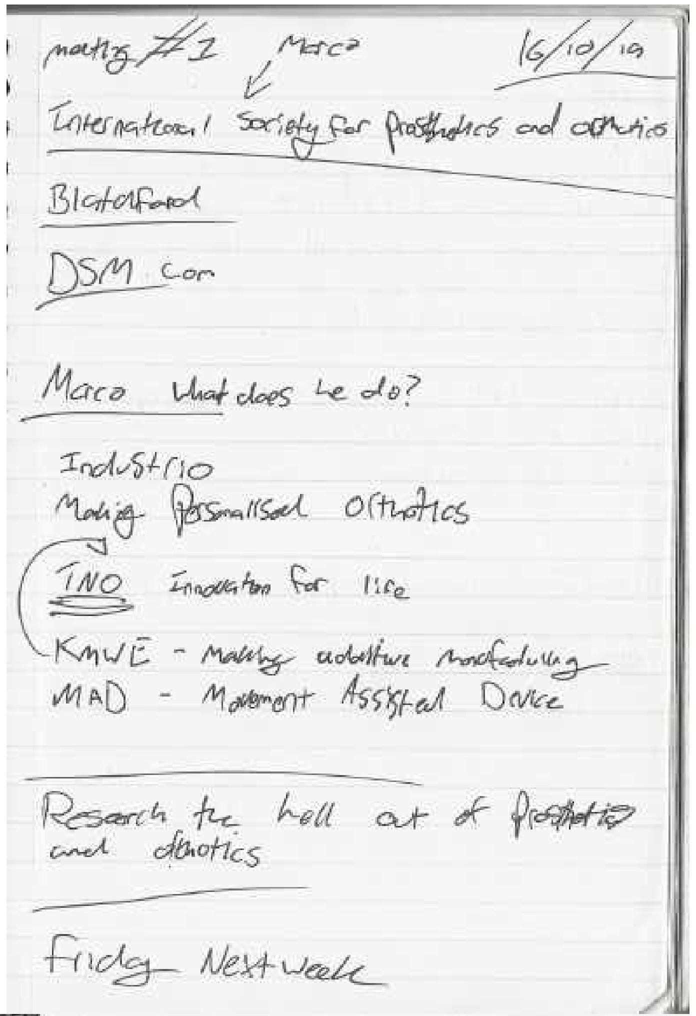
16. POWER SUPPLY:
   16.1. Able to run off any mains electricity;
   16.2. Transformer / power supply unit to be incorporated in the product;

EDITED SPECIFICATION SECTIONS MARKED AND HIGHLIGHTED AS SO

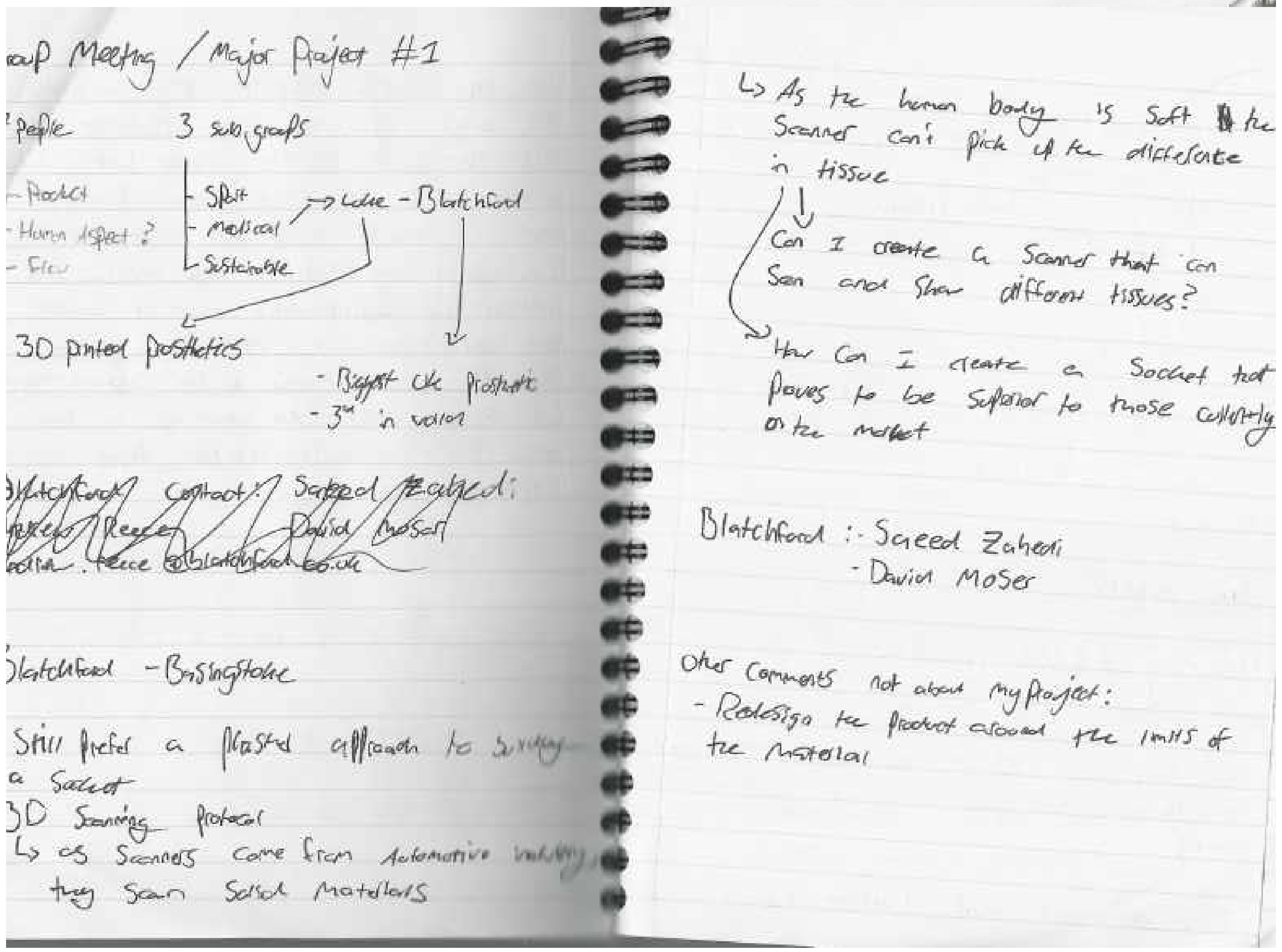
APPENDIX-15

The project supervisor and the Author agreed to meet either individually or as part of a group weekly. Meetings tended to occur on a Wednesday or Friday but have happened on all days of the week (including the weekend over Skype). Below are several pages throughout the year of meeting notes that the Author has made.

Note: This is not all the recorded meetings. If the Author were to include them all it would take up too many pages. The included meeting notes are from several points throughout the year.

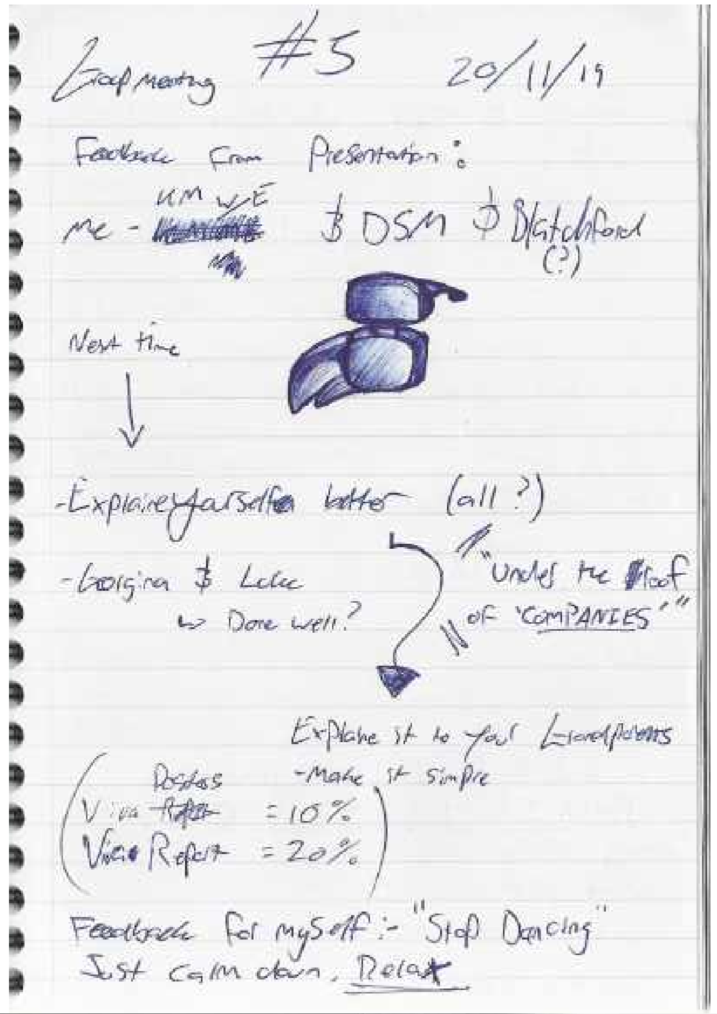


meeting #1 Marco 16/10/19
International Society for Prosthetics and Orthotics
Blatchford
DSM Con
Marco What does he do?
Industrio
Making Personalised Orthotics
INO Innovation for life
KMWE - Making additive manufacturing
MAD - Movement Assisted Device
Research the hell out of Prosthetics and Orthotics
Friday Next week

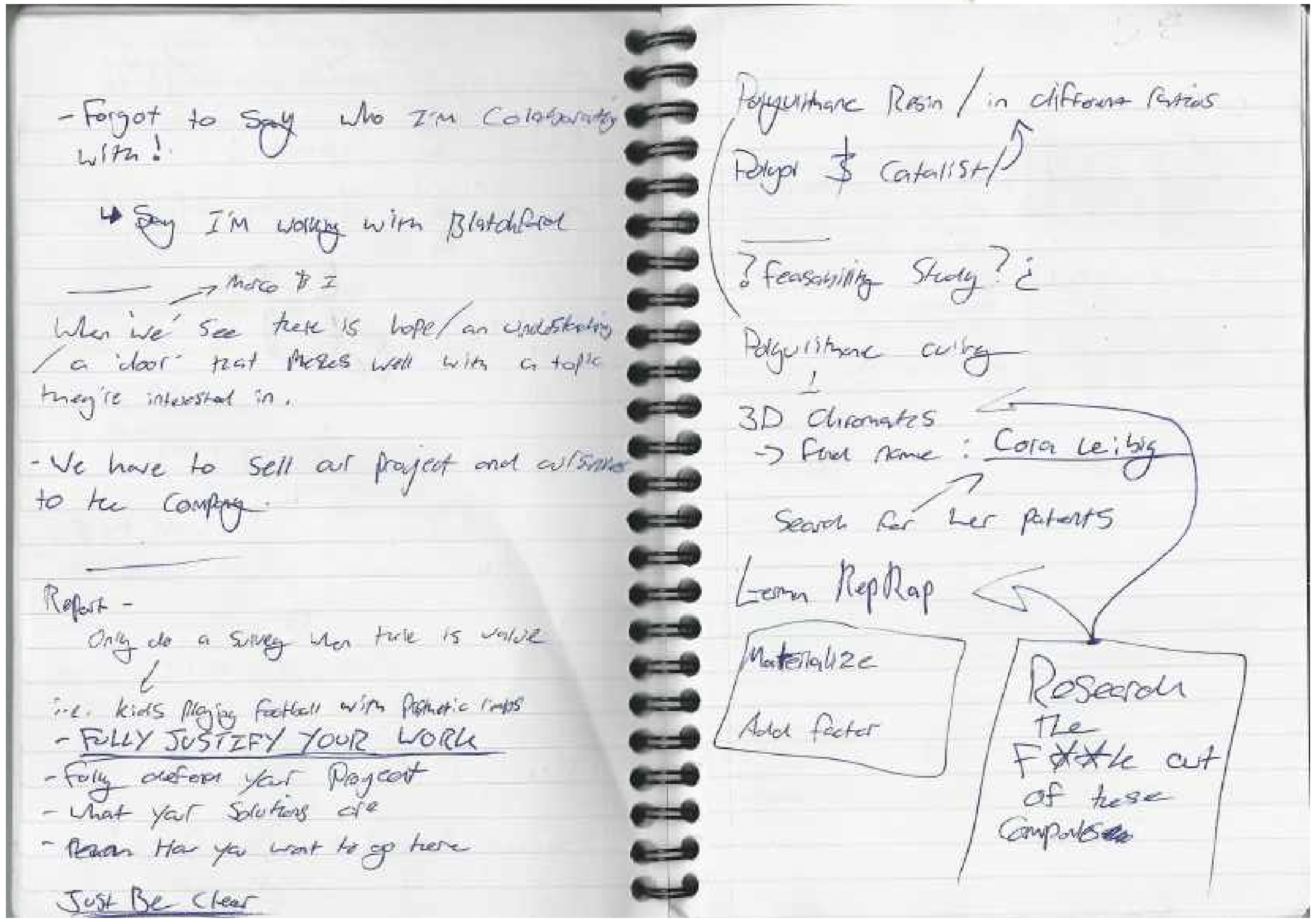


Group Meeting / Major Project #1
3 sub groups
Split
Medical
Sustainable
Luke - Blatchford
3D printed prosthetics
Still prefer a planned approach to scanning a socket
3D Scanning Protocol
As scanners come from Automotive industry they scan solid materials

As the human body is soft & the scanner can't pick up the difference in tissue
Can I create a scanner that can scan and show different tissues?
How can I create a socket that proves to be superior to those currently on the market
Blatchford :- Saeed Zahedi
- David Moser
Other comments not about my project:
- Redesign the product around the limits of the material



Group meeting #5 20/11/19
Feedback from Presentation:
Me - UMWE & DSM & Blatchford (?)
Next time
- Explain yourself better (all ?)
- Origin & Luke
Done well?
"Under the Roof of 'COMPANIES'"
Explain it to your Grandparents
- Make it simple
Viva Poster = 10%
Viva Report = 20%
Feedback for myself :- "Stop Dancing" Just calm down, Relax



- Forgot to say who I'm Colaborating with!
Say I'm working with Blatchford
Marco & I
When we see there is hope / an understanding / a 'door' that makes well with a topic they're interested in.
- We have to sell our project and ourselves to the Company
Report -
Only do a survey when there is value
i.e. kids playing football with Prosthetic limbs
- FULLY JUSTIFY YOUR WORK
- Fully defend your Project
- What your solutions are
- Reason how you want to go here
Just Be Clear

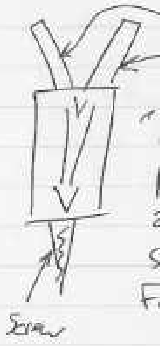
Polyurethane Resin / in different Ratios
Polyol & Catalyst
Feasibility Study?
Polyurethane curing
3D Chromatics
Find name : Cora Leibig
Search for her patents
Learn RepRap
Materialize
Add factor
Research the F***k out of these Companies

Meeting #8 ~~12~~ 11/12/19

Marco

↳ Mimic the printing head

Company I'm collaborating with . . .
who are doing this . . .
but I'm doing this because . . .



syringe of resin

"I am showing the extrusion process replicated ~~by~~ these 2-syringes which replicate similar properties as the FlexTone™ (3D Chromatic) material"

Screw

Contacted companies:
- Prosfit
- IRR → L320 bottle
- ViscoTec

- Send DP Polar to Marco
- TNO - Food Printing
- Firmware knows what the machine works

Lamp Meeting 24/01/2020

Review of the Report
- Strong Direction

Explain: novelty of your Project?
Why is it needed?

What was/is the bottleneck?

Monday

↳ focus on your idea

→ Show Marco what you have done and your direction that I'm going.

→ Create a PowerPoint showing your Direction

→ Next Meeting 3rd February, Monday

- Write an email to Marco asking for the Dimensions of the ViscoTek

- 1.2kg is good

CNC - what do their Mechanisms look like

- Find Silicone that can Set fast

↳ 1 Part + Curing agent
↳ Speak to workshops

Luke Tolchard – Polar 3D Printer

What I'm contributing and innovation:

Using Thermosetting Polyurethane (PUR) with LAM extrusion to create prosthetic sockets quicker for transtibial amputees. As the deposition of each layer is in millimetres instead of nanometres you can produce a product in a lesser amount of time.

Using PUR as the material allows for a multi-shore hardness print throughout the product, creating areas of dexterity and zones of stiffness. This provides the needed support with an amputee needs but ultimately allows for the product to 'flex' or 'deform' in regions depending on the design and user specification given.

Utilising polar 3D printing increases the efficiency of rotational/cylindrical printing which is the case when 3D printing a prosthetic socket.

Why reducing time is important? :

The average amount of time taken to produce a lower limb transtibial socket is upwards of 3-weeks and requires hundredths of man-hours to complete with highly skilled individuals. With 3D printing, the time to produce the prosthetic would be as short as a day. The amputee would then be back on their feet, walking around and relaying any feedback. So:

- The cost of production would go down;
- The prosthetist would have more time to focus on other patients;
- The company could produce more products in a shorter amount of time which increases revenue as they can accommodate more customers, and;
- The amputee/patient would have their prosthetic quicker.

How will the machine work? :

The product will use a rotating print bed that can freely rotate 360°. The extruder will be based upon a moving platform that covers the 'x-axis' whereas the print bed will move in the 'y-axis' and 'ω-axis' (A.K.A The rotating axis).

There will be two-chambers where they contain Chromatic 3D's (C3D) PUR material compounds (Isocyanate and Polyol) which get fed down to the ViscoTec extruder.

The touchscreen would be based on the front door of the machine in the current design (Fig.2) but may be changed to a 3-axis arm so the screen can be positioned wherever is most convenient like what we see on the German RepRap L320 printer (Fig.1).

How the machine will look:

The 3D printer's aesthetics will resemble that of medical equipment. It'll be made from aluminium, have a touch screen, and a glass panel to which you can look through. Something like in the original design (Fig.2).

Next steps:

After feedback on Tuesday 28th January, I ideally would like to develop a final model and start prototyping. For IRE on the 11th of February, I wish to have a cardboard prototype of my final design, whether that is a scaled-down model or full size.

I'll try and find some silicone that I can use as a replacement for C3D's PUR if I'm unable to use it.

I will produce a 1:1 model of the ViscoTec extruder and resemble its true weight (1.2Kg) so I know how much additional space is needed for the printer.

I'll begin to start thinking in detail about the glides, motors, rails, materials, other components, etc., needed for my final product.

05/02/2020

Following on from the meeting (presentation) on 03/02/2020

For next week I need to ideate more ideas and come up with a better/more suited design. These must consider:

- The drawbacks of printing thermoset polyurethane
- Having to print continuously
- What can I do with the dead space within the printer?
- Accessibility into the printer for i.e. maintenance
- The ViscoTec LAM extruder – needing to take the tip-off to replace it after each use
- Identify what makes it truly unique

For the prosthetic, as it is being printed in PUR there will be some drawbacks. For instance:

- If the print goes wrong, then the whole product must be scrapped
- The prosthetic could be heavy
- The need for large chambers of isocyanate and polyol to complete a print (Fig.1)
    - This print, for example, needs 3821720 mm^3
        - Rounded up to 4 Litres of liquid needed, or, minimum of 2L for both liquids
    - You would need material for support
    - Weight and quantity of liquids variate on infill
    - Different quantities of both liquids would be used depending on specified shore hardness (resulting in one liquid being used more than another)
        - Sensors to identify when the liquids are getting low
- Does the design need to pump, or could it be gravity fed to get the liquids to the extruder?

The mechanics of the printer and how it will work need to be thought of:

- The orientation of the extruder will depend on which solution is best for the design
- The way the door opens
- The tubes feeding to the ViscoTec extruder
- Electronics
- The different movements of the printer (extruder = *x*-axis // print bed = *y*-axis and ω-axis (rotational))

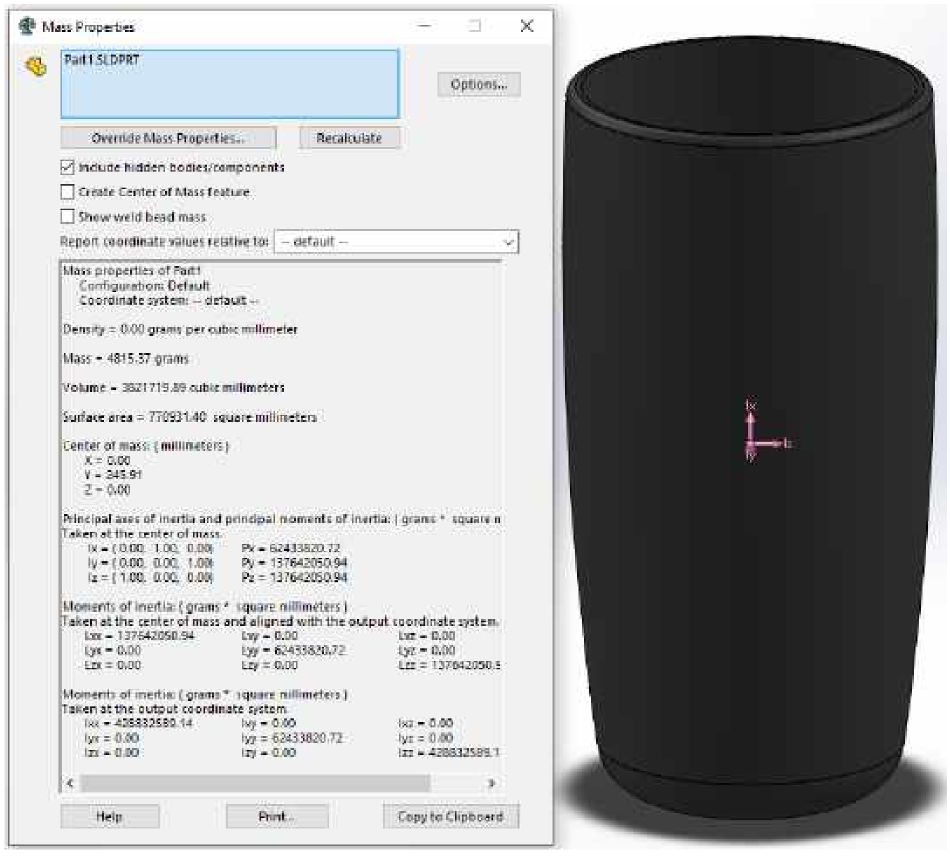
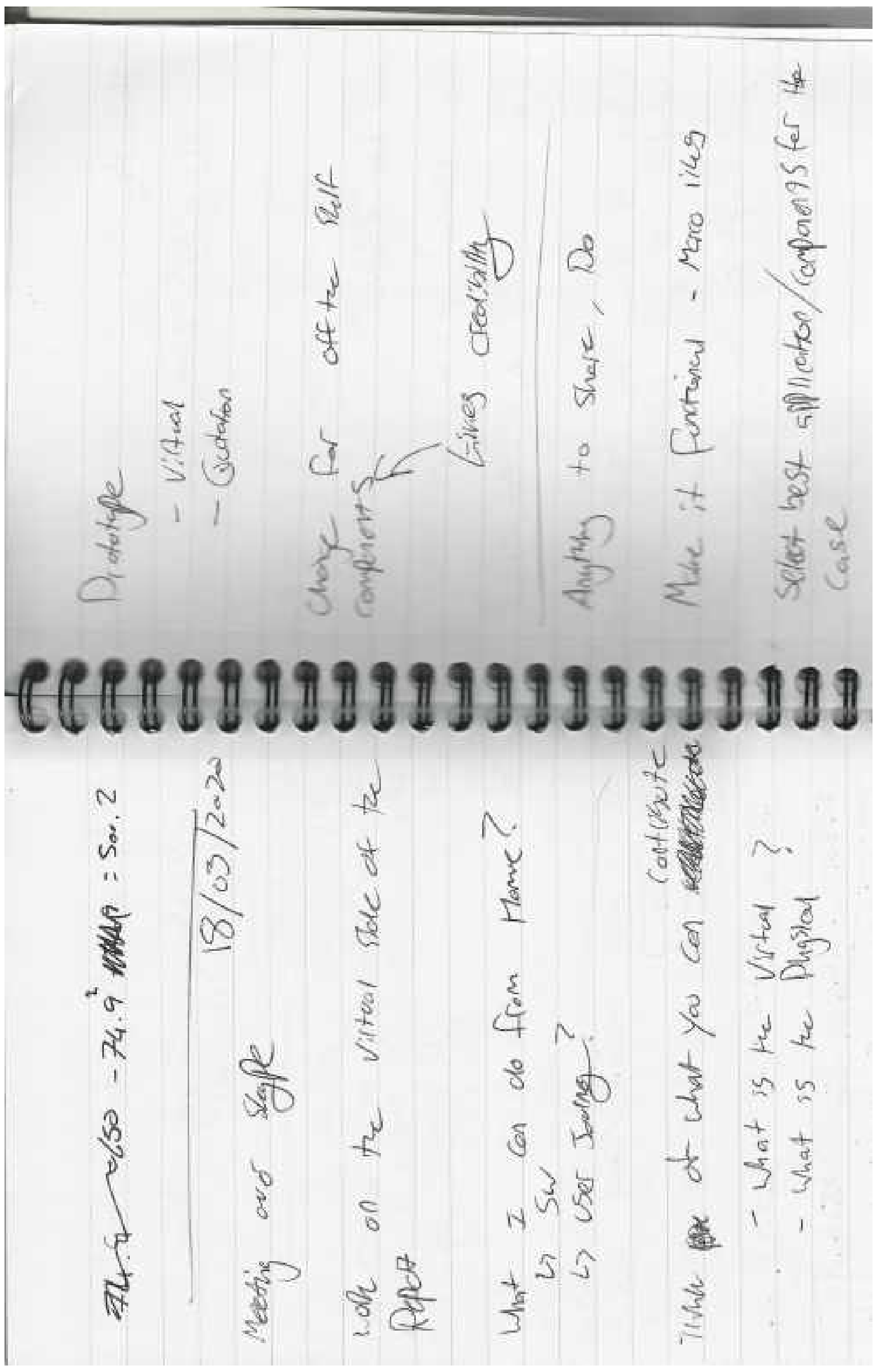
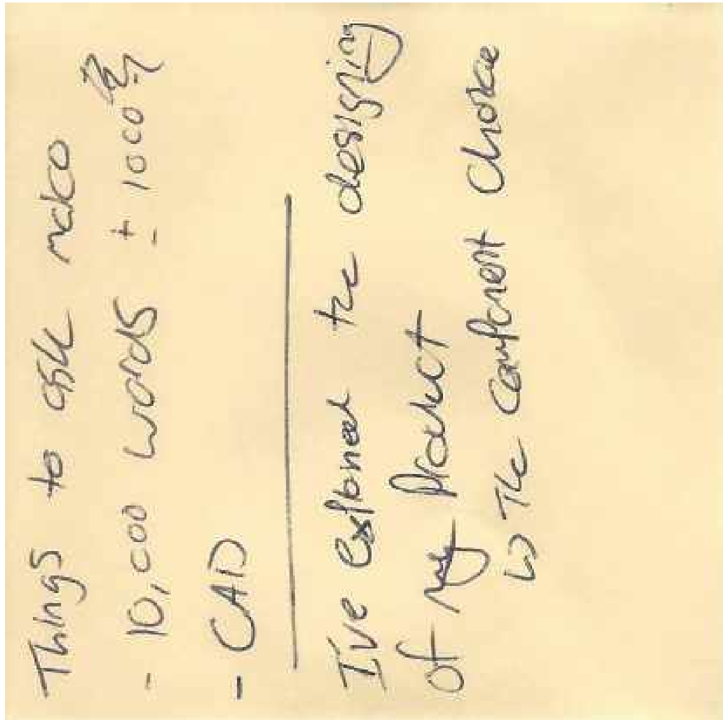


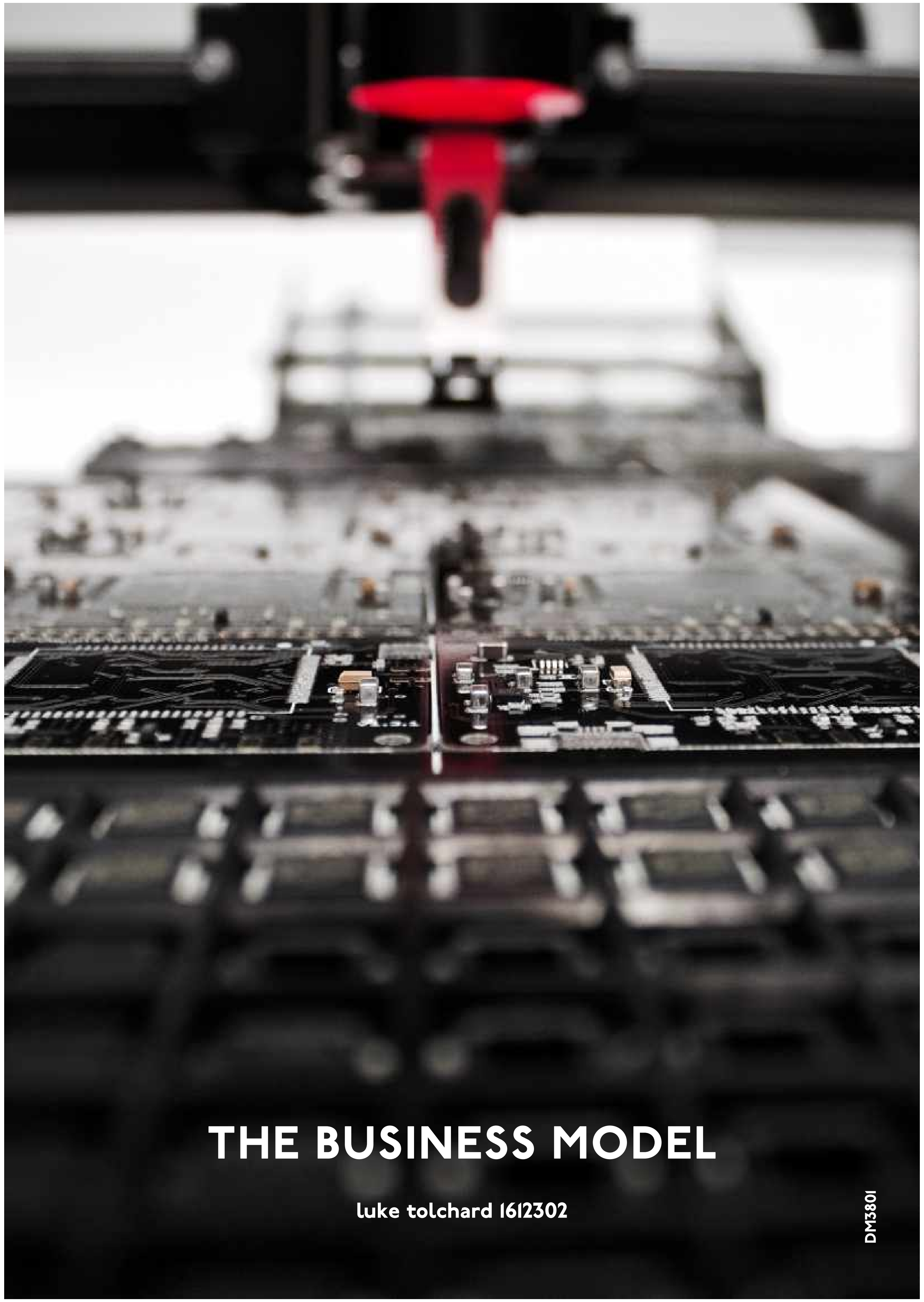
Figure 1 material properties of an XXL prosthetic

Object - XXL prosthetic:
Height = 500mm
Top radius = 125mm
Bottom radius = 100mm
Wall thickness = 10mm



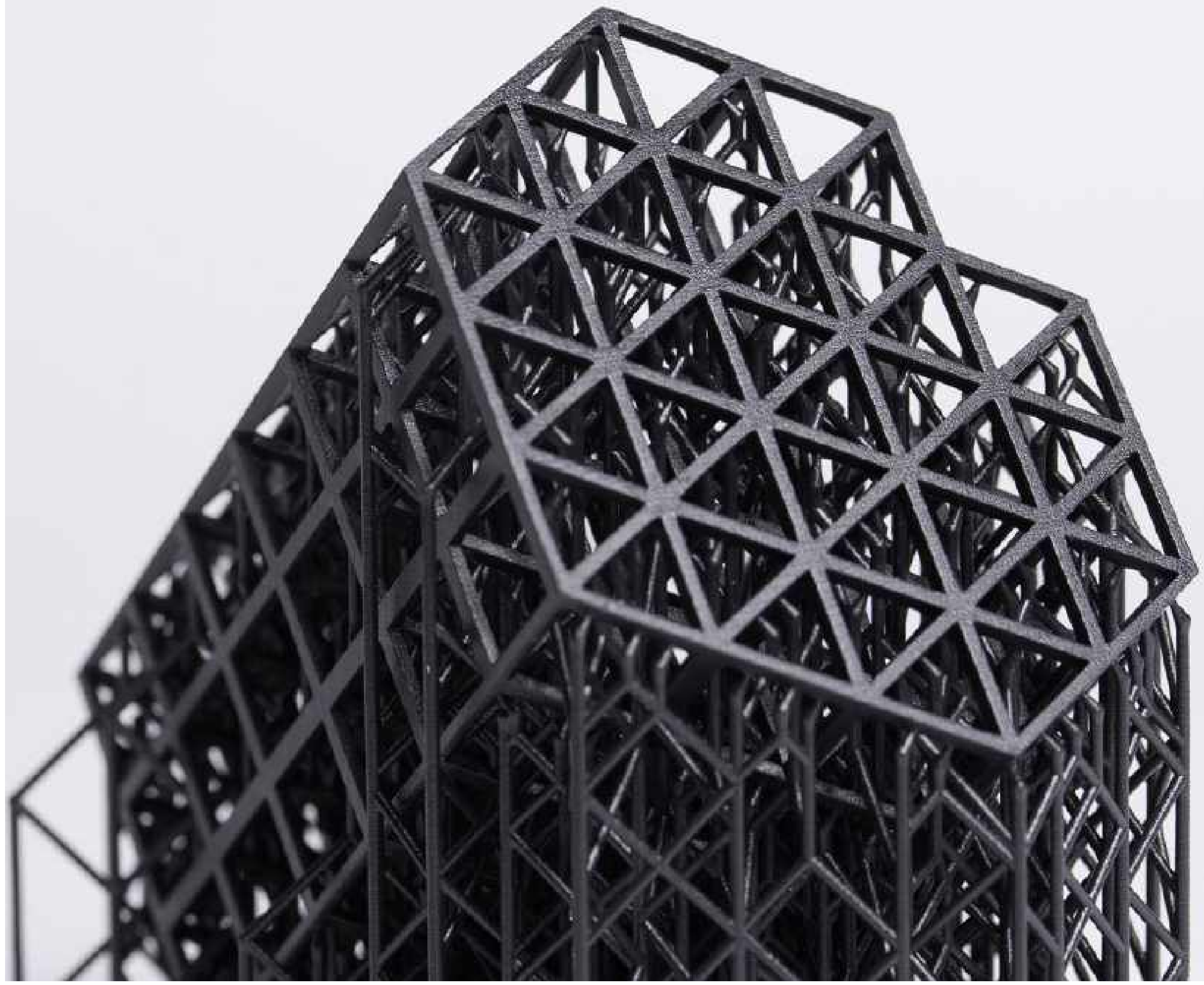


APPENDIX-16 - DIMP REPORT



CONTENTS

(Redwood, n.d.)



1 THE BIG IDEA

Every year, worldwide, more than 1-million amputations are performed (Access Prosthetics, 2017) with over 94% of amputations being of the lower limb (Pooja & Sangeeta, 2013). Transtibial (Below Knee) amputations make up the biggest percentage of all amputations undergone (Tolchard, 2019).

3D printers have gone under a lot of development since they became mainstream. Though the development of these machines is impressive there is still a lack in the market for one suited for printing medical prosthetic sockets. Using polar coordinates and LAM (Liquid Additive Manufacturing) extrusion to develop a 3D printer, this will bring significant benefits to prosthetic printing.

Combining these technologies into one 3D printer would be a first in the industry. The LAM extrusion uses thermosetting polyurethane (PUR) to produce the socket. The benefit of using PUR is that depending on the mixture of 'Isocyanates' and 'Polyol' this alters the shore hardness allowing for controlled deformations in the socket which will correlate to a higher comfort and performance for the transtibial amputee.

Polar 3D printing utilises a rotating 360° print-bed which increases the accuracy of printing cylindrical objects, like prosthetic sockets, making polar printing a practical solution.

The current method for making transtibial prosthetic sockets is incredibly time consuming for the prosthetist taking a minimum of 3-weeks (Prosthetic & Orthotic Care, n.d.) and when 3D printing is used it's never intended for long term use. My product is here to change that.

INNOVATION STRATEGY

3D printers are developing fast, it was only in 2008 that he RepRap Darwin 3D printer helped to kickstart the engine that is novel manufacturing (Flynt, n.d.). Polar 3D printers are perhaps the newest in the field. Polar printers have not been exploited for their incredible use within this environment. Polar 3D printing within the medical industry would help to expand the product range to offer customers. This is due to their excellence in printing cylindrical objects.

Furthermore, using Polar Coordinated, Isocyanates and Polyol, and LAM extrusion would result in a world first, (at least at the time of writing this report). The combined technologies would provide superior quality improvements to prosthetics specifically. This technology could also result in advancements in Soft Robotics and other soft / multi-shore hardness 3D printed products.

In Fig1 is the estimated potential value of this machine. This price is determined in Appendix-7 of **Author's** Interim Report.

Figure 1: *Perceptual map 1*

PRODUCT DIFFERENTIATION

The lack of Polar 3D Printers on the market make this an obvious avenue to develop as they provide consistent and finest quality prints for cylindrical objects. Like prosthetic sockets. As is seen in Fig2, the prosthetic and orthotic specific machines lack the ability to print cylindrical products. The second cheapest on the list and second most expensive printers both provide near excellent circular printing due to their polar printing methods.

The key difference of the product I'm developing different is the ability to print polyurethane through LAM. This combination allows for products to have multi-shore hardness throughout the print. This has been explored only by a select few companies and is the next progression in 3D printed prosthetics.

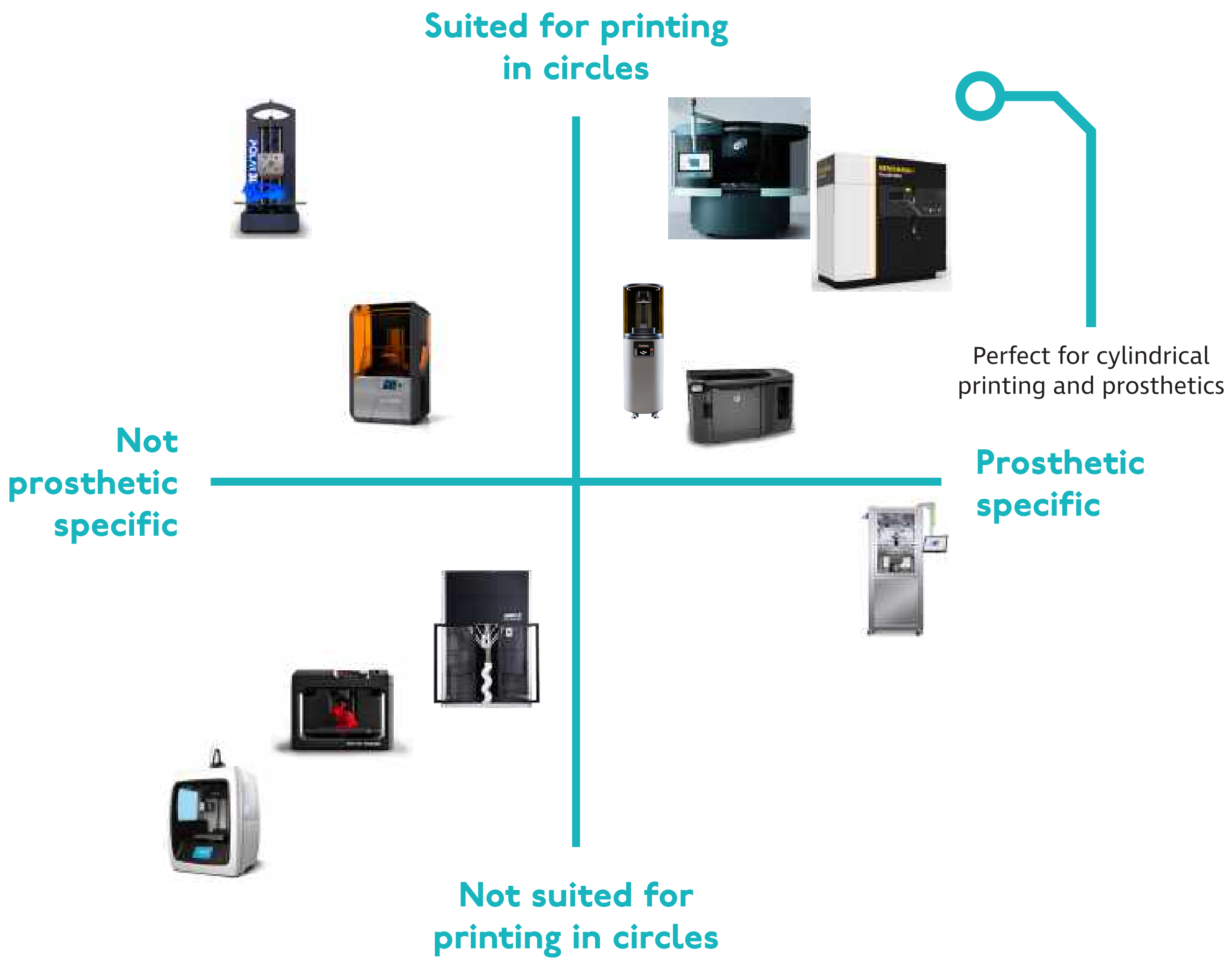


Figure 2: *Perceptual map 2*

BMC from Strategyzer (Strategyzer, n.d.)

The Business Model Canvas

Designed for: Polar 3D Printer | *Designed by:* Luke Tolchard | *Date:* 14/01/2020 | *Version:* 01

Key Partners

- DSM (Parent company interested in the field of 3D manufacturing)
- 3D chromatic (Inventor of the PUR material)
- Raw material producers
- Component producers
- Haulage companies
-
- German RepRap (produce a similar product - would be worth collaborating with them)

Key Activities

- Product development & management
- Building the website
- ISO certificate
- Setting up the 3D printer(s) in customers location

Key Resources

- Patent
- Manufacturing assembly line
- Workforce
- Equipment & technology
- Web hosting

Value Propositions

- Product development & management
- Building the website
- ISO certificate
- Setting up the 3D printer(s) in customers location

Customer Relationships

- B2B & B2B2C
- Social media
- Customer services
- Help bords/FAQ's
- On-site maintenance and assistance

Channels

- Website
- Tradeshows
- Media

Customer Segments

Manufacturer

- Producers of medical products who want a competitive edge
- Innovators and designers of prosthetics

Cost Structure

- Employees' salaries and internal individuals
- Payment to external companies and individuals
- Building rent
- Transport & equipment

Revenue Streams

- Grants & trusts
- Lease out patents
- Product purchases
- Subscription based purchases

VALUE PROPOSITIONS

The Key value propositions are outlined below:

Improving the speed at which prosthetics are produced

Usually the top prosthetic companies will have a large team of prosthetists so they can provide their expertise to as many amputees as possible. Creating a prosthetic takes hundreds of man hours spanning many weeks. The 3D printer would drastically speed up the delivery of the amputee's prosthetic getting them back up on their own two feet.

Multi-shore hardness

Prosthetic sockets are the only contact point for those with lower limb amputations and therefore must be loaded with the weight of the wearer. If there is any nagging problem with the prosthetic this relates in the amputee not wearing it. Varying the shore throughout the product and in key pressure point areas will allow for the product to conform better to the wearer's stump. When walking the socket can bend and relieve areas from stress and strain.

Fully custom

3D printing a socket from the amputees .STL file will result in a 100% fully customised product that matches the amputee exactly.

Polar coordinates

Polar coordinates possess the natural ability to print round objects in extreme detail, much better than their Delta and Cartesian counterparts.

Medical specific

Being medical specific results in a machine that has all the necessary functions that are needed for this industry.

CUSTOMER RELATIONSHIP

Open to customers

The key to maintaining a respectable customer relationship is by being open to feedback. The code used to run the 3D printers will be open source software. Customers can then edit the code and offer constructive feedback to ways we can improve the machine (requires approval). By having platforms where customers feel connected (i.e. social media). E-mail updates and events updates will be published weekly.

Help bords and forums

There will be FAQ's, forums where consumers can post questions, e-mail contact as well as call lines are open.

CHANNELS

Awareness

Social media & Adverts -
Billions of people use these social platforms and view adverts every second they are on these platforms.

Tradeshows -
Communicating your product in person to industry professionals.

Interviews -
Media and network companies want to review the freshest technology.

Evaluation

Coming across the post -
All social platforms will be used to promote this machine, but targeted advertisements will be used to promote this machine to those already in the industry.

Direct contact -
A small amount of people come to visit these but are the most likely to buy one of these machines. It's important to travel to major shows across the world to show the machine to as many people as possible.

Free advertisement -
After the initial buzz of the product; the news, bloggers, and other tech forums will want to interview myself to have fresh content for their respective platforms.

Recommended -
As the product develops a name for itself medical professionals will recommend the Polar 3D Printer as the suitable choice for them.

Purchase

Through the website, tradeshows, and retailers.

Delivery

The products are built to order so after the manufacturing stage has completed the 3D printers will be shipped straight from the factory.

Aftersales

An e-mail, call line, and chat room will be available to discuss any issues and sales.

CUSTOMER SEGMENTATION

The Polar 3D Printer's primary and secondary markets are for those who are producing prosthetics and whose who use 3D printers to print anything.

Primary

Those who will use this product for its intended purpose. This machine will assist in the production of prosthetics manufacturing, thus benefiting the company, prosthetists and employees, the customer (Amputee), and the global market for medical prosthetic products. This groups is willing to try the newest technology if it's proven itself to the industry that it can perform to the standards required. This industry is looking for ways to speed up the process of delivering prosthetics to their patients as the current time taken takes several weeks.

Secondary

This segment of the market makes up the largest percentage of where the revenue from this product will come from. This market is for the enthusiasts and other companies that want to explore the possibilities that multi-shore hardness PUR can provide. Considering that 3D printing technology is being integrated into most of the modern world it's likely that the product will be assisting most of these areas. This market refers to the: Enthusiasts; Soft robotics; Film/Movies/ Television/Set design; Construction. However, as 3D printing is making a leap into other areas not listed above so it's likely that is where the product would be seen most.

KEY ACTIVITIES

Funding
As the product isn't production ready, additional funding will be needed. Applying for government grant to assist with testing and manufacturing facilities.

Concept to production
There's development needed to ensure that this product is operation ready. It's required to pass this test before the machine can be produced and put up for sale.

Standards testing
Getting approval from standard committees that the machine is operational ready, like completing ISO/ASTM 52910:2018(en) for additive manufacturing (The International Organization for Standardization, 2018).

Branding and advertising
Brand guidelines will be set out as well as advertising spaces to be brought to publish the product to consumers.

Business collaboration
Larger parent companies would be an excellent way to gather more resources, not just financial but also knowledge based. Companies like DSM, which already have an interest in the field of additive manufacturing, would be a good business collaborator.

KEY RESOURCES

Physical
The product will be manufactured throughout Europe and China where construction and part-assembly of the product will undergo production. The final assembly will be done in Germany as this will benefit the marketing of the product.

Property
Warehouses leasing is needed and will be situated around locations of transport routes. Main areas of interest are located by port and rail services with ease of access to wide-laned roads.

Intellectual property
Branding, copyright, and product patenting to be completed.

Human
Industry partners, delivery, web developers and salespersons are needed to help get this product to where it is needed. Along with a workforce to create, make, and innovate on our product line. Within the employed workforce there will be Assistant and Line managers, Product leaders, PR and HR, Customer services, Designers and Engineers. Additional staff will be needed like Maintenance engineers and Cleaners.

Financial
Investments in the company would ensure that full-development, human resources, manufacturing, and maintenance of a commercially-viable and commercially-available product. Grants will be needed along side private investments to assist the initial growth of the company.

KEY PARTNERS

Collaborators
As mentioned under 'Key Activities' DSM would be a great collaborator as would 3D Chromatic who created this material to use. They are open to industries using their material so connecting with them would be beneficial. The knowledge and experience that companies like these can provide would excel the product quality.

News and media
Having a strong connection with the news and media would be important as having a front page news article about the product would prove dividend to the company. News outlets like '3D Printing Industry' would also benefit from having constant fresh content so applying another benefit to a collaboration with a news outlet.

Suppliers
Gathering materials would likely come from the Far East but and will require their components to be sent to the assembly plant which will likely be in Germany (as mentioned under 'Key Resources'). The components will likely be stepper motors, glass production and electronics. Aluminium sheet work will most likely be produced in China by producers like 'Tianjin Shenghui Steel Trading Co., Ltd.'.

Distribution
The output volume of products produced will be low; transport would likely be done by a couple of Class 6 Medium Duty Trucks, 12ft. – 22ft. If additional transport is needed, external companies like Eddie Stobart or local haulage companies will be used.

COST STRUCTURE

Manufacture
It's likely that all the components will come pre-manufactured making for quick assembly. This will require toolsets and fasteners (screws/rivets). The cost of these are low, also accommodating for workspaces. Equipment used to move the components from one place to another would be required. Machines like forklifts, pallet trucks, and overhead cranes would be used to move components around the warehouse. The average cost of the above components is listed below:

- Toolset - £500 (Multiple would be needed)
- Forklift - £8,500 (2nd hand)
- Pallet truck - £200
- Overhead crane - £1,000

Employee wages
The minimum hourly UK wage for over 25's is £8.72 (GOV.UK, 2020). This would be the base price for low priority jobs like cleaners, HR, and customer services but could jump up to £15 depending role importance.

REVENUE STREAMS

The physical product could range between £30k - £100k depending if it's sold under a brand name or not.

Under brand name
Leasing out the patent to companies the Polar 3D Printer will sell for maximum price as the name of the brand will assist in the sale of the product

Individual
Without the support of a brand name the product will sell for £30k - £50k.

Leasing out the 3D printer
There will be an option open for companies to pay for the machine over 3-years. This provides a constant, monthly/yearly income. This option comes with free, minor, maintenance with options to upgrade to a newer model after the lease period has concluded.

(Redwood, n.d.)

3 APPENDIX

S

- Ability to print a multi-shore hardness product without the need to change filament.
- Polar coordinates have exceptional printing for cylindrical objects.
- A medical-focused machine.
- Accuracy in XY-axis to +/- $5_{\mu m}$ making this unrivalled for any prosthetic printing.
- Will deliver amputees a better suited and personal product.
- Can be used in the same room as people and doesn't produce particulates.

W

- Requires a larger work area to be housed.
- Layers need time to set so the print would take longer.
- Expensive due to novelty of the machine.
- Could be classed as experimentative as its new technology so companies wouldn't want to invest.
- There could be a new technology that comes out after the launch of this product, making this obsolete.
- Requires there to be a .STL file of the amputated area, therefore, the company supplying would need to invest in a 3D scanner.

O

- Innovation and new technology could progress future models of this machine.
- Initial revenue would go towards a successor.
- Software updates would continue to improve the machine.
- Amputations are constantly happening. 1-million per year. There aren't enough prosthetists to cover this market. This is where this Polar 3D Printer fits in.
- The model at launch would get a lot of press coverage as it would be a world first. This would broaden the market and entice amputees to ask their prosthetist for this method of manufacturing.

T

- This design requires patenting, the threat of a competitor is extremely likely.
- The unorthodox use of PUR LAM would be pushed away by competing companies as it would shock the market. Potentially ruining the reputation.
- Cheaper FDM alternatives for printing can pose a quick suppression of this machine.
- Extensive publicity and resources would have to be used to get initial publicity.

Figure 3: *SWOT Analysis*

4 REFERENCES

3D Natives, n.d. 3D Printer : RenAM 500Q. [Online]
Available at: https://www.3dnatives.com/en/3D-compare/imprimante/renam-500q
[Accessed 14 January 2020].

3d printers online store, n.d. Flashforge Hunter DLP Resin 3D Printer. [Online]
Available at: https://www.3dprintersonlinestore.com/flashforge-hunter-dlp-3d-printer
[Accessed 14 January 2020].

3D Printing.com, 2016. Robo 3D C2. [Online]
Available at: https://3dprinting.com/pricewatch/3d-printer/robo-3d-c2/
[Accessed 14 January 2020].

3D Printing.com, 2017. Carbon M2. [Online]
Available at: https://3dprinting.com/pricewatch/industrial-3d-printer/carbon-m2/
[Accessed 14 January 2020].

3D Prints.com, 2019. The Ultimate Polar 3D Printer Review You'll Want to Read. [Online]
Available at: https://3d-prints.com/2019/01/11/the-ultimate-polar-3d-printer-review-youll-want-to-read/
[Accessed 14 January 2020].

Access Prosthetics, 2017. 15 Limb Loss Statistics that May Surprise You. [Online]
Available at: https://accessprosthetics.com/15-limb-loss-statistics-may-surprise/
[Accessed 28 November 2019].

Flynt, J., n.d. A Detailed History of 3D Printing. [Online]
Available at: https://3dinsider.com/3d-printing-history/
[Accessed 2020 January 10].

Francis, S., 2017. HP and Deloitte partner to provide digital technologies for industrial companies. [Online]
Available at: https://roboticsandautomationnews.com/2017/09/01/hp-and-deloitte-partner-to-provide-digital-technologies-for-industrial-companies/13927/
[Accessed 14 January 2020].

German RepRap, n.d. L320 3D printer. [Online]
Available at: https://www.germanreprap.com/printer/L320.aspx
[Accessed 14 January 2020].

GOV.UK, 2020. National Minimum Wage and National Living Wage rates. [Online]
Available at: https://www.gov.uk/national-minimum-wage-rates
[Accessed 14 January 2020].

Pooja, D. G. & Sangeeta, L., 2013. Prevalence and aetiology of amputation in Kolkata, India:. A retrospective analysis, 31(1), p. 38.

Printed Electronics Now, 2019. dp polar, ALTANA Presenting 3D Printing Solution for Industrial Series Production. [Online]
Available at: https://www.printedelectronicsnow.com/contents/view_breaking-news/2019-11-14/dp-polar-altana-presenting-3d-printing-solution-for-industrial-series-production/
[Accessed 14 January 2020].

Prosthetic & Orthotic Care, n.d. Prosthetic Timeline. [Online]
Available at: http://www.pandocare.com/prosthetic-timeline/
[Accessed 2 December 2019].

Redwood, B., n.d. The Advantages of 3D Printing. [Online]
Available at: https://www.3dhubs.com/knowledge-base/advantages-3d-printing/
[Accessed 14 01 2020].

Robo Savvy, n.d. MakerBot Replicator Desktop 3D Printer 5th Gen (Refurbished). [Online]
Available at: https://robosavvy.com/store/makerbot-replicator-desktop-3d-printer-refurbished.html
[Accessed 14 January 2020].

Strategyzer, n.d. Canvas - Business Model Canvas. [Online]
Available at: https://www.strategyzer.com/canvas/business-model-canvas
[Accessed 14 January 2020].

The International Organization for Standardization, 2018. ISO/ASTM 52910:2018(en) Additive manufacturing — Design — Requirements, guidelines and recommendations. [Online]
Available at: https://www.iso.org/obp/ui/#iso:std:iso-astm:52910:ed-1:v1:en
[Accessed 14 January 2020].

Tolchard, L., 2019. Increasing Comfort for Transtibial Amputees with Improvements to Prosthetic Design and Function Through 3D Manufacturing Method. Interim Report, 1(1), p. 1.

WASP, n.d. Delta WASP 3MT INDUSTRIAL 4.0. [Online]
Available at: https://www.3dwasp.com/en/professional-3d-printer-delta-wasp-3mt-industrial/
[Accessed 14 January 2020].

APPENDIX-17

YOUTUBE LINK FOR THE CORRESPONDING VIDEO THAT ACCOMPANIES THIS REPORT:

HTTPS://YOUTU.BE/V40L5BTKDLE