Development of Low Cost Inkjet 3D Printing for the Automotive Industry

A thesis presented in partial fulfilment of the requirements for a degree of

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Abstract

The aim of this project is to develop a low cost, powder based 3D printer that utilises inkjet printing technology. The 3D printer uses a standard drop-on-demand inkjet print head to deposit a binder onto the powder bed one layer at a time to build the desired object.

Existing commercial 3D printers that use inkjet technology are large and expensive. They do not allow much control to adjust printing parameters, meaning it is difficult to conduct research with different materials and binders. Due to these factors it is not viable to use one for research purposes.

The automotive industry uses 3D printing technology heavily throughout the prototyping process, some manufacturers have even started using the technology to produce functional parts for production vehicles. Ford Motor Company helped develop 3D printing technology and brought it to the automotive industry while multiple university's in America were researching the technology.

Based off an open source design, the printer developed in this project has been customised to allow full control over printing parameters. The body of the printer is laser cut from acrylic. All mechanical components are off the shelf items wherever possible to keep costs down and allow the print area to be easily scaled. Binder is deposited with an HP C6602A print head which is filled with regular black printer ink. The ink is deposited onto a bed of 3D Systems VisiJet PXL Core powder. Custom made parts manufactured in house allow for the print head to be easily changed to whatever is needed. The print head used is refillable and can therefore be filled with custom binders.

With the 3D printer developed in house, all aspects can easily be adjusted. Having full control over printing parameters will allow research to be conducted to develop new 3D printable powders and binders, or to improve the printing quality of existing powders and binders.

The 3D printer has also been developed so that it is easy to adapt to other features to increase its capabilities. With the addition of a UV light source, UV curable binders could be researched; or with the addition of a laser, powder sintering could be researched.

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Abbreviations

ABS	Acrylonitrile butadiene styrene
AM	Additive Manufacturing
CAD	Computer Aided Design
CIJ	Continuous Inkjet Coding
CJP	ColourJet Printing
DMP	Direct Metal Printing
DOD	Drop On Demand
DPI	Dots Per Inch
EBM	Electron Beam Melting
FDM	Fused Deposition Modelling
GUI	Graphic User Interface
LOM	Laminated Object Manufacturing
MJP	MultiJet Printing
PCB	Printed Circuit Board
PLA	Polylactic Acid
RP	Rapid Prototyping
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SLA	Stereolithography

SPI	Serial Peripheral Interface
STL	Stereolithography (file format)

Chapter 1. Introduction

Three-Dimensional printing (3D printing) technology, also known as Rapid Prototyping (RP) or Additive Manufacturing (AM), is a technology that has been growing quickly over recent years and revolutionising the manufacturing industry. It has evolved from a technology capable of producing simple prototypes to a technology capable of producing functional parts as well as functional moulds that can be used to cast parts through other traditional manufacturing methods. This speeds up the manufacturing process significantly.

The vast majority of commercially available 3D printers are expensive, in the tens or even hundreds of thousands of dollars, sometimes even into the millions of dollars. Since it is generally not feasible to spend such large sums of money on 3D printers for research purposes, especially when conducting research using small quantities of materials, it was decided to develop a low cost 3D printer instead.

The automotive industry has been a large user of 3D printing technologies for many years. The technology has allowed the industry to improve their design and manufacturing processes to create higher quality parts at a much faster rate and at a lower cost.

The aim of this project is to develop a low cost 3D printer that utilises inkjet printing technology. The developed 3D printer will use traditional inkjet printing technology to deposit a binder material onto a powdered medium. The developed 3D printer will be used to research printable materials and binders for future applications. The printer would also be built so that in future it could easily be fitted with external devices to increase its capability. Such devices could include a UV light source for UV curable resins, or a laser for powder sintering. With built in adaptability the developed 3D printer will increase the university's ability to research inkjet 3D printing technology and materials.

The objectives of this project are to:

1. Investigate the current state of 3D printing technology, including currently available low cost 3D printers and the current state of 3D printing in the Automotive industry.

   In order to develop a low cost 3D printer that is suitable for research purposes, existing technology must be understood. To keep the cost of the developed 3D printer as low as possible, existing technology will be applied wherever possible.
   3D printing has had a large impact on the automotive industry. Investigating the way the automotive industry uses 3D printing will indicate how inkjet 3D printing could be applied to the industry.

2. Investigate the applications of inkjet printing technology with 3D printing.
   Inkjet printing technology will be investigated to determine the applications for current technology and to determine what can be implemented in a 3D printer in order to develop an efficient system at a low cost.

   Through investigating current inkjet technology, it can be determined which aspects of inkjet technology can be applied to a low cost 3D printer.

3. Develop a low cost, powder based 3D printer using inkjet printing technology.
   To keep costs down, the 3D printer will be developed using readily available, off the shelf parts, wherever possible. Any custom parts will be developed in house in the most cost effective way.
   The 3D printer must be developed to allow a variety of powdered materials to be used within its parameters.

4. Design future capability into the printer hardware.

The 3D printer must be designed so that it can easily be adapted to use other 3D printing technologies. Using in house technologies will allow for parts to be easily duplicated or modified if/when necessary.

1.1 Thesis Outline & Contributions

Chapter 2 introduces the current state of the additive manufacturing industry and how the automotive industry utilises 3D printing technology. Inkjet printing technology is discussed to introduce its applications in the 3D printing industry. Existing 3D printing technology is discussed, with a further in depth discussion of low cost 3D printers as well as commercial inkjet 3D printers

Chapter 3 details the mechanical components of the 3D printer developed in this project. The design of the body and motor sub-assemblies, as well as the gantry is discussed.

Chapter 4 details the electronic components of the 3D printer developed in this project. Important parts of the circuit are highlighted in detail. as well as electronics prototyping and printed circuit board design.

Chapter 5 discusses the software used to control the 3D printer developed in this project. The process that the user goes through to control the 3D printer is outlined, as well as the communication to the microcontroller.

Chapter 6 details the implementation and testing of the developed 3D printer. Problems that were faced during these tests are discussed. Adjustments made to the 3D printer hardware and software to correct these issues are discussed.

Chapter 7 discusses the deliverables of this project and how the objectives have been successfully met.

Chapter 2. Literature Review

2.1 Additive Manufacturing

Three-Dimensional printing technology, also known as Rapid Prototyping or Additive Manufacturing, has been around since the 1980s. Hideo Kodama of Nagoya Municipal Industrial Research Institute (Japan) invented the first two 3D printing methods in 1981. These methods used controlled Ultra-Violet light exposure to cure a photo-hardening polymer (Kodama, 1981).

Three-Dimensional printing technology has developed from a technology capable of producing rough prototypes to a technology capable of producing final products. There are multiple processes used by 3D printing technologies, these include but are not limited to, Fused Deposition Modelling (FDM); Selective Laser Sintering (SLS); Stereolithography (SLA); Selective Laser Melting (SLM); MultiJet 3D printing; Laminated Object Manufacturing (LOM); and Inkjet 3D printing (Yan & Gu, 1996).

3D Printer Technology	Material Medium
Fused Deposition Modelling	Filament
Inkjet	Powder bed & binder
Laminated Object Manufacturing	Roll of raw material
MultiJet	Resin/Wax bottle
Selective Laser Melting	Powder bed
Selective Laser Sintering	Powder bed
Stereolithography	Resin bath

Table 1 - 3D printer technologies and the material medium they print with

Rapid Prototyping has widespread use in the industrial and manufacturing sector, and is used by large corporations to improve the development of their products. Rapid Prototyping allows designers and engineers to design parts using CAD software, and then quickly turn them into a working prototype without the need for expensive tools, thus allowing the prototype to be produced at a relatively low cost. This allows the designer/engineer to physically handle the part and find any unforeseen errors within the CAD model. Another advantage of rapid prototyping is the ability to develop tools for part moulds. The rapid prototyped part can even be used as a master pattern in some situations. With the ability to quickly and cheaply prototype parts, it is possible to get higher quality, more complex parts to production sooner and at a lower overall cost (Yan & Gu, 1996).

Each different technology has its own advantages and disadvantages due to the natures of the technology. For example, Fused Deposition Modelling is very easy to implement at a low cost for plastic printers (such as ABS or PLA plastics). These are common for consumer level 3D printers. However, when extruding plastics it is a common problem for parts to warp due to temperature differences within the part as it prints. As the print starts, all the extruded plastic is an even temperature. As the print progresses the starting layers begin to cool down, while the new material being deposited on top is still hot. This means that ideally the printer will have a controlled environment around the print bed (some consumer level FDM 3D printers have this, many don’t. The vast majority of commercial level FDM 3D printers do have controlled environments), however in doing so this makes it difficult to have a large print volume, especially with a low cost machine. (Ainsley, Reis, & Derby, 2002)

Other technologies, such as Stereolithography (SLA) and Inkjet 3D printers do not have the same issues as no heat is required throughout the printing process. As no heat is required, it is theoretically possible to scale the print volume to any size. The downside to this is that they both require material to be deposited before a layer can be printed (SLA has a resin bath and Inkjet has a powder bed). This means extra material is required than the part needs in order to complete the print (FDM extrudes the required amount of material, including support material), this increases the initial cost of the print as a significant amount of extra material is required. As the size of the print area is increased, the initial costs of running the machine also quickly increase. Because of this, large machines are not very common.

Laser based 3D printing technologies, such as Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM), are generally only commercial level technologies, though there are some emerging low cost SLS 3D printers as discussed in section 2.4.2. There are a few reasons for this, such as cost, external hardware required (3-phase power, compressors, etc.), machine size, peripheral equipment (for cleaning parts and preparing prints i.e. sieve, mixer, bead-blaster). These technologies also require extra equipment in order to make them safe to use. SLM/DMP 3D printing systems must fill the print chamber with an inert gas such as Nitrogen or Argon. The inert gas prevents the metal power from oxidising or combusting (3DSystems, N.D.-d)

2.2 Inkjet Printing Technology

The original concept for inkjet printing was patented by Lord William Kelvin, a 19th century physicist and polymath, “for the direction of droplets through electrostatic forces.” This technology was not actually developed until the 1950s due to the inability to “generated detailed instructions to steer the droplets” (Brian Derby, 2010).

Siemens first introduced commercial inkjet printing technology in the 1950’s on a medical strip chart recorder. Inkjet printers that could print digital images were developed by Epson, Hewlett-Packard (HP), and Canon in the 1970’s where they started to become consumer level items (Brian Derby, 2010).

Inkjet 3D printing technology mainly uses one of two methods to deliver the ink onto the powder print bed. These two methods are Drop-on-demand (DOD) Inkjet printing or Continuous Inkjet printing. Each method has its own advantages and disadvantages (Ainsley et al., 2002).

2.2.1 How an Inkjet Print Head Works

Inkjet print heads can be split into two main types based on the way they operate: Continuous (also known as Continuous Inkjet Coding or CIJ) and Drop-on-Demand (DOD).

Continuous inkjet technology uses a stream of ink, continuously flowing from a nozzle, by use of pressure, to form drops. The stream of ink is broken into individual drops through the introduction of disturbances at a particular wavelength. The drop formation can be accurately controlled through use of a "regular disturbance at the correct frequency (for example with a piezoelectric transducer)" (Martin, Hoath, & Hutchings, 2008). Once the stream has been broken into uniform, individual drops, certain drops are "selected individually for printing" (Martin et al., 2008). One commonly used method for selecting drops is to use a conductive ink that is charged via induction as the drop forms. This method uses an electrode near the stream "held at an appropriate potential" (Martin et al., 2008) and allows each drop to be charged with a different voltage. The drops then fall through an electric field. This electric field deflects the charged drops by a different amount depending on their charge. Charged drops are directed to the printing medium, whereas uncharged drops fall into the catcher and are fed back into the ink reservoir to be reused (Blazdell & Evans, 2000).

Drop-on-demand inkjet technology uses one nozzle or an array of nozzles on the print head to eject individual drops of ink (per nozzle) when needed. The two most common methods of ejecting the ink are “the creation of a vapour bubble within the ink using a heater pad (‘bubble jet’) or the distortion of a piezoelectric ceramic element” (Martin et al., 2008). Thermal DOD print heads are used by Canon, Hewlett-Packard (HP), and Lexmark. Piezoelectric DOD print heads are used by Epson and Brother Industries (Haigh, 2016).

As the drop is ejected from the nozzle it is first followed by a tail that is still attached to the nozzle due to surface tension of the ink. At some point after the initial ejection, the tail breaks away from the drop. Some of the tail returns to the nozzle, while the rest either joins the drop or breaks away entirely forming “smaller satellite drops”. Once a drop has been ejected, the cavity created in the nozzle must be filled, and “any acoustic disturbance must have attenuated enough to not affect the formation of the next drop” (Martin et al., 2008).

Drop-on-demand inkjet technology is simpler in principal as it only needs to eject ink when required, as opposed to controlling a continuously flowing stream of ink; however it can be harder to manufacture the print head (Martin et al., 2008).

2.3 Inkjet 3D Printers

Inkjet printing has been used commercially for graphical applications for a number of years. Recently inkjet printing has been investigated for use in “displays, plastic electronics, rapid prototyping, tissue engineering, and ceramic component manufacture” (B Derby, 2011). In conventional inkjet printing, the print head separates individual drops on the printing surface. These individual drops are controlled so that the desired graphic effect is achieved. Due to the nature of the new applications, the drops are required to be connected to one another in order to create a continuous structure, whether 1, 2, or 3-Dimensional (B Derby, 2011).

There are a range of commercially available Inkjet 3D printers available today, a few of which are listed in Table 2, that are mainly split into two types. One of these types, known as material jetting, the print head ejects the build material onto the print bed (Wohlers & Caffrey, 2015). The parts are built up layer by layer, usually from a UV cured resin with a wax support material. These parts require post processing to clean the support material off after printing, though ejecting the print material from the print head has some advantages over a powder bed as it is very easy to print in multiple materials at the same time. This can be done through different nozzles in the print head for the different materials, allowing parts to be 3D printed with different, customisable physical properties. The other type of inkjet 3D printer, known as binder jetting, uses a powder bed that the print head deposits a binder onto. These 3D printers can come with full colour capabilities, as discussed in section 2.3.1. After printing the parts only need to be removed from the powder bed and brushed clean, there is no need for support material as the part is supported in the powder bed, similar to the SLS 3D printing process (3DSystems, N.D.-b).

3D Printer	Manufacturer
S Print/M Print Range	ExOne
Jet Fusion	HP
Objet Series	Stratasys
ProJet Series	3D Systems
ProJet MJP Series	3D Systems
VX Series	Voxeljet

Table 2 - Available 3D printers that use inkjet technology

3DSystems MultiJet Printing (MJP) printers use piezo print head technology in combination with SLA style printers. The MultiJet print heads deposit “photo-curable plastic resin or casting wax materials layer by layer” (3DSystems, N.D.-e). This process allows the printers to achieve a layer resolution of as low as 13 microns, with an X-Y print resolution of 750*750 DPI (3DSystems, N.D.-c) in 3D printers such as the 3D Systems ProJet 5500X (Figure 1).

Figure 1 - 3D Systems ProJet 5500X Multi-material 3D printer (Grunewald, 2015)

Figure 2 - Example of a part 3D printed in the in-house ProJet 5500X

ExOne manufacture a range of production and prototype 3D printers that use inkjet technology. The production 3D printers range in print sizes from

400x250x250mm up to 2200x1200x600mm. The prototyping 3D printers come in 400x250x250mm for the M-Flex metal 3D printer (Figure 3) and 800x500x400mm for the S-Print sand casting 3D printer (ExOne, N.D.-c).

ExOne offer a range of materials with their 3D printers, with a focus on casting materials and metals. Along with the range of materials are a few different binders suited for different applications (ExOne, N.D.-b).

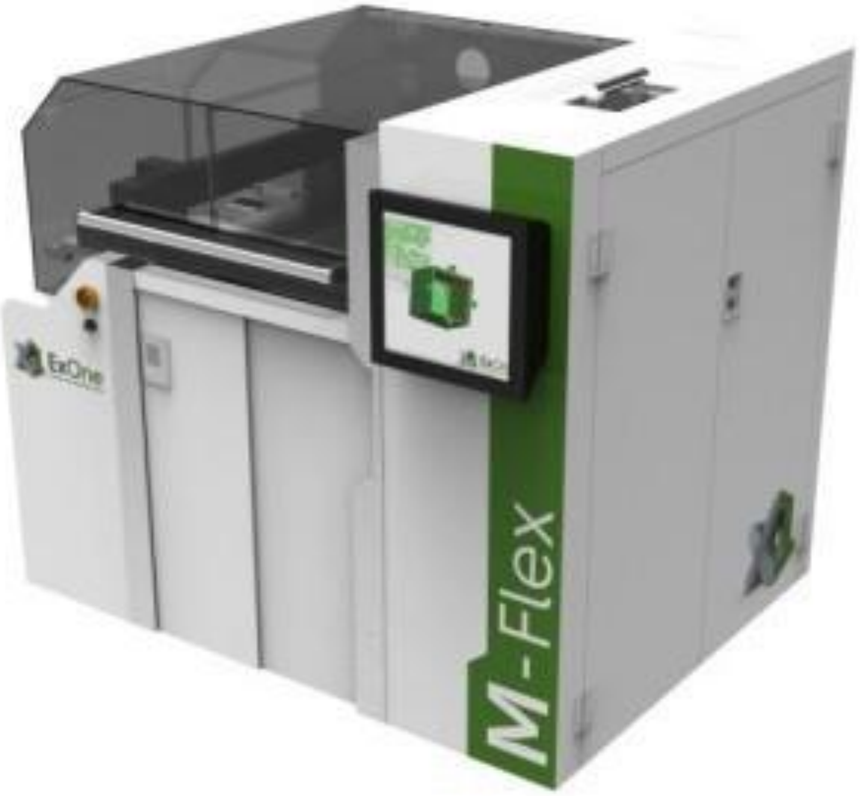


Figure 3 - ExOne's M-Flex 3D Printer (Maxey, 2014)

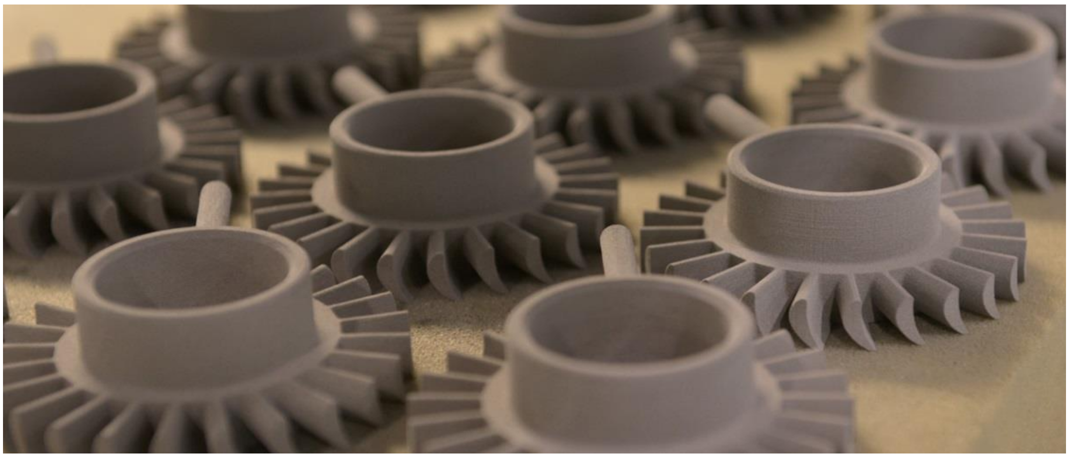


Figure 4 - ExOne 3D printed sand parts (ExOne, N.D.-a)

Voxeljet, a German 3D printer manufacturer, has a range of Inkjet based 3D printers capable of printing with plastics and cast-able sand (Silica sand). Voxeljet 3D printers have print areas ranging from 300 x 200 x 150mm (up to 300dpi resolution) up to the world's largest industrial 3D printer, the Voxeljet VX4000, with a print area of 4,000 x 2,000 x 1,000mm (up to 300dpi resolution) (Voxeljet, N.D.).

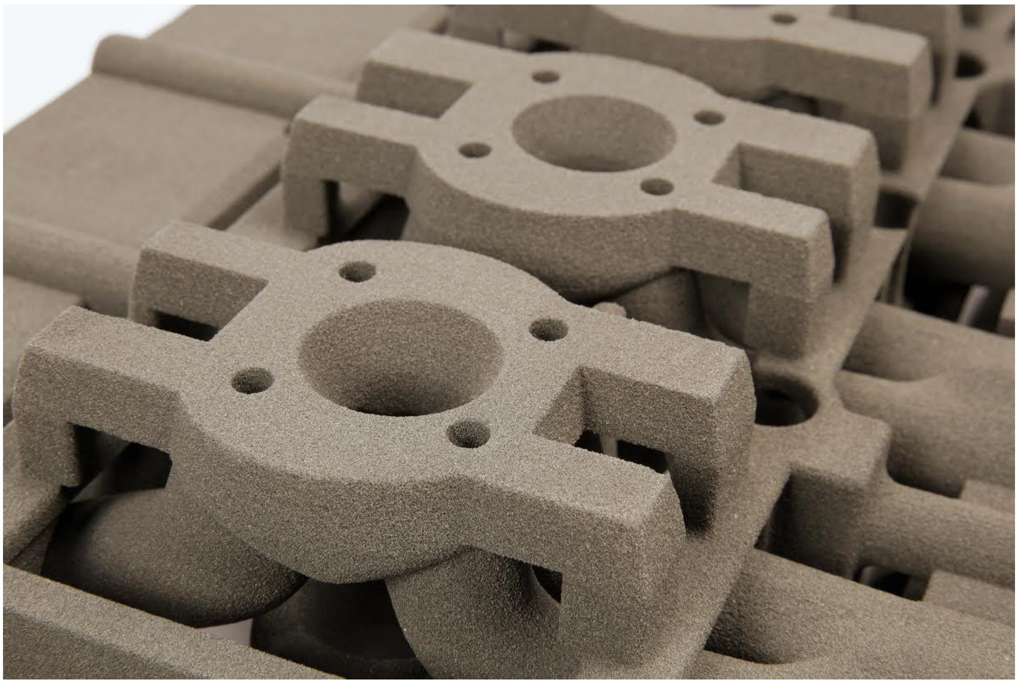


Figure 5 - Sand part 3D printed in a Voxeljet machine (Hipolite, 2014)

The Voxeljet VXC8000 is also the world's only continuous 3D printer. The printer takes advantage of the lack of external inputs that inkjet 3D printing requires, so it can have a continuous print bed on a conveyor belt. Having the print bed continuously moving on a conveyor, along with a diagonal print area (Figure 6), the VXC800 has a print area of 850 x 500, with theoretically infinite length (Voxeljet, 2013).

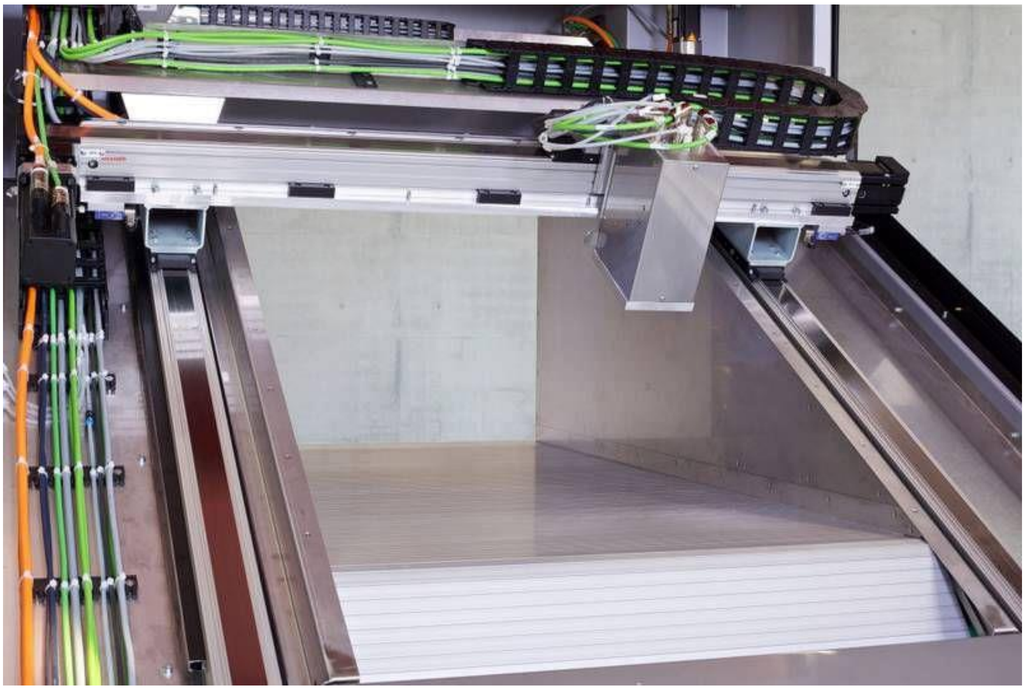


Figure 6 - View of the Voxeljet VXC800 angled print area and conveyor (3ders, 2012)

HPs new range of Multi Jet Fusion 3D printer's jet an infrared absorbing ink onto a bed of thermoplastic powder. The powder bed is the radiated by infrared lamps that cause the areas of powder where the binder has been deposited to melt and fuse the powder. The inkjet arrays in the Multi Jet Fusion 3D printers are capable of ejecting 30million droplets per second over an area of 1 inch. The Multi Jet Fusion 3D printers are said to produce parts up to 10 times faster than current 3D printers. Currently the only ink colour available is black; however more colours will be rolled out in the future. This will eventually enable full colour capabilities. The two current models in the range offer a build area of 406 x 305 x 406mm (HP, N.D.).

Figure 7 - HP Multi Jet Fusion 3200 3D Printer (Cleary, 2016)

2.3.1 Full Colour Inkjet 3D Printing

Inkjet 3D printing has the advantage over other 3D printing methods of being able to print in full colour without the need for complicated mechanisms to feed in coloured material to the printer. There are some existing devices that can be used in conjunction with FDM 3D printers to achieve full colour 3D prints, however using these results in a large material bank with multiple different colour spools feeding into the device (Mills, 2015). Due to the nature of feeding in plastic filaments, it is not possible to mix colours during the print process. There are also potentially some mechanical issues with these as they cut the different colour filaments into small pieces of the required size and feed them into a single guide tube to the nozzle. Feeding in individual pieces of filament can result in blockages within the tube or nozzle due to sections overlapping one another as they are forced up the guide tube. Some different colours also make it difficult to get a clean colour change as they contaminate each other when going through the print nozzle. For example switching from black to white produces grey until all the black has been removed from the nozzle, this can take a while due to the colours being so contrasting with one another (Figure 8).

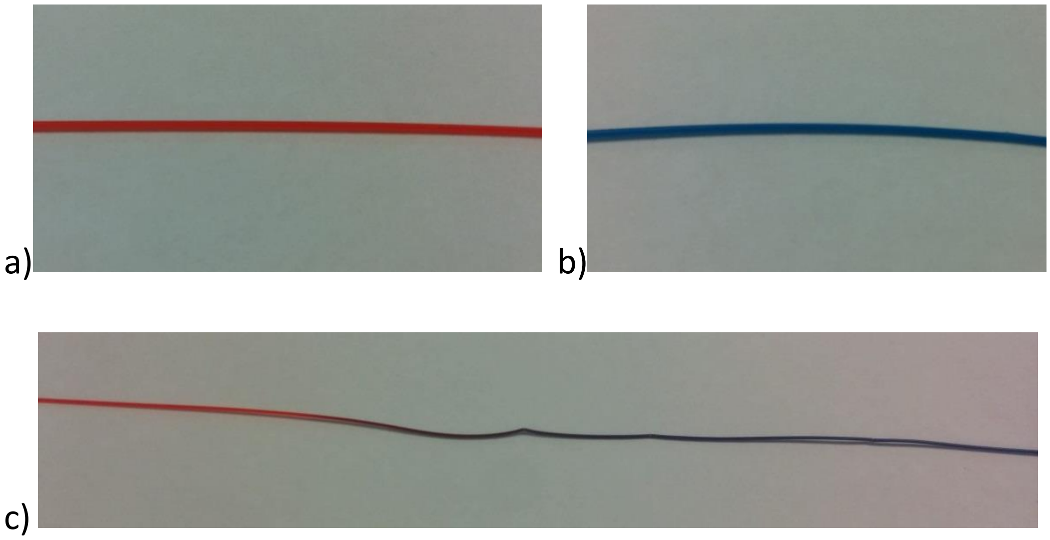


Figure 8 - FDM colour changing done with an in-house FDM 3D printer: a) red filament full colour; b) blue filament full colour; c) colour change from red to blue showing contamination

Full colour Inkjet printing does not have the same issues as the different colours are stored in separate material banks and are individually ejected in minute droplets, only being mixed to the desired colour when the ink is already on the print bed. This is the same method traditional colour inkjet printing uses to achieve full colour printing.

3Dsystems has a range of full colour 3D printers (ProJet CJP range). The smaller versions only offer CMY printing (ProJet CJP 260C and ProJet CJP 360) with a resolution of 300x450DPI, whereas the larger versions offer full CMYK printing (ProJet CJP 660Pro and ProJet CJP 860Pro) with a resolution of 600x540DPI. 3Dsystems offers a proprietary powder for use with their full colour 3D printer range, known as VisiJet PXL (3DSystems, N.D.-a).

Figure 9 - 3DSystems ProJet CJP 660Pro full colour 3D printer (3DSystems, N.D.-b)

Figure 10 - Sample part 3D printed on the 3D Systems ProJet CJP 660Pro (DesignPoint, N.D.)

2.3.2 Inkjet 3D Printable Materials

Inkjet 3D printing currently uses materials that are either photo-curable resins in combination with wax that is deposited directly onto a build plate, or a binding agent that is deposited onto a powdered print bed.

As some 3D printer manufacturers already have commercial inkjet 3D printers on the market there are a range of suitable materials available. Most of these powders and binders are proprietary compounds manufactured by the 3D printer manufacturer.

3D Systems CJP 3D printer range uses a proprietary material known as VisiJet PXL Core that can be printed with one of 4 binders (ColourBond, StrengthMax, Salt Water Cure, and Wax). VisiJet PXL Core has been used during testing for this project as several Kgs were donated (3DSystems, N.D.-a).

3D Systems MultiJet Printer range uses wax support material to print UV cured plastic/elastic materials. These materials are proprietary “UV curable plastics and UV curable elastomeric materials” (3DSystems, N.D.-c).

A common material for inkjet based 3D printers is a Plaster/Gypsum compound. This material is used largely in full colour 3D printers as it produces vibrant models. The material is brittle in nature so is rarely used with other 3D printing technologies. After printing it is common for these materials to be coated in a sealant to give them extra strength. The sealant is also used to preserve colours in full colour applications (RepRap, 2016).

A large use of 3D printing in the automotive industry is to produce complex moulds for sand casting large metal parts. Using a cast-able/silica sand moulds can be 3D printed that can then be used directly for metal casting. Usually the moulds are 3D printed in multiple parts and assembled into the final casting mould. This is done so that the foundry involved in the casting process can ensure that the mould is clean of any excess powder after the 3D printing process to ensure a clean cast without contamination. Any powder left in the mould from the 3D printing process would result in voids in the finished cast part (Bunkley, 2014).

Metal parts can be produced through inkjet 3D printing with metallic powders. The powder is bonded with specially formulated binders that will burn out during post processing. After the printing process is complete the parts are removed from the powder and then dried in a kiln to ensure there is no moisture in the parts. This baking process will also harden the binder in the parts. Once dried the parts are then infused with bronze to properly harden them. Since the parts are porous from the powder printing process, the bronze is easily absorbed into them to produced solid metal parts (i.materialise, 2010)

Inkjet 3D printers are capable of printing in a wide range of materials, with most commercial machines focusing on cast-able sands, gypsum, plastics, and waxes. Each company has their own proprietary materials and binders to go with their inkjet 3D printers.

2.3.3 Automotive use of Inkjet 3D Printers

The Automotive industry (as well as many other companies) currently uses 3D printers to prototype parts long before production is ready to begin. This means parts can be perfected before tooling costs are considered, resulting in parts that have been designed far better. In the past, when companies had to invest lots into tooling early on in the process, they were better off to make minimal changes after going through the tooling process as it would be expensive to have to go through the tooling process again. Some automotive manufacturers are even using 3D printed parts as functional pieces of their cars, rather than just as prototypes (Mearian, 2014) (Koenigsegg, 2014b).

Koenigsegg Automotive (a Swedish Hyper car manufacturer) use 3D printed Titanium parts (SLM 3D printed) in their Koenigsegg One:1 Hyper car. An example of one of the functional 3D printed parts is the exhaust outlet on the rear bumper (Figure 11). At the time these were the largest Titanium parts ever 3D printed, they are also about 1kg lighter than the equivalent machined Aluminium piece. Since Koenigsegg is not producing cars in large numbers (less than 25 annually) it is worth using 3D printed parts instead of machining them or going through the tooling process as it is far cheaper due to the complexity of the part. If the part were machined a large block of material would be required, which would be very expensive. Machining it from a large block would also result in a large amount of material going to waste (Koenigsegg, 2014b).

Figure 11 - Titanium 3D printed exhaust for the Koenigsegg One:1 (Wade, 2015)

Another example of a functional 3D printed part used in Koenigsegg's cars are the twin turbos (Figure 12), which are a patented design. The turbos have two internal channels that twist around one another through the exhaust housing of the turbo. As the design is very complex, the turbos are Titanium 3D printed because they cannot be manufactured through traditional manufacturing processes, such as casting or machining them. Koenigsegg tried to cast them but were not successful and made the decision to 3D print them instead (Koenigsegg, 2014a).

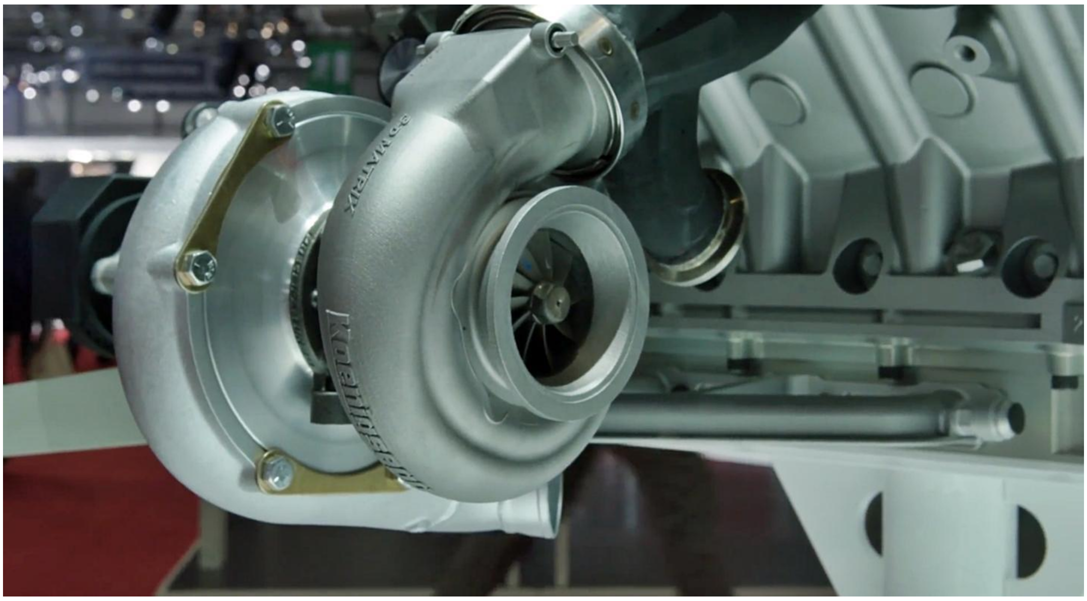


Figure 12 - Koenigsegg's 3D printed Titanium turbo (Klapman, 2014)

Koenigsegg also use 3D printed ABS plastic parts inside their production cars (air ducts/guides, parts inside the wing mirrors, etc.) for "parts that are fairly arbitrary and not very highly loaded." These parts are printed using FDM technology as strength is not an issue and it is cheap to do so (Koenigsegg, 2014b)

Ford Motor Company learned of 3D printing technologies while the technology was still experimental and being developed at multiple American Universities. Ford saw the potential of the two technologies (SLS and 3D printing sand), so helped bring the technology into the automotive industry (Fossen, 2005).

When Ford first starting using 3D printing technology, they were producing around 4,000 prototype parts annually, now Ford has five "3D prototyping centres" that each produce more than 20,000 parts annually. These figures show how much of an impact 3D printing technology has had on Fords manufacturing process (Mearian, 2014).

Inkjet 3D printers are capable of printing moulds suitable for making casting moulds. The ability to 3D print parts of the mould simplifies the casting process significantly. It allows more complex parts to be cast as all the internal cavities can be printed as moulds and assembled into one piece. Due to the complexity of some parts (such as engine blocks or heads) it is not necessarily desirable to print the entire mould as one piece. In the case of an engine block there are lots of small internal cavities (oil channels, water channels, etc.) that would mean it is difficult to ensure all the unbound powder is removed from the mould after the printing process. Because of this it is easier to print the internal cavity pieces separately and assemble the mould. This ensures a much cleaner mould and therefore a much more reliable casting. The cast part usually has dimensionally important parts machined to the desired finish after the casting process is complete (for example the top of the cylinder bank on an engine block). Multiple parts can be set up to print in one machine instead of having to be handmade individually. This streamlines the manufacturing process as well as significantly reducing the manual labour involved throughout the manufacturing process (DRIVE, 2013) (Mearian, 2014).

2.4 Currently Available Low Cost 3D Printers

In recent years there have been a number of low cost 3D printers come to market (Table 3). Most of these use FDM 3D printing technology; however there are a few that use other styles of 3D printing such as SLA and SLS.

3D Printer Name	Manufacturer	Technology Type	Price
CubePro	3D Systems	FDM	US$4499
Onyx One	Markforged	FDM	US$3499
Replicator+	Makerbot	FDM	US$2499
Replicator Mini+	Makerbot	FDM	US$999
Up Plus 2	Tiertime	FDM	NZ$2125
Up Mini 2	Tiertime	FDM	NZ$980
Ultimaker Original+	Ultimaker	FDM	€995
Ultimaker 2+	Ultimaker	FDM	€1895
Zortrax M200	Zortrax	FDM	US$1990
B9Creator V1.2HD	B9Creations	SLA	US$4595
Ember	Autodesk	SLA	US$7495
Form 2	Formlabs	SLA	US$4199
ProJet 1200	3D Systems	SLA	US$4900
Ice1	Norge Systems	SLS	US$13000
Kit	Sintratec	SLS	€4999

Table 3 - Some of the currently available low cost 3D printers

2.4.1 Hobbyist 3D Printers

There are a range of low cost 3D printers currently available on the market aimed at hobbyist users; a large number of these are available in kit forms to reduce the cost. Many of these low cost 3D printers have been funded through crowdfunding campaigns. The majority of these 3D printers use FDM technology, which is relatively cheap and easy to implement. FDM 3D printing is easy to use with minimal training and requires minimal peripheral equipment (most are self-contained and only require a standard power port). There are some low cost desktop SLA and SLS 3D printers; however these are priced slightly higher than the low cost FDM equivalent 3D printers (3DHubs, 2016).

2.4.2 Low Cost Powder 3D Printers

There are a few emerging companies that have recently crowdfunded projects to bring low cost SLS 3D printers into the marketplace. Two examples of these are Norge Systems and Sintratec.

Norge Systems funded their SLS 3D printers, the Ice1 and Ice9 (Figure 13), through Kickstarter before partnering with Prodways to bring their 3D printers to market. The original crowdfunding campaign offered the Ice1 to backers for £5000 and the Ice9 for £19000, with a market sale price of £9000 and £34000 respectively (Norge, 2014).

Figure 13 - Norge Ice1 (left) and Ice9 (right) (Krassenstein, 2014)

Sintratec is a low cost SLS 3D printer that was funded through a successful Indiegogo campaign. The Sintratec SLS 3D printer kit (Figure 14) is priced at €4999, possibly the cheapest laser sintering 3D printers for sale. The Sintratec uses a low power diode laser and a “mechano” style body. This makes it small and in turn keeps the cost down. The crowdfunding campaign offered the Sintratec Kit to backers for US$3999, with the option of a fully assembled version for US$9980 (Solenicki, 2015).

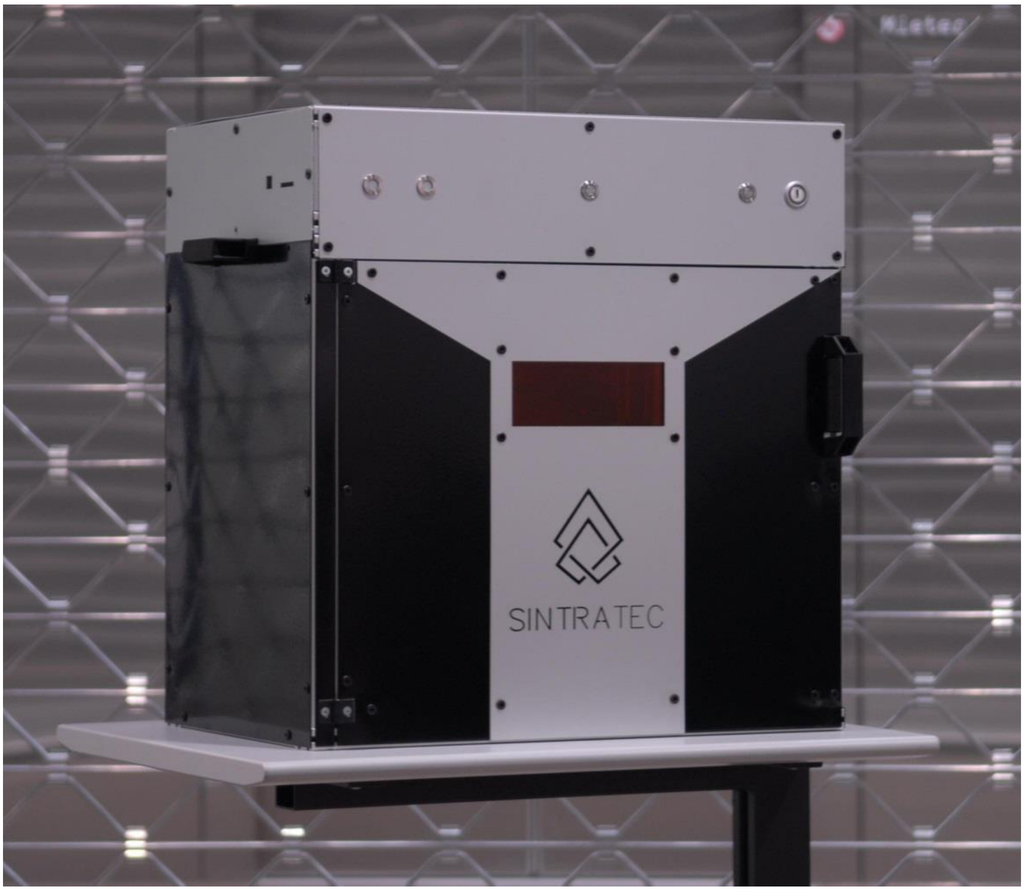


Figure 14 - Sintratec Kit SLS 3D printer (Goehrke, 2014)

2.5 Chapter Summary

The literature review covers the Additive Manufacturing industry and the applications it has in the automotive industry. Covered in further detail is the inkjet 3D printing process, as well as how the most common types of inkjet print heads work. For this project a Drop-on-demand print head is used as it is cheap, readily available, and easy to implement.

3D printing has been around for a few decades now, with the technology making numerous advances, especially in recent years. There are a range of 3D printing technologies available, each offering their own advantages and disadvantages.

Low cost 3D printers are becoming more and more common, with most of them focused on FDM 3D printing technology there are a few emerging in the market using other technologies.

Inkjet 3D printers are available on a commercial level implemented in a few different ways for different applications. There are a range of materials offered in these commercial machines, most of which are made by the 3D printer manufacturer and are proprietary compounds. The main material types used in these commercial machines are casting sands, plaster based materials, and UV cured resins. A 3D Systems powder known as VisiJet PXL Core was donated for use in this project.

None of these commercially available machines are viable to use for researching new materials and binders as they are designed to work with these proprietary compounds, so do not offer much accessibility to machine settings for research purposes.

Chapter 3. Mechanical Components

The main idea behind the physical design of the 3D printer was to use an open-source design to save time and reduce cost. The original design is taken from the open-source PWDR design, originally designed by Alex Budding of the University of Twente, Enschede, Netherlands. This style of 3D printer is easy to implement and does not require complex parts or manufacturing methods to produce.
In order to achieve the low cost aspect of this project, the mechanical components for the developed 3D printer were sourced from local companies wherever possible.

All parts are off the shelf items or manufactured in house through advanced manufacturing techniques, laser cutting or 3D printing. The only parts that are exceptions to this are the shafts that need to be cut to length, and the roller shaft that needs to be turned down at both ends to fit within the printer body.

3.1 3D Printer Body

The body of the 3D printer is made 26 pieces laser cut from 8mm and 4.5mm acrylic (Table 4), which are both standardised sizes and are readily available. The acrylic was laser cut in house using a Universal Laser Systems PLS6.150D universal laser cutter. The laser cut parts are assembled using finger/slot joints, each of which has a slot cut out to hold a captive nut. Each corresponding piece has a hole cut out for a bolt to ensure a strong connection. This ensures the printer body is strong and rigid and that it can contain the powder without the need for rubber or fabric seals along the joints. It also means that the printer body can be disassembled fairly easily as there are no permanent connections made. In order to ensure there are no gaps along the height of the Z axis travel the screw connections are placed on the finger section instead of the slot. To account for this a small piece is attached on the outside of the joint to help pull the joint closed.

Laser cut piece	Quantity	Thickness
Front	1	8mm
Back	1	8mm
Side 1	1	8mm
Side 2	1	8mm
Build piston end	1	8mm
Piston divider	1	8mm
Feed piston end	1	8mm
Z motor mount	1	8mm
Electronics mount	1	8mm
Electronics cover	1	8mm
Piston side clamps	6	4.5mm
Gantry locators	4	4.5mm
Tensioner back	2	4.5mm
Tensioner side	4	4.5mm

Table 4 – 3D printer body bill of materials

The Body of the 3D printer (Figure 15) is a total of 491mm long by 320mm wide and 415mm high. Within these dimensions are the two powder chambers which measure 150mm*150mm, with Z axis travel of 150mm. The two powder chambers, the print piston and feed piston, are moved along the Z axis by linear drives mounted beneath them. There is an empty space at both ends of the Y axis which will catch any excess powder from layers being spread throughout the printing process, helping to contain any mess made from excess powder. Electronics are housed in a small compartment at one end of the Y axis.

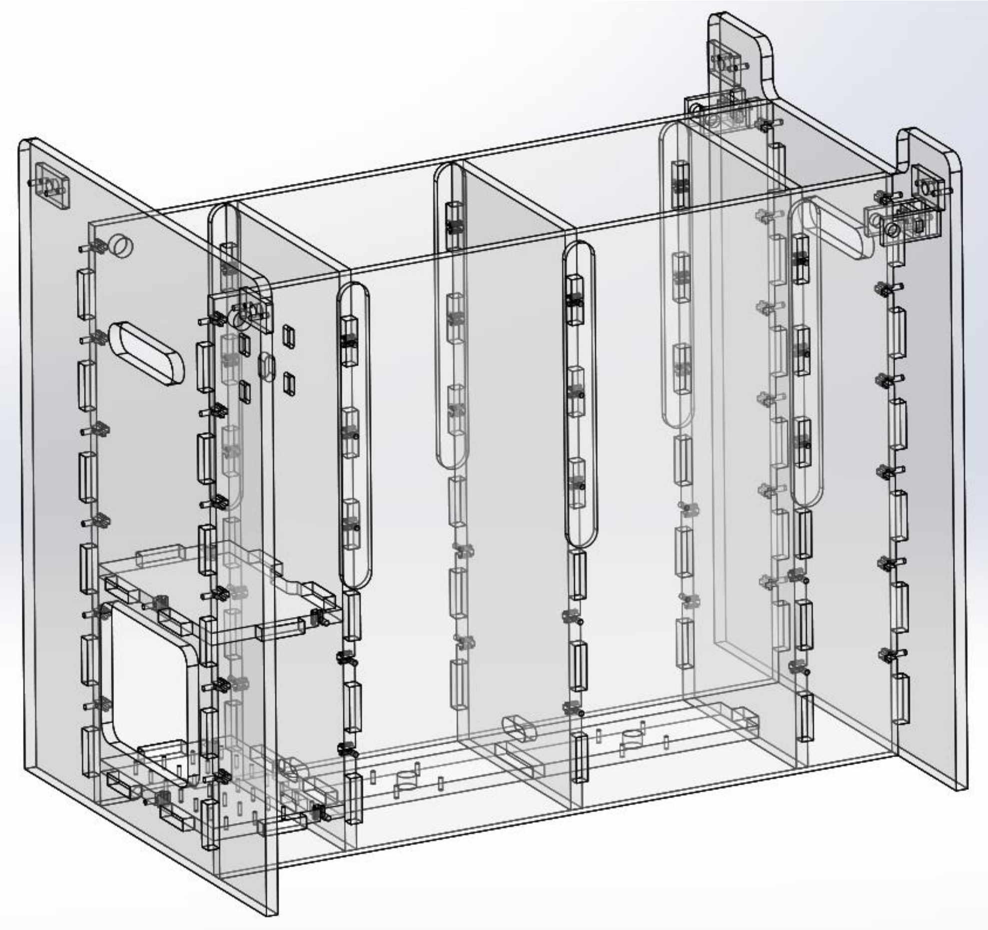


Figure 15 - CAD model of the laser cut body

3.2 3D Printer Pistons

The pistons used for the print and feed pistons are laser cut from 8mm and 4.5mm acrylic as the main body of the 3D printer. The upper piece of the piston, which forms the bottom of the print/feed powder beds, is 8mm thick to ensure that it is rigid and will not bend if it gets stuck when moving up or down. This piece was cut slightly oversized and then sanded to ensure a tight fit into the 3D printer body without too much friction preventing it from travelling smoothly. The other pieces are cut from 4.5mm thick acrylic.

Laser cut piece	Quantity	Thickness
Piston upper	1	8mm
Piston sides	2	4.5mm
Piston lower	1	4.5mm

Table 5 - 3D printer piston bill of materials

To drive the pistons, the linear drive nut is bolted directly to the lower sections of the pistons (Figure 16). To ensure a full 150mm of travel, the upper and lower pieces of the piston are mounted 157mm apart. This leaves enough space for the linear drive nut with no chance of the lead screw damaging the bottom of the powder bed when lowered completely.

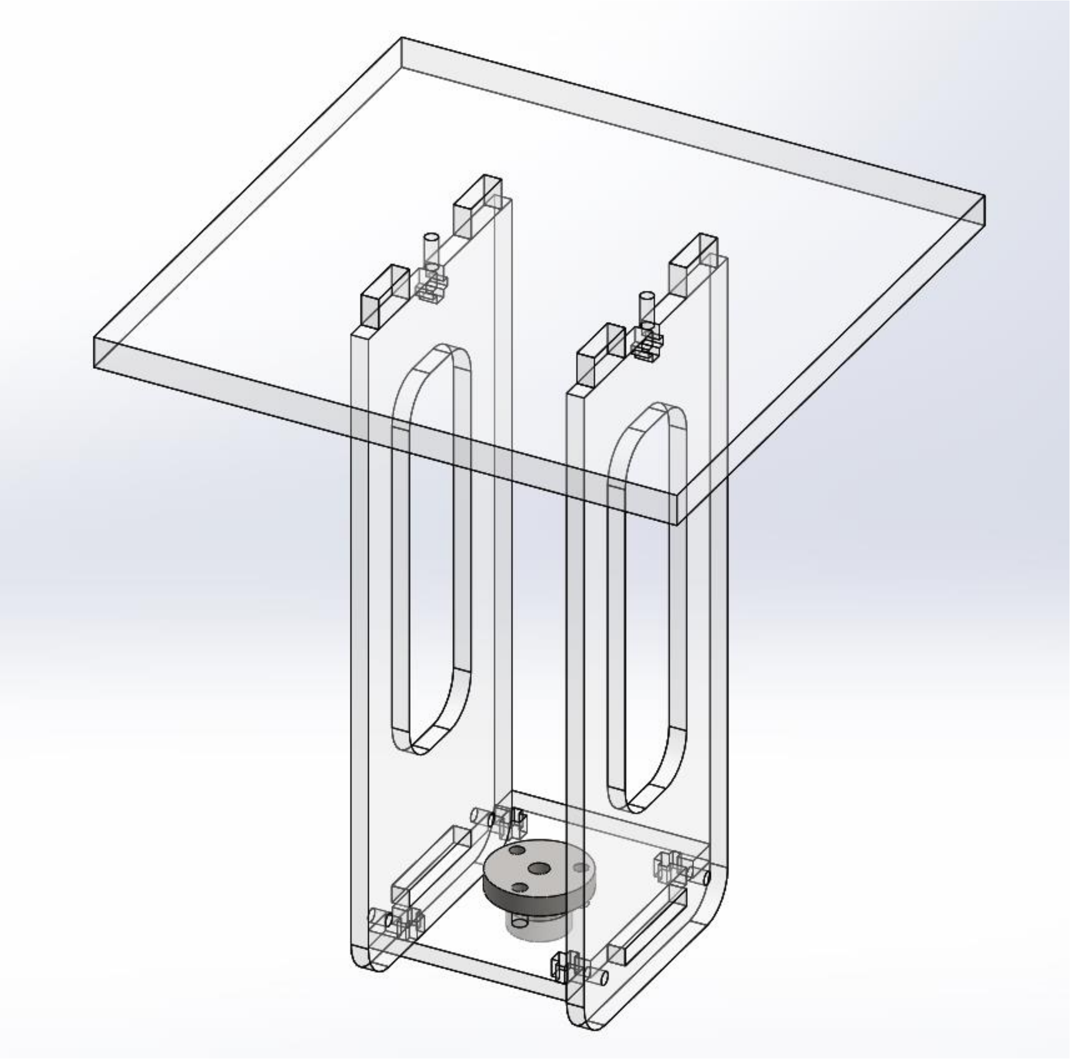


Figure 16 - CAD model of laser cut piston

3.3 Motor Sub-assemblies

There are two small sub-assemblies of that house the motors for the X axis and Roller. These sub-assemblies are mounted on the Y axis shafts and contain the linear bearings for the Y axis, as well as the bushings for the roller to mount into. Both of the housings have holes cut into the front pieces to accommodate the two X axis shafts. These sub-assemblies each mount onto one side of the Y axis and together support the X axis shafts, roller, and the print head mount.

The X axis motor sub-assembly (Figure 17) is made from four separate pieces laser cut from 4.5mm acrylic (Table 6). The X axis motor is mounted in this sub-assembly perpendicular to the X axis shafts. A slot is cut into the front piece of the sub-assembly to allow the timing belt to pass through to the motor and pulley.

Laser cut piece	Quantity	Thickness
Front	1	4.5mm
Motor mount	1	4.5mm
Side	1	4.5mm
Back	1	4.5mm

Table 6 - X axis motor sub-assembly bill of materials

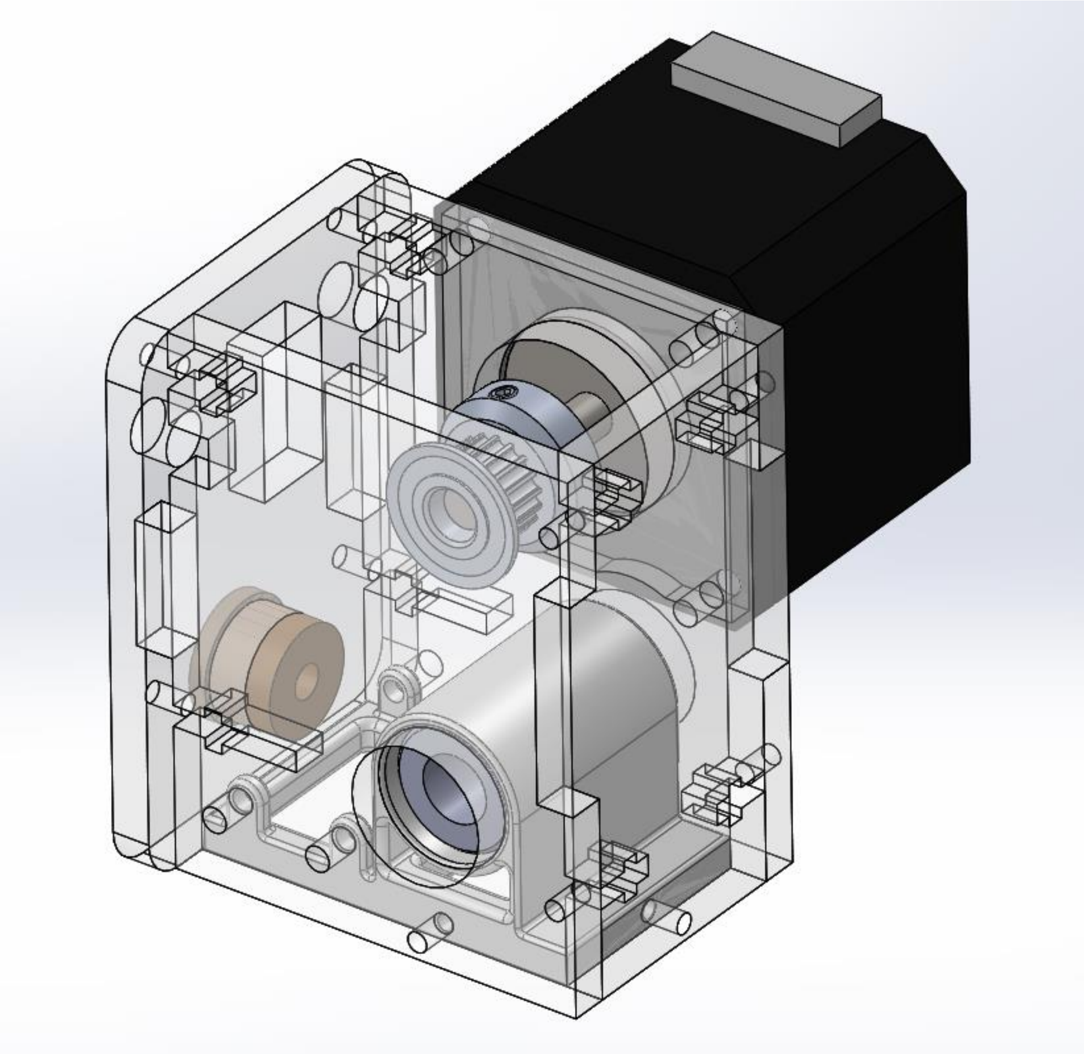


Figure 17 - X Axis motor assembly

The Roller motor sub-assembly (Figure 18) is mostly the same as the X axis motor sub-assembly, though there are a few small changes to the pieces. The Roller motor is mounted parallel to the X axis, so the motor is mounted to the front piece instead of the side. In order to ensure the roller motor timing belt is properly tensioned, the mounting face has slots cut into it instead of holes. This way the motor screws can be loosened so the motor can be slid up and down to appropriately tension the timing belt. This sub-assembly also houses a pulley for the X axis timing belt.

Laser cut piece	Quantity	Thickness
Front	1	4.5mm
Side	2	4.5mm
Back	1	4.5mm

Table 7 - Roller motor sub-assembly bill of materials

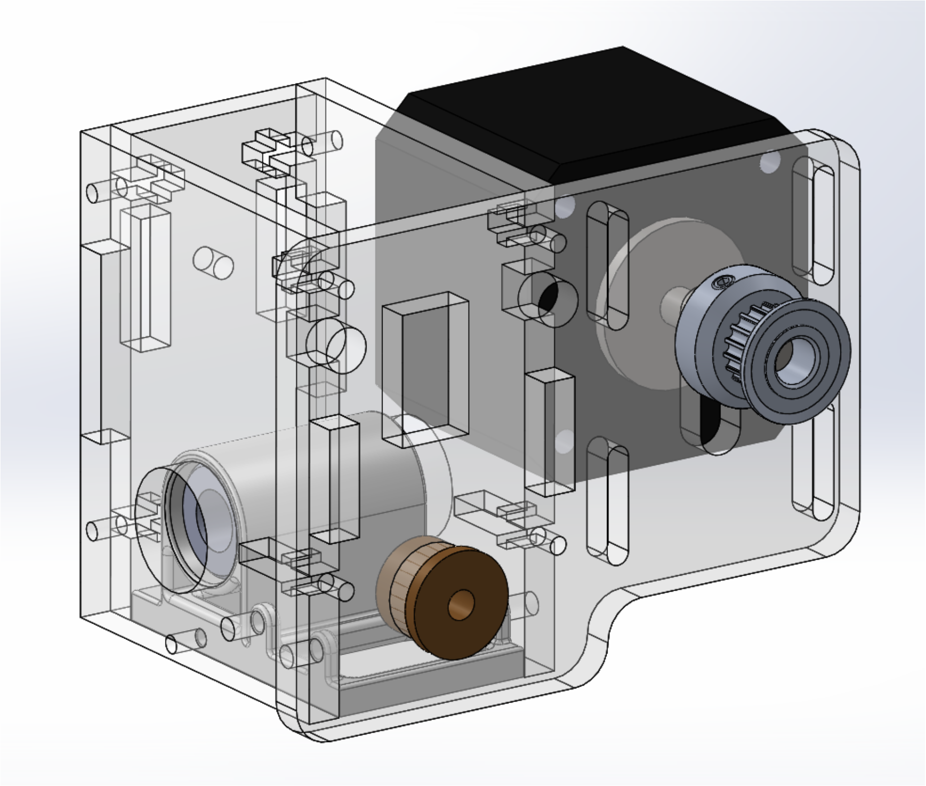


Figure 18 - Roller motor assembly

3.4 3D Printer Gantry

The shafts used for the 3D printer’s gantry are 4, 6, 8, and 10mm diameter silver steel shafts, all of which were sourced in house and cut to the appropriate lengths. The Y axis shafts are held in place by small pieces of acrylic that are laser cut with a 10mm diameter hole in them. The pieces slide onto either end of the shafts and are then screwed to the main body of the 3D printer. This simple system allows the shafts to be held in place securely, but also makes it easy to remove them if necessary. The X axis shafts slot into similar holes cut into the motor housing assemblies, which are held in place on the Y axis shafts.

All pulleys, belts, and bearings used were sourced through the internal workshop from local suppliers. The nine pulleys used are a standard size and are readily available through SDP-SI. Each of the pulleys that are mounted on a motor has had the centre hole drilled to 5mm diameter so they fit over the motor shafts. The timing belts used on the Y axis drive shaft and the roller shaft are 112mm and 130mm respectively. For the main Y axis timing belts a long belt was purchased and cut to the appropriate lengths as this is cheaper than buying individual belts. This timing belt was then clamped in place on the bottom of the X axis motor housings.

The Y axis timing belts are tensioned via a pulley at the end of the Y axis. This pulley is mounted in a bracket that slots into the main body of the 3D printer and can be pulled closer to the body by tightening a screw, which will then increase the tension on the belt. The Y axis drive shaft and roller timing belts are tensions by moving the corresponding motors up and down in slotted grooves, thereby reducing or increasing the tension on the belts.

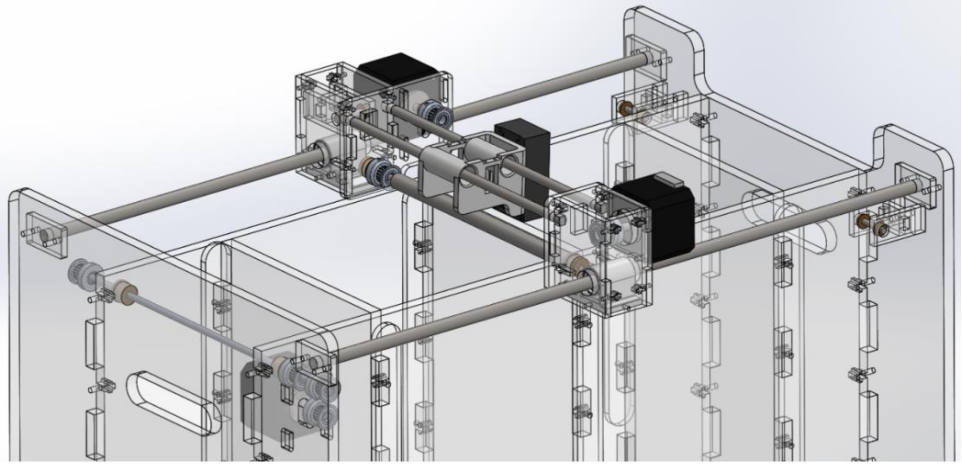


Figure 19 - Gantry assembly

3.5 Chapter Summary

This chapter covers the design and components used in making the body, motor sub-assemblies, and gantry of the developed 3D printer. The 3D printer body is made from 38 pieces of laser cut acrylic. All laser cutting has been done in house using 8mm and 4.5mm thick acrylic. The 3D printer gantry is built using readily available shafts, bearings, bushings, pulleys, and timing belts.

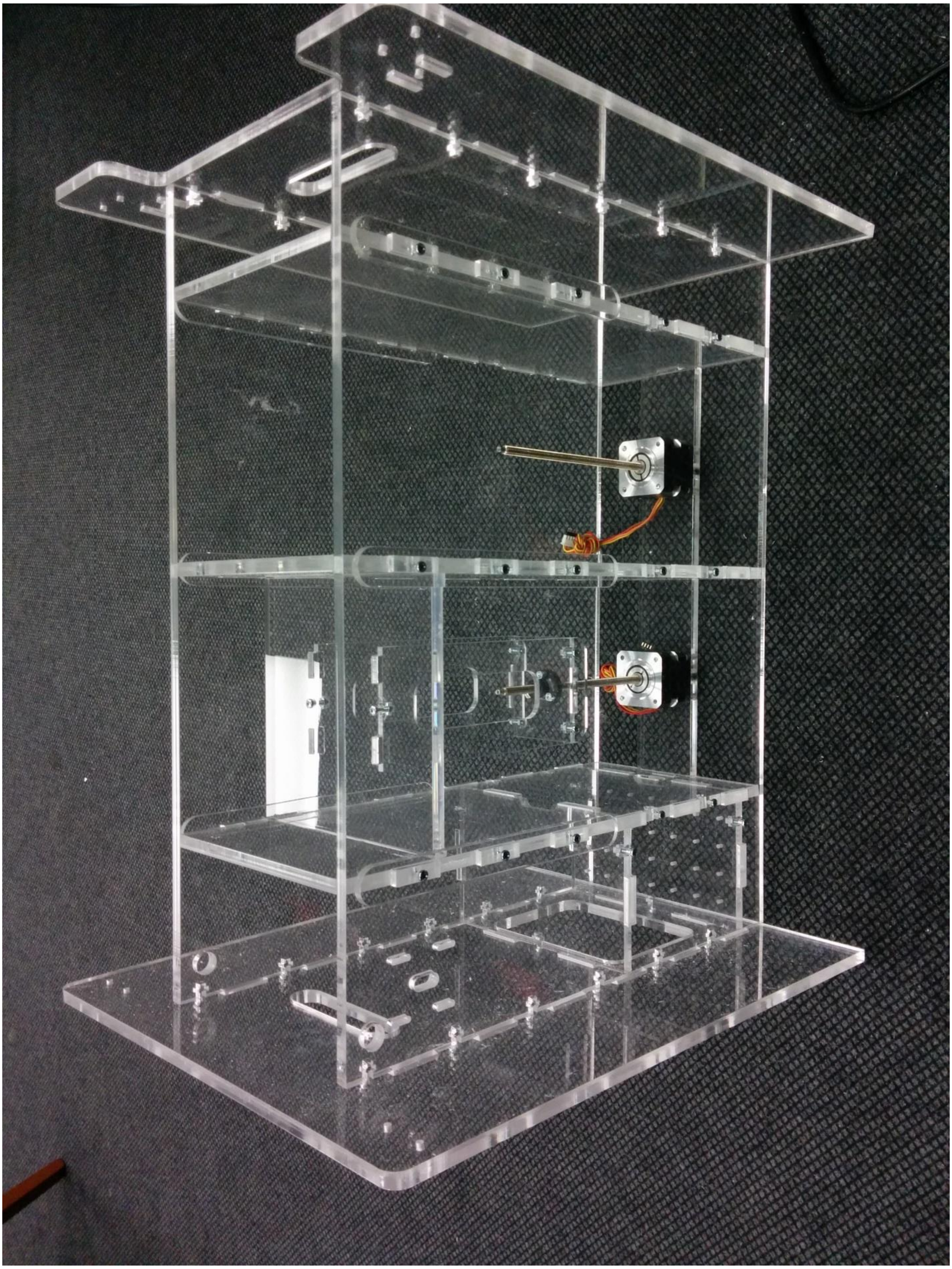


Figure 20 - Laser cut body fully assembled

Chapter 4. Electrical Components

The original open source circuit had various errors through it. Due to documentation issues with the original schematics, the circuit was remade. The main idea behind the circuit was kept so that the new design used readily available components. The new circuit was prototyped in sections using breadboards. The motor control circuit and print head circuit were prototyped individually before being combined into one circuit on a veroboard. This was done so that any issues would be easier to identify and solve. Once the total circuit was proven to work, a PCB was designed and manufactured.

Since the Arduino Mega used to control the 3D printer has more input/output pins than are required for this project in its current state, extra pins were allowed for future development of the 3D printer.

4.1 Arduino

Arduino Mega 2560 provides 54 digital input/output pins; it also provides 16 analogue input pins. 28 pins are required for the printer circuit. Four pins (50-53) are used for the SD card interface. These four pins are built into the Arduino Mega to have SPI (Serial Peripheral Interface) capability. Ten pins (36-45) are required for the stepper drivers; each driver needs a “step” and “direction” input from the Arduino. Fourteen pins (22-35) are required for the Darlington Arrays. Since 28 pins (minimum) are required, the best option was to use an Arduino Mega 2560 as it is a commonly available and cheap option. Other possibilities such as a Raspberry Pi or a PIC controller could have been used, however as the original open-source design used an Arduino there was no point in redesigning lots of the circuit/code to accommodate the change. The extra input/output pins available on the Arduino Mega 2560 also allow for further features to be added to the 3D printer. For example the PCB (discussed in section 3.2.6) allows for 10 extra connections to the Arduino so bump switches can be added to improve functionality.

Figure 21 - Arduino Mega 2560 Microcontroller (Arduino, N.D.)

4.2 Stepper Motor Drivers

Another component from the original circuit design that keeps the circuit simple is the use of SparkFun EasyDriver and BigEasyDriver Stepper Motor Drivers to drive the five stepper motors. The stepper motor drivers are easy to implement and only require four input and four output connections. The four input connections required are power/ground, step signal, and direction signal (step and direction signals come from the Arduino). The four output connections are the four motor coils for the stepper motor.

Each stepper motor driver produces a lot of heat. Since the heat produced could potentially damage the drivers over time, small heat sinks were made to remove this heat from the driver board. To increase cooling efficiency, a fan was also placed above the drivers to create airflow over them. This fan also cools the LM317T voltage regulator. As the Z-axis drivers (BigEasyDrivers) are not running the majority of the time (only activating to move the powder/print bins one layer at a time, or being manually stepped), heat sinks were not needed as the chips on the driver boards did not have time to heat up enough.

EasyDrivers stepper motor drivers require an input voltage of minimum 4.75V to operate, with a maximum input of 30V. Each EasyDriver can provide from 150mA to 700mA per phase of the stepper motor continuously (peak output current 850mA). EasyDriver stepper motor drivers are designed to operate between temperatures of -20°C to 85°C, though they have a built in thermal shutdown temperature of 165°C. Since the three stepper motors for the X and Y axes, and Roller will be running for a significant portion of the print time, heat sinks were used on the EasyDrivers to ensure they would run at a suitable temperature (Allegro, N.D.-b)

BigEasyDriver stepper motor drivers require a minimum input voltage of 8V to operate, with a maximum input of 35V. Each BigEasyDriver can provide an output current of up to 2A or up to 1.7A with no need for a heatsink (Allegro, N.D.-a)

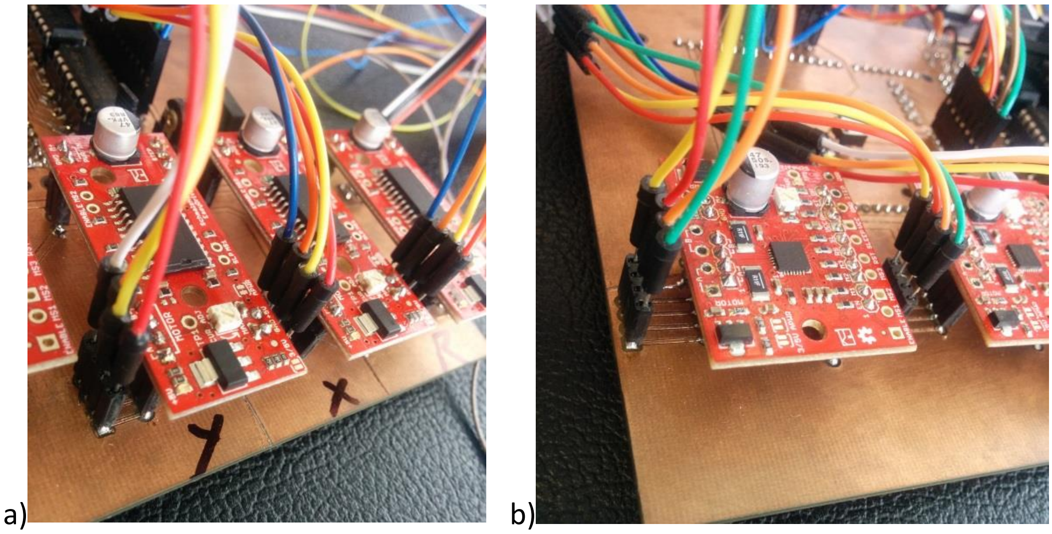


Figure 22 - Stepper Motor Drivers during testing of the first prototype. a) X/Y/Roller motor Easy Drivers; b) Z motors BigEasyDrivers

4.3 Stepper Motors

The original open-source design used three stepper motors for the X-axis, Y-axis, and on the Roller, as well as two stepper motors with built in lead screws/linear drives for the two Z-axis motors. These motors are readily available, easy to use, accurate, and relatively cheap so there was no need to change the motor choice. Stepper Motors are easy to implement when used with Stepper Motor Drivers, as discussed in the previous section. In order to control the stepper motors, the controller must send a step and direction signal to the stepper driver, which in turn sends the appropriate signals to the stepper motor (Figure 23). There is no need to program the stepper motor step phasing into the Arduino as the stepper driver controls this automatically.

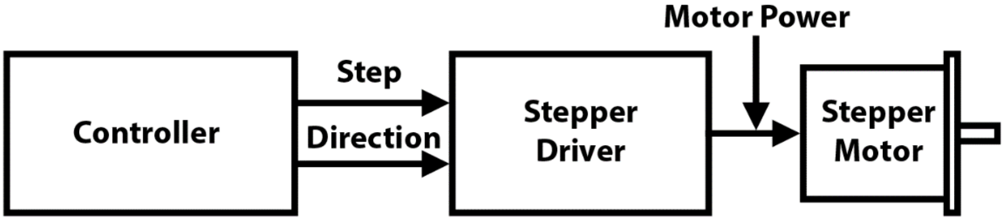


Figure 23 - Stepper Motor Control Flow Diagram

In order to calculate the achievable resolution from the stepper motors the step angle is used to calculate the number of steps per rotation for the motor. This is then converted to the number of steps actually taken depending on the step mode used (full step, half step, or micro step). With the total number of steps per rotation calculated, this can then be converted into linear motion of the gantry by calculating the circumference of the pulley on each motor. The three X, Y, and Roller axis stepper motors used have a step angle of 0.9° ±5% (Nanotec, N.D.-b)

$$360 degrees \ \div 0.9 \ degree \ steps = 400 \ full \ steps \ per \ one \ rotation$$

The stepper motor drivers are connected so that the stepper motors are doing 1/8th micro steps, which is 3200 steps per rotation.

$$400 \ \div \frac{1}{8} \ = \ 3200 \ micro \ steps \ per \ one \ rotation$$

The pulleys used have a diameter of 9.6mm. This equates to a circumference of 30.16m (2dp).

$$9.6mm \ * \ \pi \ = \ 30.159289mm$$

With 3200 steps per rotation, and a pulley circumference of 30.16mm, each step taken moves the pulley and belt by 0.009425mm

$$30.16mm \ \div \ 3200steps \ = \ 0.009425mm \ per \ step$$

From the above calculations the number of steps required to move along the X and Y axes can be calculated.

The X axis travel is 137mm long; therefore it will take 14536 micro steps to travel from one end to the other.

$$137mm \div 0.009425mm\ per\ step = 14535.809\ (14536) steps$$

The Y axis travel is 328mm long; therefore it will take 34801 micro steps to travel from one end to the other.

$$328mm \div 0.009425mm\ per\ step = 34801.061\ (34801) steps$$

The length of the build platform and feed piston along the Y axis is 310mm; therefore it will take 32891 micro steps to travel the full distance.

$$310mm \div 0.009425mm\ per\ step = 32891.247\ (32891)\ steps$$

The two Z-axis motors have a step angle of 1.8° ±5%. The linear drive has a pitch of 1mm (T6*1) (Nanotec, N.D.-a).

$$360° \div 1.8° = 200\ steps\ per\ one\ rotation$$

With 200 steps per rotation and a 1mm pitch along the linear drive, travel per step is 0.005mm.

$$1mm \div 200steps = 0.005mm\ per\ step$$

In order to achieve a layer thickness of 0.15mm the z axis will need to move 30 steps.

$$0.15mm \div 0.005mm\ per\ step = 30\ steps$$

From these calculations the 3D printer motor control can be programmed with the axis lengths with regards to the number of steps required to travel the full lengths.

4.4 Darlington Arrays

Two ULN2003A Darlington Arrays are used to control each of the nozzles on the print head. Each chip has an array of seven NPN Darlington transistors, therefore two are required to control all 12 of the print head nozzles. Each of the seven outputs on the Darlington Arrays can provide a signal of 50V at 500mA (600mA peak) (STMicroelectronics, N.D.-b).

The Darlington Array inputs are given signals from the Arduino pins 22-35 and the COM pin is supplied with 22V through the LM317T Voltage Regulator circuit.

4.5 Print head and Carrier

To deposit binder onto the powder an HP C6602A print head is used. The C6602A is a thermal Drop-on-demand print head that comes with black printer ink. A thermal DOD print head is best suited for this project as it is easy to implement and can work with a range of binders.

The HP C6602A print head is readily available, cheap, and can be refilled once empty. To refill the print head the binder can be injected into a small hole in the top of the print head by using a syringe. Since it is a thermal DOD print head it can be refilled with a range of liquids, including water/alcohol mixtures.

The print head is mounted in an HP Q2347A Carriage Assembly. This carriage is designed to house the C6602 range of print heads and includes the ribbon cable required for the print head connections.

The C6602 range of print heads each have 12 nozzles with a swath width of 1/8th of an inch, or 3.175mm. They require a 21V pulse 6µs long in order to eject ink from a single nozzle. To fire nozzles one after another a 0.5µs delay is required, and an 800µs delay between pulses on one nozzle (Lewis, N.D.)

4.6 Power Supplies

The circuit uses two separate power supplies to drive the print head control as well as the stepper motor control. Both power supplies were obtained from the electronics lab and so did not need to be purchased. An advantage to having two separate power supplies allowed the different sections to be easily isolated during testing, including having them connected to a common ground or completely isolated.

The Darlington Arrays, and subsequently the print head, are powered with a 24V 2.0A DC power supply. This power supply is connected to an LM317T voltage regulator circuit (Figure 24). This circuit regulates the voltage to 22.08V, a suitable level for the print head signals through the Darlington Arrays. The formula for the output voltage from the LM317T is:

$$V_{out} = 1.25V * (1 + \frac{R1}{R2})$$

To achieve the desired voltage of 22V, a 240Ω resistor is used for R1, and a 4kΩ resistor is used for R2 (STMicroelectronics, N.D.-a).

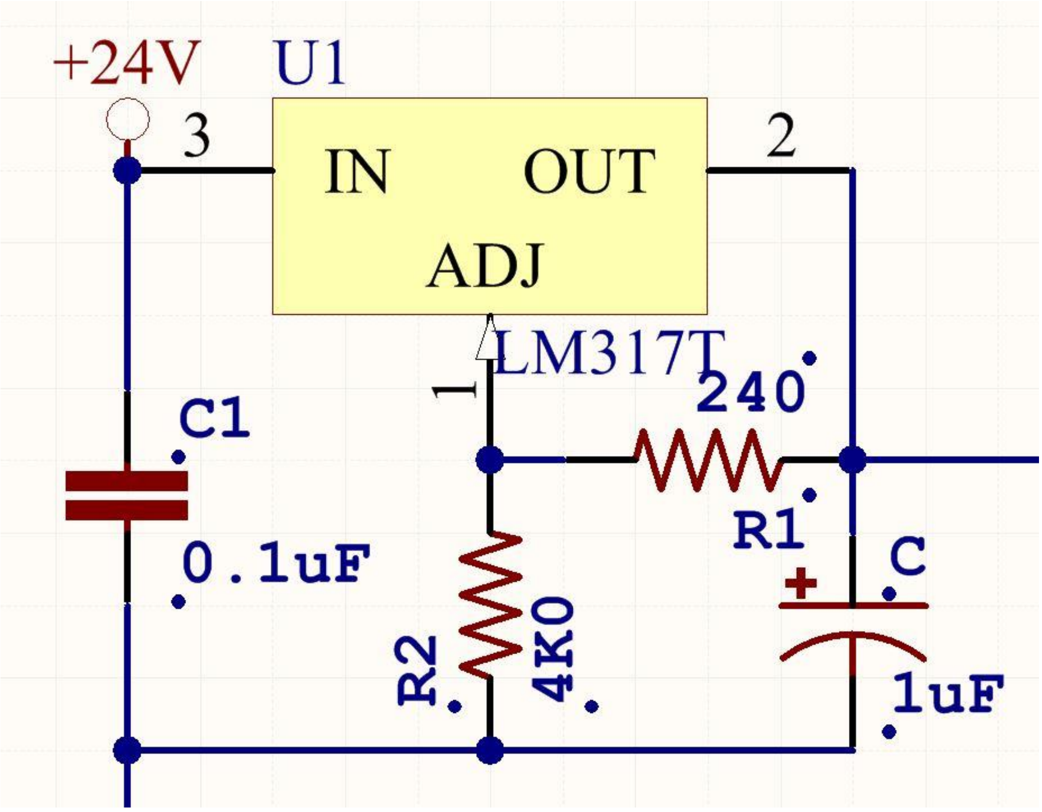


Figure 24 - LM317T voltage regulator circuit

To power the stepper motors and stepper motor drivers an 18V 2.67A DC power supply is used. This power supply is able to drive all the stepper motors at the same time if required.

A 9V 0.8A DC power supply is used to power the cooling fan. The fan was added to the 3D printer after initial testing had begun. A suitable fan and power supply were sourced in house through the electronics lab.

4.7 Prototyping Electronics

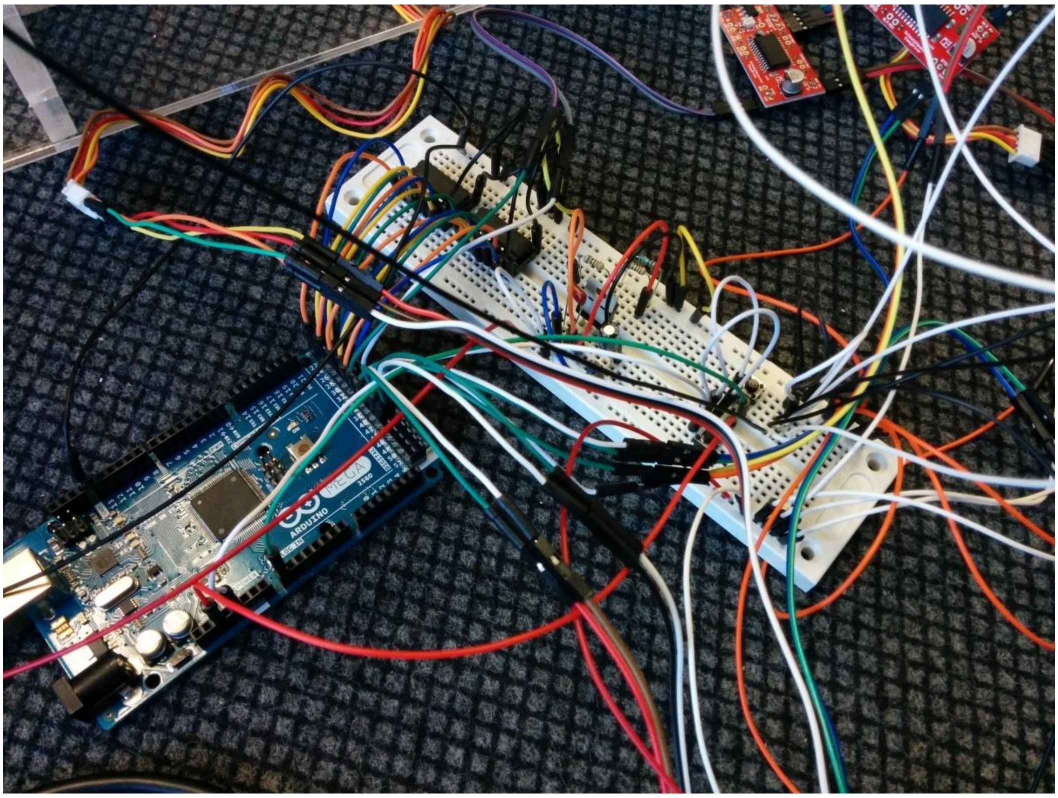


Figure 25 – Breadboard prototype of all electrical components

Initial electronics testing was done on a breadboard; however this quickly became complicated as a number of jump wires were required in order to complete the circuit and have all the stepper motor drivers attached. Due to the large number of jump wires between the Arduino and breadboard (Figure 25), this circuit was difficult to problem solve. A number of issues were encountered because of bad connections and faulty jump wires. To make the circuit more reliable and easier to work through, the breadboard was pulled apart and a Veroboard designed and made instead.

4.8 Veroboard Prototyping

Since the Breadboard quickly became difficult to work with, all the components on it were moved to a Veroboard. This new Veroboard reduced the number of jump wires required. It also allowed the stepper motor drivers to be connected via header pins as the tracks could be cut between them (this could not be done on the breadboard, hence they were connected with jump wires). Most of the jump wire connections required on the breadboard were replaced with far more reliable track and solder joints on the Veroboard. Various jump wires were still required to between the Veroboard and the Arduino; however these were far easier to manage and diagnose any connection issues.

This prototype was far easier to run tests with and was suitable to use while a proper PCB was designed (Figure 26).

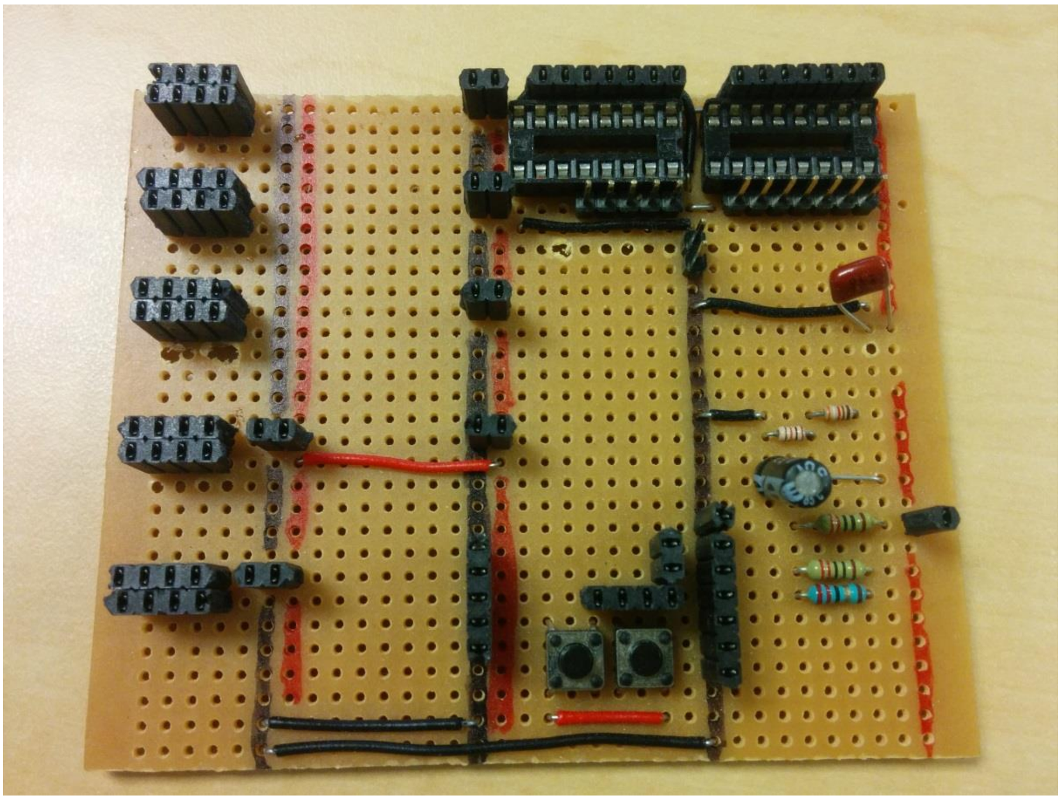


Figure 26 - Veroboard Prototype

During testing of the stepper motor control the motor directions were determined and the current supply from the stepper motor drivers was set. The current supply from each stepper motor driver is set through a variable resister on each driver. To find the minimum current required the variable resistor was set to the minimum value, the motors were then run and the variable resistor was slowly turned up until the motors could drive on the gantry. Once the minimum current required to drive the stepper motors was determined the variable resistors were turned up slightly to ensure the motors would always have enough current supplied without drawing more than is required, which would be wasted and potentially overheat the stepper drivers. At this stage heatsinks were also added to the three EasyDrivers.

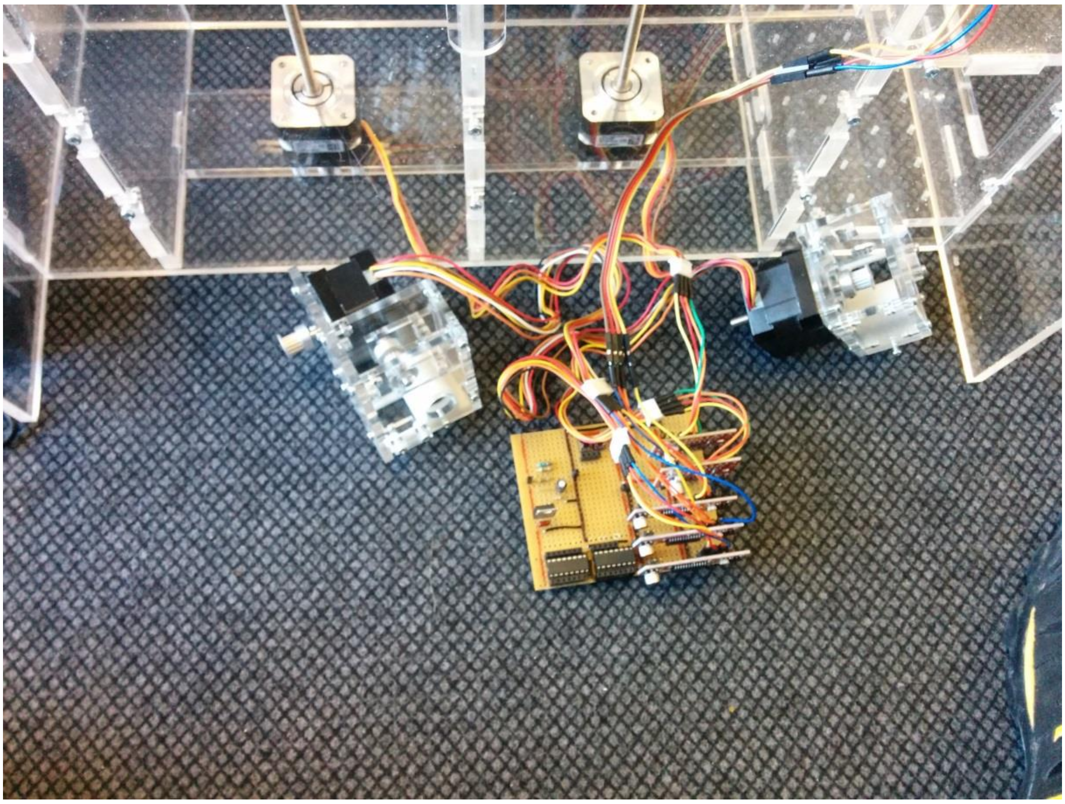


Figure 27 - Veroboard Prototype set up to test the stepper motors

4.9 Printed Circuit Board

The Printed Circuit Board went through a few iterations before a final design was reached. The first PCB design was routed on a single sided copper board, as this was the only available option at the time. This board was large and bulky because of this restraint. Due to some issues with the in house PCB mill, this board could not be used. The routing issues resulted in a number of connections being short circuited. Because of these issues this board was discarded and a new PCB was designed.

The second designs had the two main sections of the circuit (print head control and stepper motor driver control) on separate PCBs (Figure 28). These PCBs were double sided and stacked together onto the Arduino, significantly reducing the size of the boards. This set up made each PCB very simple, which made them easy to diagnose in case there were any issues. The PCBs were routed in-house and tested; after they had been tested the design was developed further.

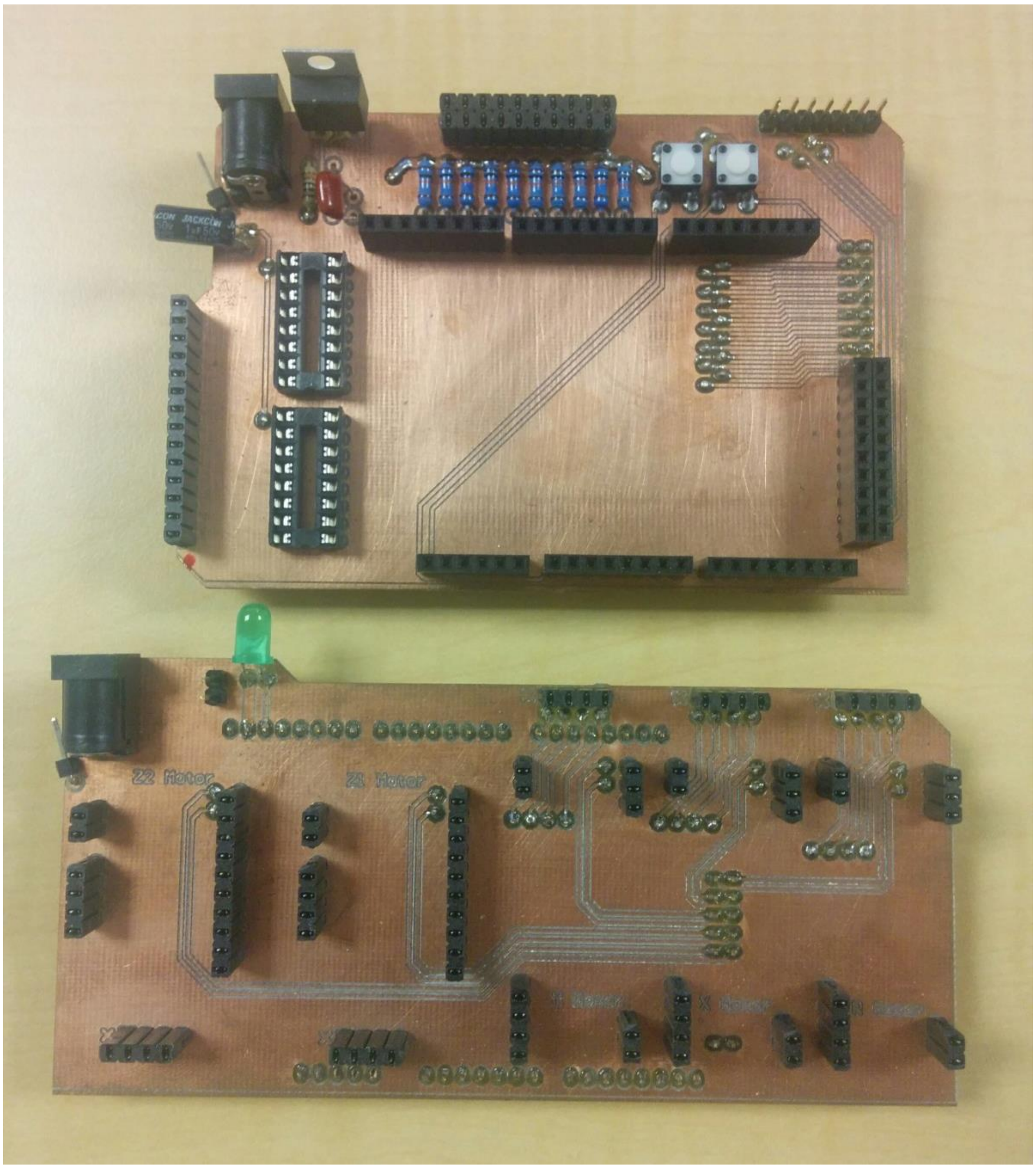


Figure 28 – Prototype 2 circuit boards. Upper board is print head control, lower board is motor control

The third and final iteration combined the two circuits onto one board. The board layout was fairly similar to the original two boards but had the components packed together tighter and far more efficiently. The board was also routed in house and tested in the printer.

The final PCB was designed so that it would neatly fit into the boundaries of the original printer body electronics space, and to have as few external connections as possible. The connections that were required are: 5 motors each with 4 wires, 7 wires for the Arduino SD card module (2 ground wires for safety), 14 wires for the print head connection (1 ribbon cable). There are two power inputs into the PCB, 18V and 24V, as well as the Arduino’s own input via USB.

An extra two header pins were included, so that the two ground circuits (Arduino ground and Power supply grounds) could be made common if needed (during testing this caused issues with the Arduino SD card module).

20 extra connections (2x10 header pin block) were included to be used later. 10 of these were connected to the Arduino 5V supply and the other 10 were connected to pins 2-11 of the Arduino, with pull down resistors.

As standard header pin connections were already available, and small, the PCB was marked with an “x” on the ends of the connections to make it easy to get the connection correct. This was done so the PCB could be used to identify connections since the in house PCB mill cannot silk screen boards. Custom made cables were also marked to match. When the PCB was professionally made all connections were silk screened appropriately.

Each PCB was manufactured (routed) in-house to test. Once the final design was reached and successfully tested, it was sent to be professionally made through SeeedStudio (Figure 29). All PCB assembly was done in-house (soldering etc.)

Another small PCB was made to accommodate the print head connection. The factory mount for the print head includes a ribbon cable (flexible circuit board) that is approximately 450mm long. In order to extend this so that it could be easily and securely connected to the driver circuit, a small PCB was routed to mount the ribbon cable connector to (the connector is a surface mounted component, so a PCB was the best way). This PCB then connects the ribbon cable connector to standard header pins. A custom ribbon cable was made to connect the two PCBs together.

4.10 Chapter Summary

This chapter discussed the electrical components used in the circuit of the developed 3D printer. In order to keep costs down low cost, open source components are used. The base of the circuit is an Arduino Mega 2560, which is an open source development board. The stepper motors are controlled by SparkFun Easy driver and BigEasy driver stepper motor drivers. These are readily available and easy to implement. The print head is controlled through a pair of Darlington Arrays, which are powered through a voltage regulated circuit.

Also covered in this chapter are the prototyping of the circuit and the development of a Printed Circuit Board. The PCB went through a few iterations that were manufactured and tested in house before arriving at a final design that was then manufactured professionally.

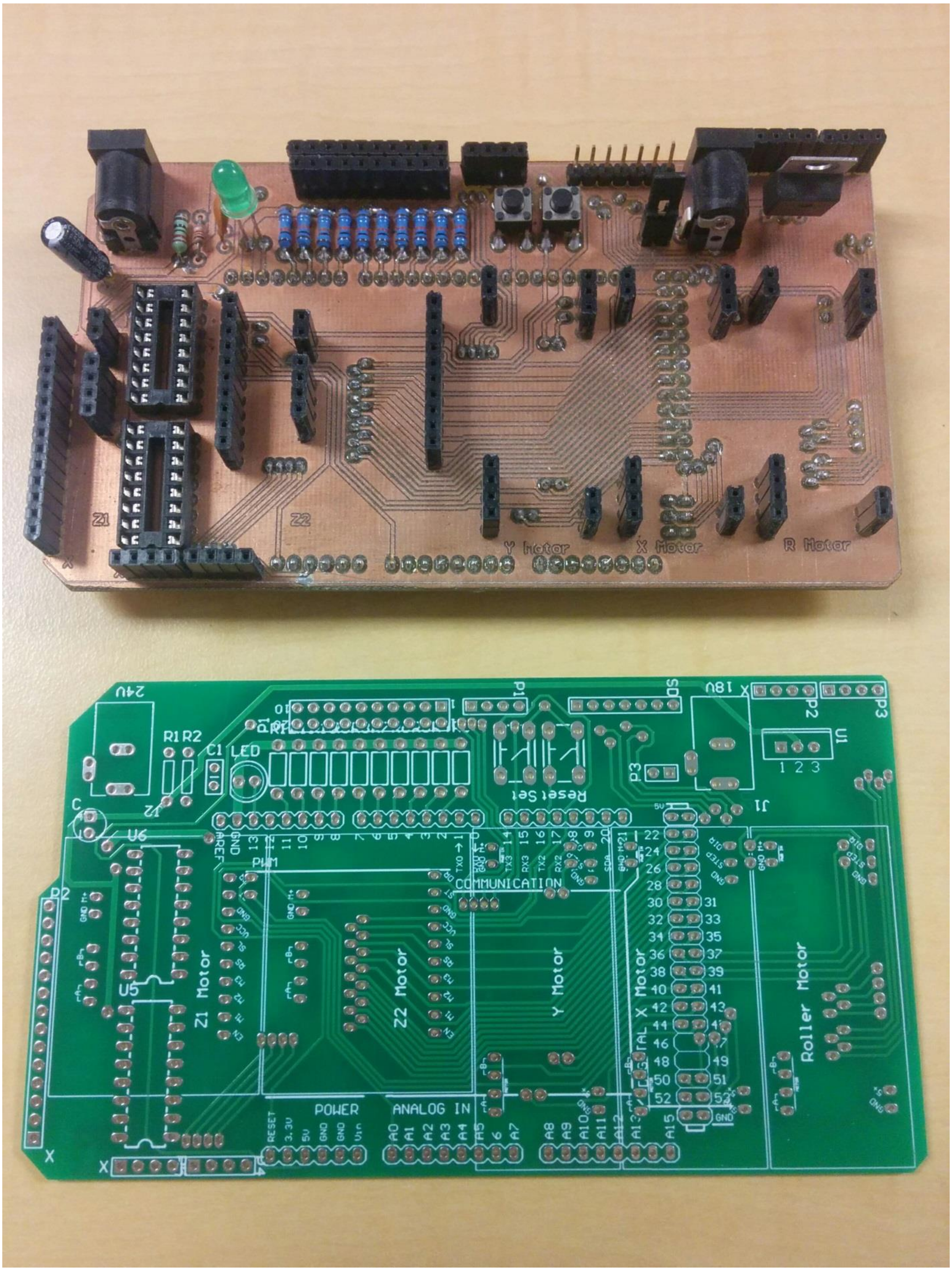


Figure 29 - Final PCB design prototype and professionally manufactured PCB

Chapter 5. 3D Printer Software

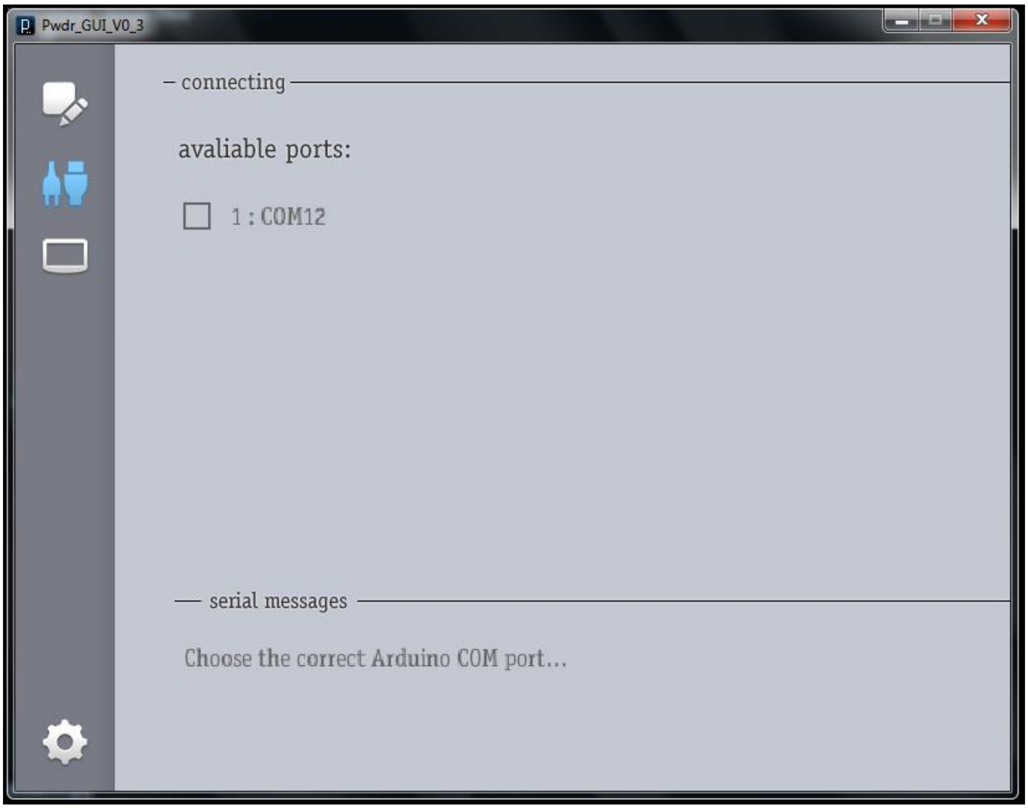
In order to be able to use the 3D printer for research, access to print settings is an important factor. To ensure the software can easily be edited in future if necessary, open source software has been used. This gives the user the ability to access or modify any of the print settings as required.

This software reads in an STL (STereoLithography) file, which is a commonly used file for 3D printing (Chua, Leong, & Lim, 2010). STL files were created by 3D Systems and are designed to contain surface geometry information of a 3D part (Burns, 1993).

5.1 Graphic User Interface (GUI)

The open source design already had a working GUI (Graphic User Interface), so there was no need to create one from scratch, though a few small changes were made to improve operation of the existing one.

The original GUI required the serial connection (COM port) to be hardcoded. Since the COM port can change depending on the number of devices connected to the PC this was changed so that the GUI displays a list of devices. When the GUI is started, the home page asks for the COM port to be selected. To do this the user navigates to the connection tab (Figure 30) and then selects the appropriate COM port from the list.



avaliable ports:

☐ 1 : COM12

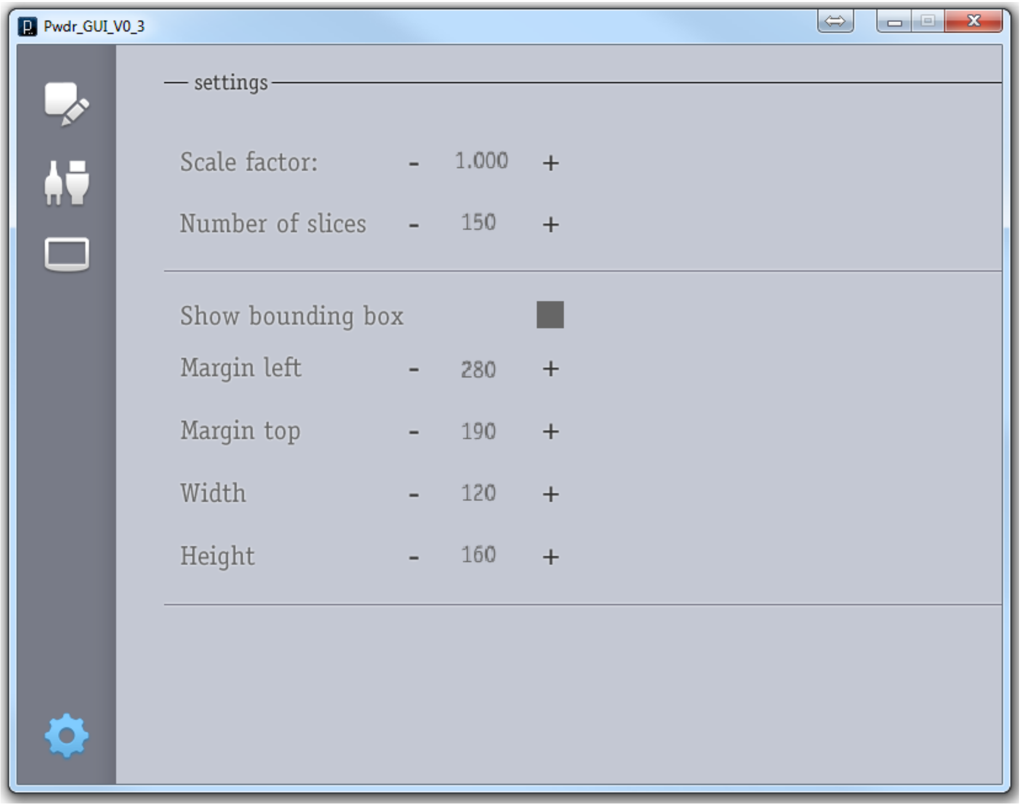
Choose the correct Arduino COM port...

Figure 30 - GUI COM port selection page

5.2 Slicing

Once the part STL file has been loaded, the GUI allows for print parameters to be determined. For example the bounding box of the print area can be set, as well as the desired number of layers. Setting the number of layers for the part to be printed in defines the thickness of each layer as the parts Z dimension is divided by the set number of layers.

These settings are currently manually selected in the GUI (Figure 31). There are default settings automatically entered when the software is started. Changing these settings allows the user to adjust various mechanical properties of the printer. Setting the bounding box of the part means that the print head will only travel the set distance. This improves the print time as it cuts out movement over empty space.



Scale factor: - 1.000 +

Number of slices - 150 +

Show bounding box ■

Margin left - 280 +

Margin top - 190 +

Width - 120 +

Height - 160 +

Figure 31 - GUI Settings Screen. From this screen the print settings can be chosen

Once the slices have been generated (Figure 32), they are saved into a folder (determined by the software location) along with a text file that contains the print parameters. This folder is created in a sub directory to where the software is loaded. The folder containing these sliced files and the text file can then be copied to an SD card and plugged into the printers Arduino SD module. For testing layers of 0.15mm were used.

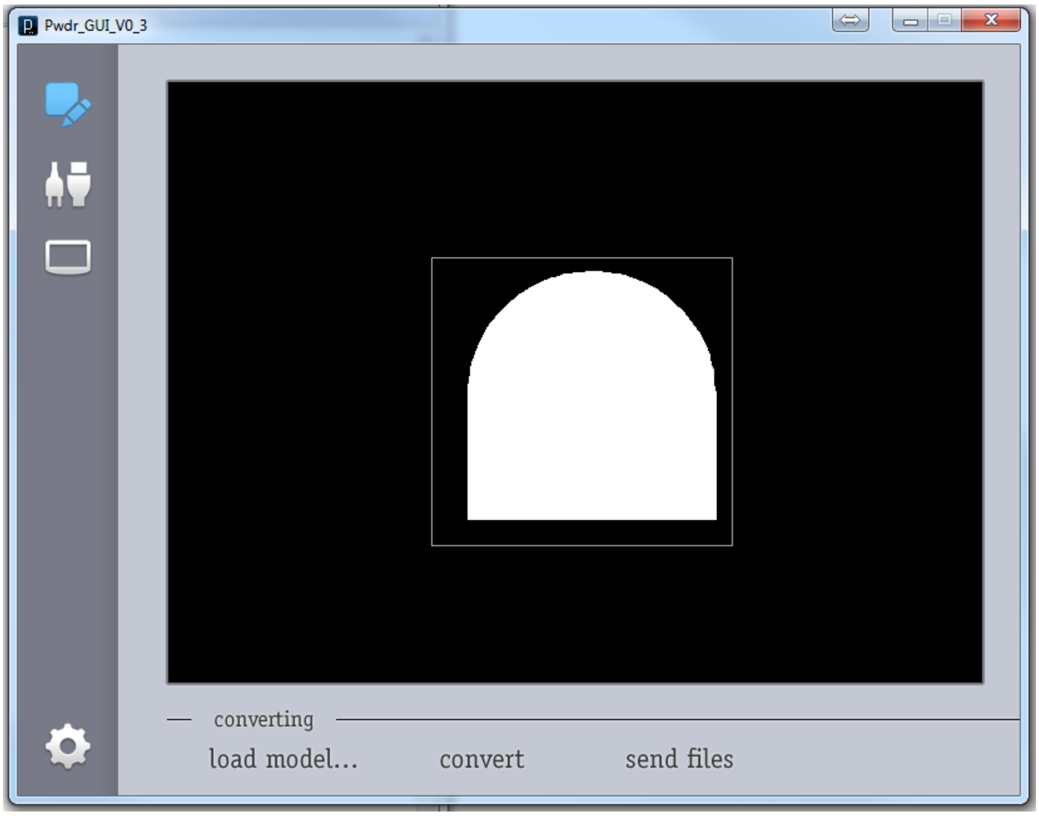


Figure 32 - GUI display of slices being generated. Part is indicated in white. Box surrounding part shows print head travel

5.3 Printing

After the files have been created, and the SD card inserted into the Arduino SD module the GUI can then be connected to the printer via serial connection. This is done by navigating to the connection tab and selecting the appropriate COM port from the list. If there are no other devices connected to the PC then the Arduino COM port will be the only one displayed in the list. Once the connection has been made, the GUI prompts the user to connect power to the printer; this means the GUI can now control the printer gantry and the print can be started. To set the home position of the gantry, the print head needs to be driven to the home position (upper left corner), and then the position values reset via the GUI reset button. This can be done by manually jogging the X and Y axes in the GUI.

Alternatively the gantry can be manually positioned before the circuit is powered. Once the gantry is homed, the print head can be moved to the “initial position”; this positions the print head within the print area and gives it a starting point. After all the above steps have been taken, the print can be started.

5.4 Arduino Software

The Arduino Software from the original open source design had most of the control program done, though some changes needed to be made so that it would work properly. Since the Arduino has built in Serial Peripheral Interface capabilities the pins used for the stepper motors and print head controls were reassigned. For the Arduino Mega 2560 pin 50 is Master In Slave Out, pin 51 is Master Out Slave In, pin 52 is Serial Clock, and pin 53 is Slave Select.

To accommodate the change of pins, the stepper motor pins were changed to 36 & 37 for the Roller motor, 38 & 39 for the X motor, 40 & 41 for the Y motor, and 42 & 43 for the print piston motor, 44 & 45 for the feed piston motor. The Print head/Darlington arrays use pins 22-35.

5.5 Chapter Summary

This chapter covers the software used to control the developed 3D printer. The user loads the 3D print file into the GUI, after which they can select the required printer settings and then create the sliced files. The sliced files are then saved onto an SD card and transferred to the 3D printer.

The Graphic User Interface communicates with the Arduino controller via a serial connection, this connection allows the user manually control the 3D printer to job the gantry around or move the Z axes up and down for loading/unloading powder, as well as to set up a 3D print.

Chapter 6. Implementation

Once the 3D printer's mechanical components had been assembled and the electronic circuit the 3D printer could be tested. Several tests were performed before any powder was put into the 3D printer. This was done because cleaning powder after every test was deemed unnecessary for the first stages.

Figure 33 - Successfully 3D printed part

6.1 Testing

For initial print testing a sheet of paper was laid across the print bed. Laying paper across the print bed created an easy way to test the printer without the need to fill it with powder. Since filling the printer with powder can be a messy process, meaning it is not always quick and easy to set up for a number of test prints, paper provided a quick and easy solution. This test allowed the print head to be checked for operation as well as the homing function, print start, and accuracy of the gantry. As the printer would take all the steps to spread a new layer, but not be able to since there was no powder, each layer would be printed in the same place on the paper.

Using paper as the printing medium would not cause any issues as the initial binder used is regular printer ink. The saturation value was lowered to give a clearer print on the paper. This made it easier to see exactly how the print head was performing and to check if all of the nozzles on the print head were firing.

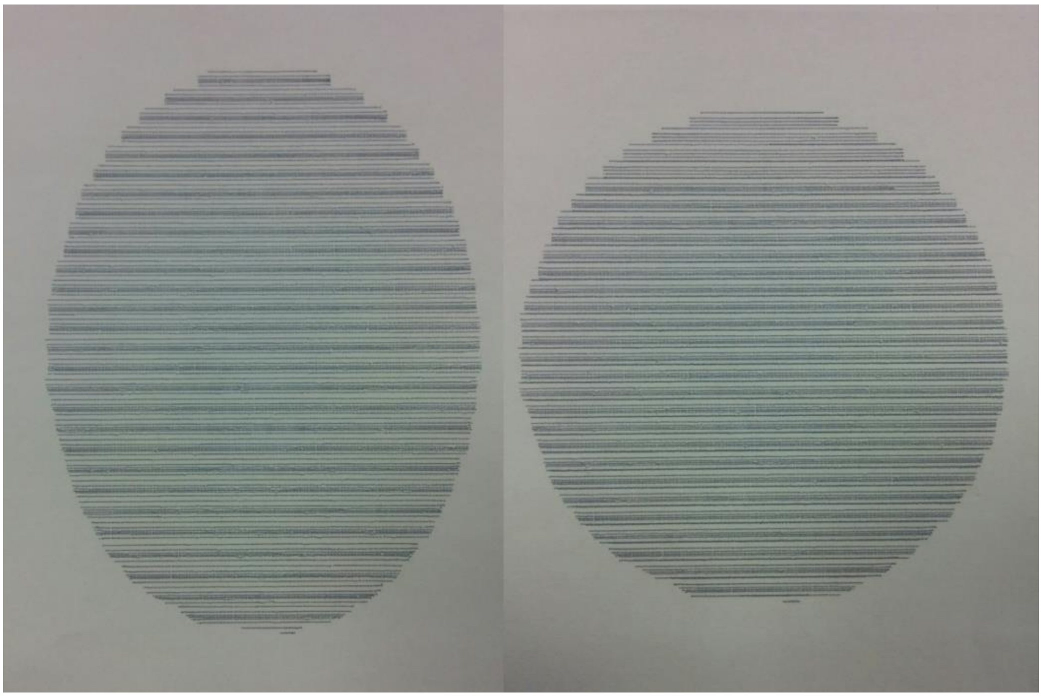


Figure 34 - Initial test print onto paper of a circular shape. Left shows Y axis error with elongated part, right shows corrected print

The first few tests done were to check the accuracy of the gantry movement. Different shapes of known dimensions were sliced and printed onto paper for a single layer, shapes tested included circular, square, and triangular. After the layer had finished printing the print was cancelled and the shape measured.

The first couple of tests indicated that there was a problem with the Y axis control. This was clearly shown in the paper test by the circular shape being elongated into an oval (Figure 34), though the print head swath width appeared to be correct. The Y axis step size was recalculated in relation to the step spacing for the print head, and the Arduino software updated. At this stage it was also discovered that the X and Y axis were not perpendicular to one another, meaning that parts would not be true. To correct this, the belt on one side of the Y axis was removed; the gantry was then adjusted until and X and Y axes were perpendicular to one another and the belt was then put back in place.

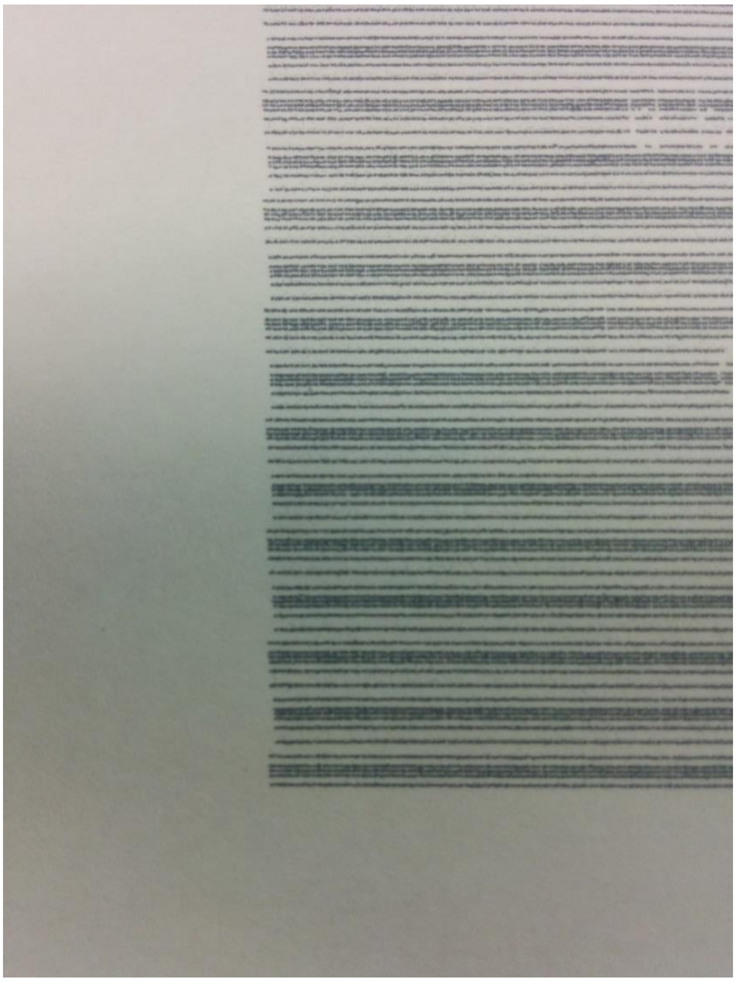


Figure 35 - Square test print indicating X and Y axis are not perpendicular

Once the print sizes and gantry were corrected, the test prints were left to run for multiple layers. Doing this allowed the layer spreading and print head home location to be tested. The first instance of this test showed that once the first layer had finished printing, the gantry would travel to the end of the printer ready to spread a new layer and then the print and feed pistons would move. At this stage it was discovered that the Y axis travel distance was wrong and the gantry would hit the end of the printer, causing the stepper motor to skip while it tried to drive the gantry further. It was also discovered that the two pistons were moving in opposite directions to how they should be moving, the feed piston lowered while the print piston raised. The gantry then moved as to spread a new layer of powder, with the roller counter rotating correctly, until the gantry hit the far end of the printer, causing the stepper motor to skip again. The print head then went to return to the part location to print the second layer, though because the stepper motor had skipped it returned to the wrong place. To correct these issues the wiring for the feed and print piston motors were swapped, and the Y axis travel length was adjusted in the code. To find the correct value for the Y axis travel, the gantry was moved by hand to each end of the printer, and the distance travelled measured. The number of steps required to travel the full length was then calculated from this length, as opposed to the overall Y axis length.

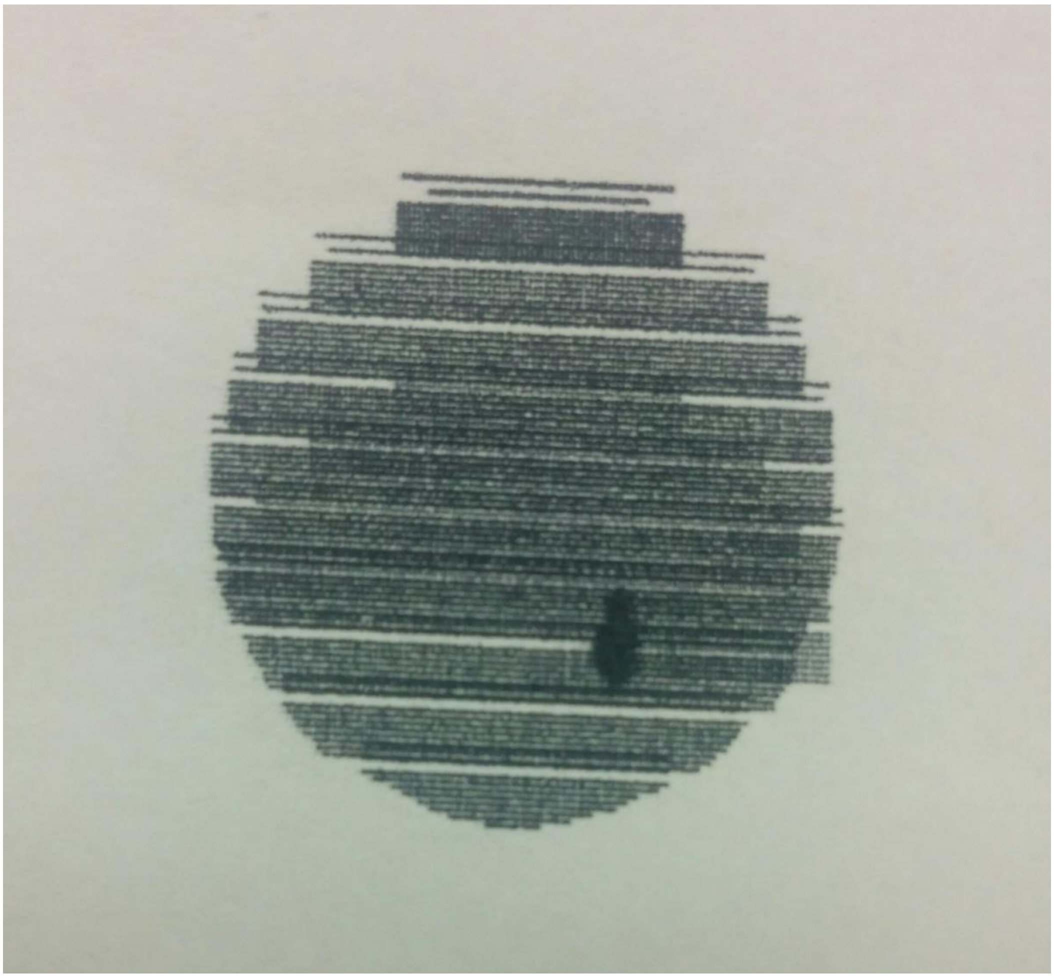


Figure 36 - Test print showing print head location issues. Layer 2 can be seen within the first layer

One of the problems during testing was getting all 12 of the nozzles in the print head firing consistently. Stopping prints halfway through would sometimes cause blockages in the nozzles. There were a couple of causes for this, during the prototyping stage there were some connection issues due to loose/faulty jump wires, this was fixed when a PCB was made. During the testing stage some of the problems included powder or dirt getting onto the print head and ink drying on the print head between tests. During testing one or two layers were printed, then the print could be cancelled so the results could be analysed. This appeared to sometimes leave ink in the channels of the print head. This ink would then dry and cause a blockage. The other main cause of blocked nozzles was powder getting stuck to the print head (Figure 37). Before all powder spreading issues were sorted the print head would sometimes be driven/dragged through the powder in the printer.

To clean the print head after getting blocked nozzles, a cotton bud was used to gently rub ethanol onto the surface with the nozzles. If this did not work, the print head was left to soak in ethanol for a couple of hours. Because of the problems with blocked nozzles, a couple of spare print heads were ordered.

With initial testing focused on fixing issues with the printer’s mechanical functions, a print head with blocked nozzles was used in order to save costs. All mechanical issues could be addressed without the need for all 12 nozzles to be firing all of the time.

Figure 37 - Close up of the print head showing ink that has dried on the nozzle surface and powder stuck to the surface

6.2 Hardware Adjustments

During the testing phase some changes were made to the 3D printer hardware to improve functionality. The first change that was made was to swap the bushings that were initially used in the X and Y axes for linear bearings. During operation it was found that sometimes the friction between the bushings and shafts would overcome the stepper motors ability to drive the gantry. To fix this issue the bushings needed to be upgraded to linear bearings. To fit the new bearings new housings would need to be made. Housings were designed and 3D printed in house. The initial prototypes were printed in house on a desktop FDM 3D printer from ABS plastic. This was a quick and cheap option to test the functionality of the new housings. Once they were successfully tested they were 3D printed in house in a TPM Elite P3200 SLS machine from Nylon powder. The Nylon 3D prints are far more robust than the ABS prototypes. Since they were printed in an SLS machine, with no need for support material, all excess material was removed from the designs to make them as cheap as possible.

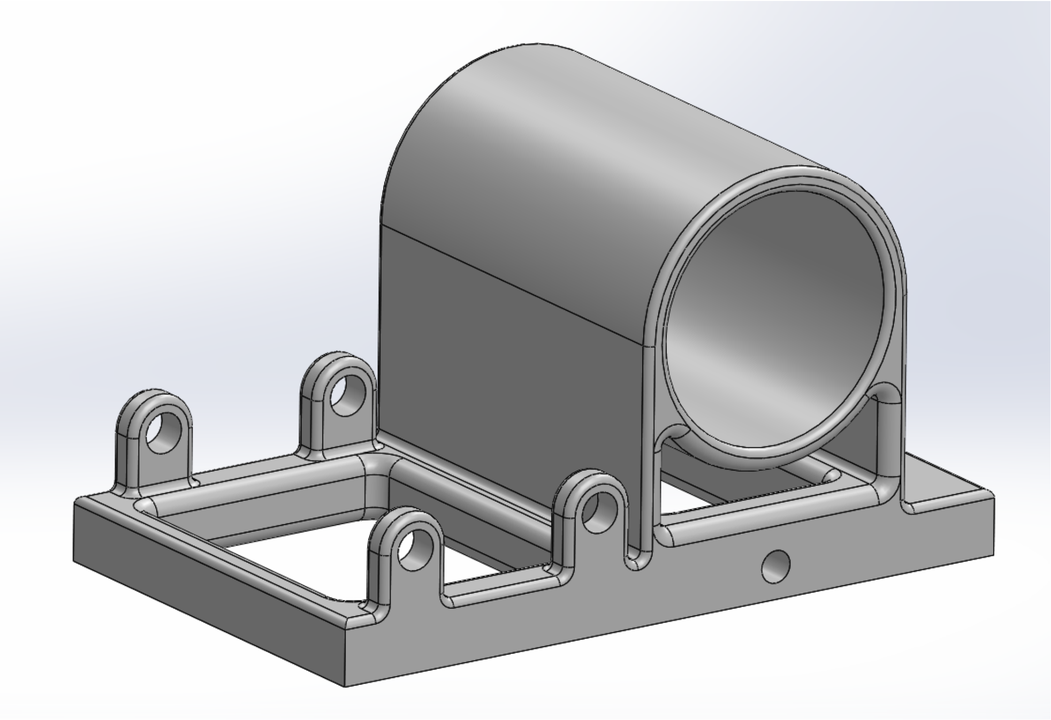


Figure 38 – CAD model for Y axis linear bearing housing

The two rotating shafts (Y-axis drive shaft and the Roller shaft) still use bushings as there is no linear movement and there were no issues with these rotating within the original bushings.

The housings for the Y axis bearings (Figure 38) were designed to attach to the existing laser cut parts to avoid the need to modify more pieces than was necessary. In order to achieve this, the housings would slot into the bottom of the existing assembly on each side of the Y axis. The only modifications that needed to be made to the existing laser cut parts was to add a hole in three of the pieces so that the new bearing housing could be secured in place by three screws.

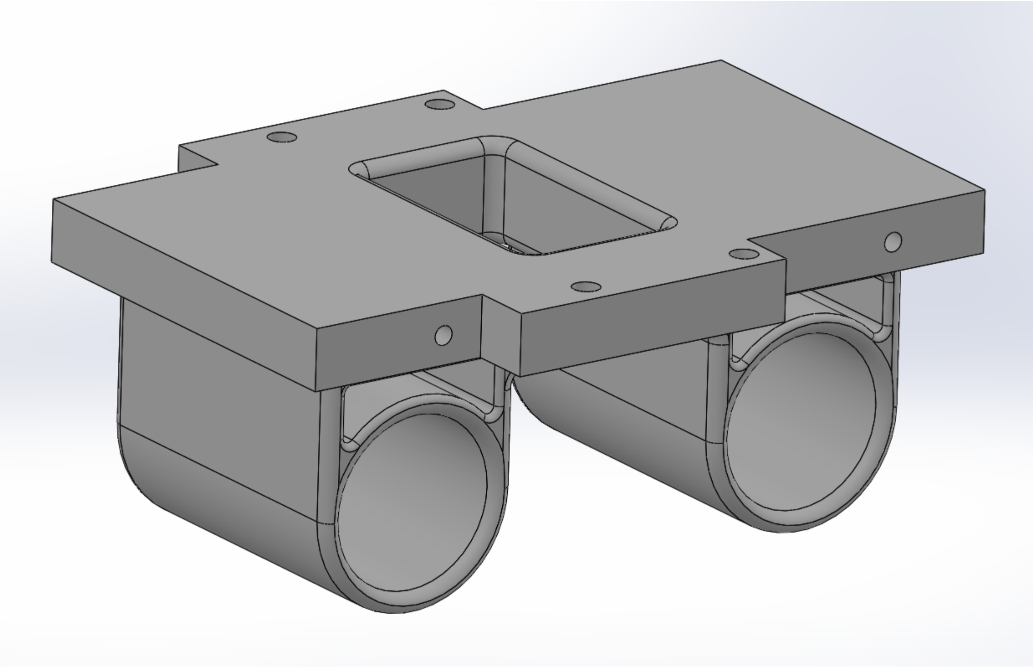


Figure 39 - CAD model for X axis linear bearings housing

A housing for the X axis bearings (Figure 39) was designed to fit within the existing laser cut housing for the print head. This housing was successfully tested, though after a couple of prints it was discovered that the new housing made it difficult to adjust the print head height. The placement of the bearings partially blocked the hex nuts holding the print head cartridge in place.

Since the print head housing needed to be modified so the print head would be able to be adjusted more easily, it was decided to make an entirely new housing for the linear bearings and print head from scratch.

The new housing (Figure 40) allowed for easier adjustments to the print head height. This is done through hex nuts that are held captive to prevent them from rotating, though still freely able to slide up and down. To adjust the print head height with the new housing, the print head is removed from the cartridge assembly and screws are loosened. Once loosened the cartridge assembly can be slid up or down as required and the bolts tightened. In order to make this same adjustment with the laser cut housing, the hex nuts would need to be held in order for the bolts to be loosened and retightened, which is difficult to do due to the size of the mount.

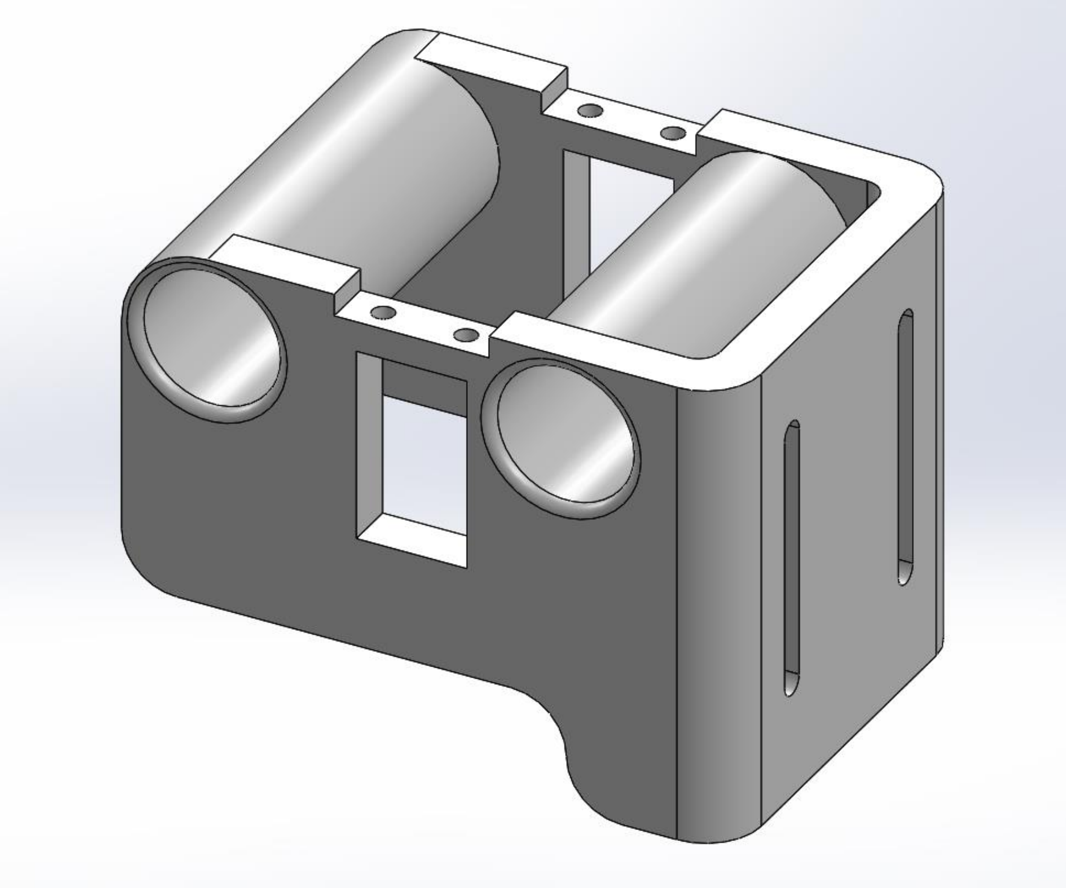


Figure 40 - Updated X axis housing to accommodate linear bearings and improved print head adjustment

Small ribs were added along the edge of the Y-axis to prevent powder from tipping over the edge when spreading a new layer (Figure 41). This was done by laser cutting strips of acrylic 2mm wide x 3mm thick x 475mm long and gluing them in place along the edges of the Y axis. The Roller shaft was then turned down at both ends to fit within the gap between the two raised edges.

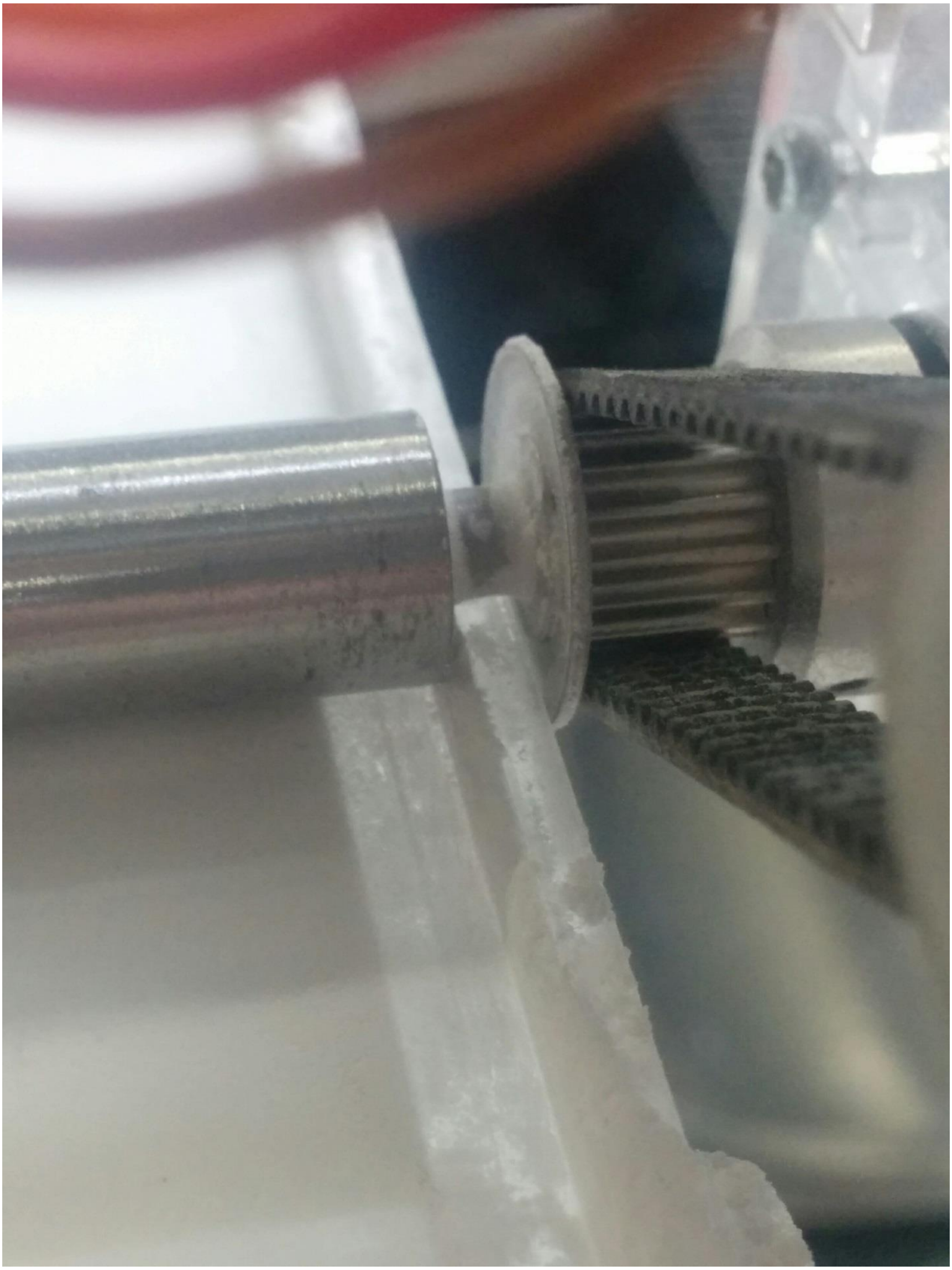


Figure 41 - Close up of added rib on Y axis

With these extra guide rails in place, a lot less powder falls off the edge of the print bed. This means that powder can be more efficiently spread, with less going to waste. It also ensures that the entire print bed gets a new layer of powder, rather than the far corners sometimes missing powder from the new layer. With powder being more efficiently spread and less/none falling off the sides, less powder is needed for each layer spread. This in turn means less powder goes into the overflow section, resulting in less waste and less clean up required after the print.

While the ribs were being added to aid the spread of powder, a slot was added to the end of the Y axis where the X axis motor comes into contact with the main body. This slot extended the Y axis travel by approximately 10mm. This was done because there would sometimes be a small build-up of powder left at the end of the print bed after a new layer had been spread. If this build up was big enough, the print head would be dragged through it when it returns to the print position for the next layer (Figure 42). This would result in an uneven print bed, which would in turn mean that the powder would not bond properly to the layer beneath due to the changing thickness. Another problem with the print head being dragged through this powder is that some of the powder would get stuck to the print head. This powder would sometimes cause blockages with some of the print head nozzles.

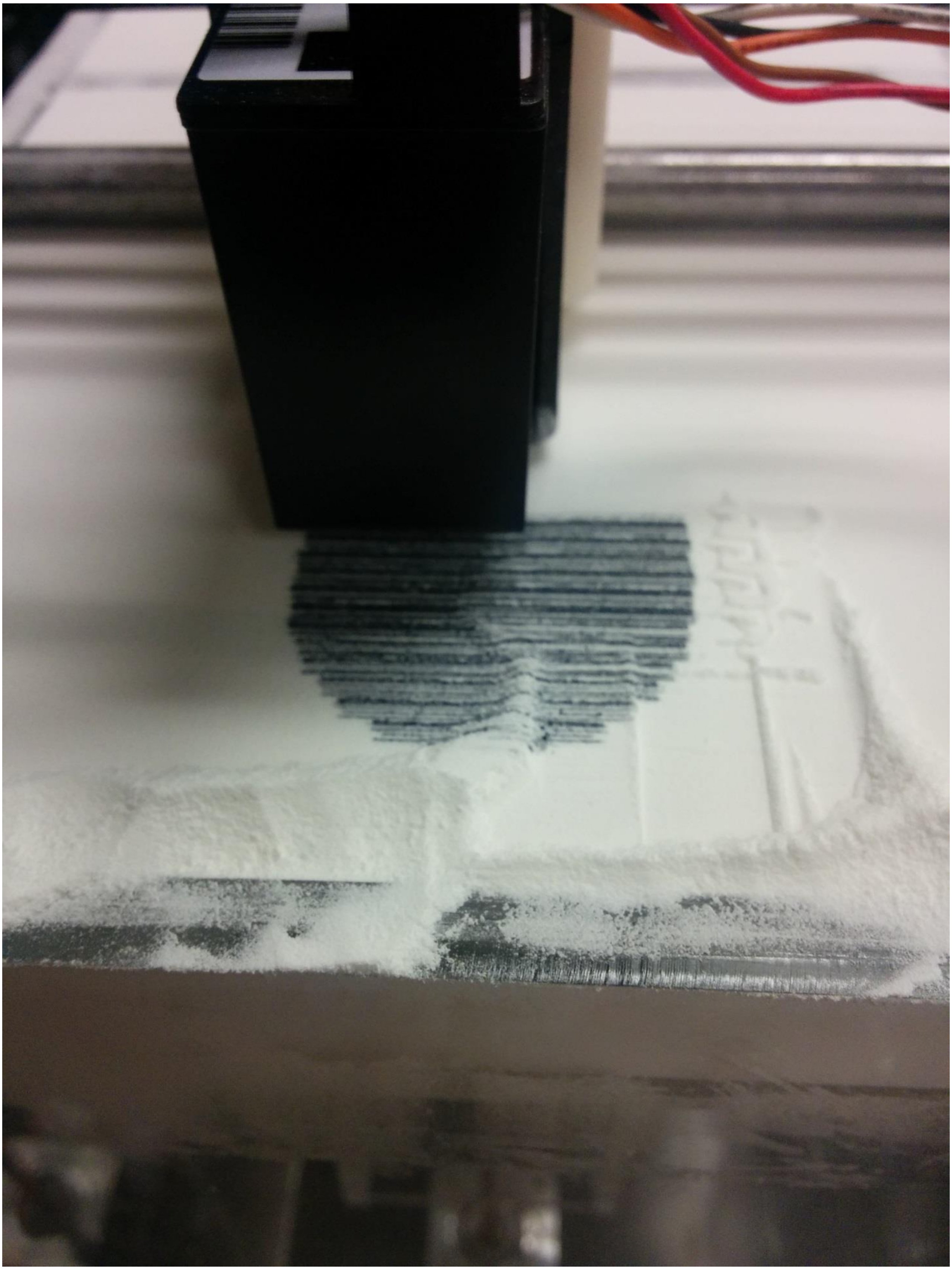


Figure 42 - Powder build up at the end of the Y axis

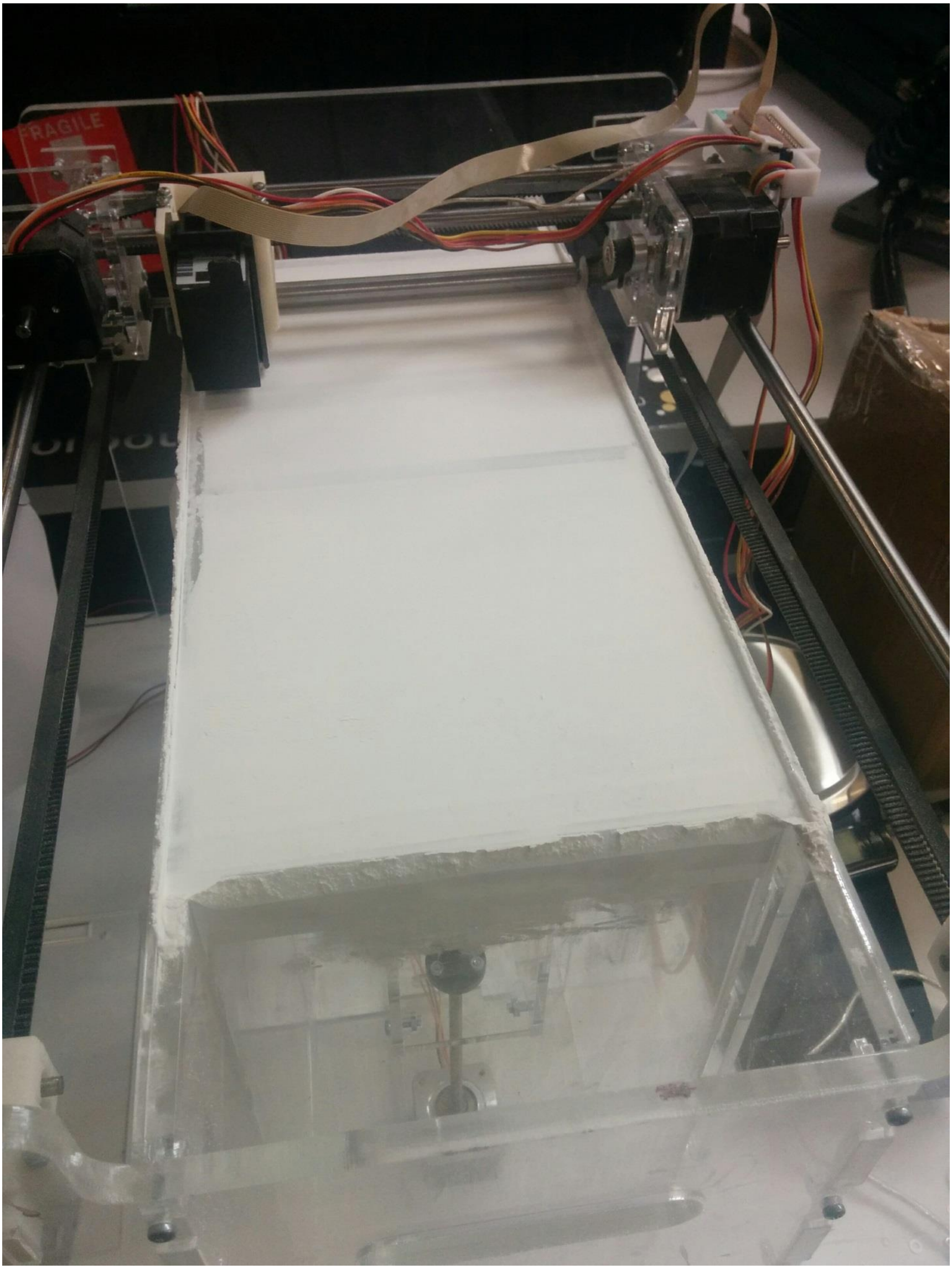


Figure 43 - Smooth layer spread after modifications

6.3 Software Adjustments

While testing how effectively the standard ink could bind the powder together, the print head was fired for several seconds in one location, thereby depositing excess ink onto the powder. This test produced a small clump of powder that was successfully bonded and could be handled. This test also revealed an issue with jetting too much ink at once, overspray (Figure 44). This could potentially cause dimensional accuracy issues in the printed part as well as contaminate powder in the build piston.

Figure 44 - Test with stationary print head showing inkjet overspray

To determine the correct factor of ink to be jetted each layer, a single layer was printed and then removed from the build piston. Once the layer could be removed from the print piston without falling apart the print was left to run for multiple layers.

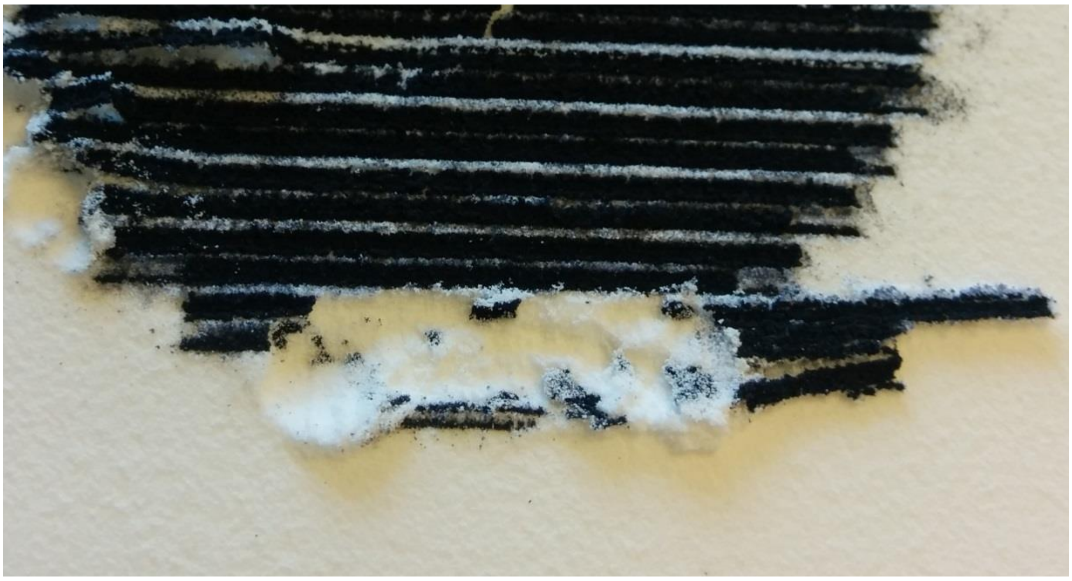


Figure 45 - Single printed layer partially bonded

Each layer is printed twice before a new layer of powder is spread. This is to ensure the binder penetrates the powder enough without having too much overspray from jetting too much ink out of the print head at once. With the saturation value too high it was found that the ink would not dry before a new layer of powder was spread on top of the recently finished layer. To allow the ink to dry properly, a delay of 5 seconds was added after the layer is printed for the first time before the print head passes over to print the layer a second time. A delay was also added after the second pass of the layer before the new layer is spread to ensure the ink is dry. These delays successfully allowed the ink to dry enough so that a new layer of powder would spread without damaging the existing layer.

Figure 46 - Ink soaking through into a fresh layer of powder

6.4 Chapter Summary

This chapter discussed implementation and testing phase of the project. Discussed are some of the issues that were encountered with evenly spreading layers of powder as well as accurately depositing and binding the powder.
The testing process undertaken to discover these problems has been discussed, as well as the hardware solutions to fix the issues.

Also covered are the software adjustments that were made to allow the binding process to work successfully. The amount of ink deposited on the powder as well as the amount of time for the ink to dry were tested and adjusted until a working solution was found.

Chapter 7. Results and Discussion

7.1 Investigate the current state of 3D printing technology, including currently available low cost 3D printers and the current state of 3D printing in the Automotive industry.

As discussed in Chapter 2, 3D printing technologies are well established in a variety of machines ranging from large scale commercial 3D printers to small, desktop sized 3D printers for the hobbyist market.

There are a number of FDM 3D printers available at a low cost, with a large portion of them priced under US$2000. As well as the available low cost FDM 3D printers there are several low cost SLA 3D printers suitable for hobbyist use, as well as some other 3D printing technologies emerging in the hobbyist market

At the commercial end of the 3D printing industry there is a large range of 3D printers that offer a wide range of materials. Some of the available commercial 3D printers use inkjet technology to produce parts for a range of purposes, including metal parts, cast-able moulds, and full colour models.

The Automotive industry widely uses 3D printing technologies for prototyping new designs as well as producing parts used in their vehicles. 3D printing has been used in the automotive industry for a number of years and has helped to revolutionise the development process for manufacturers. It has allowed them to improve part designs faster, and at a much lower cost.

Recent technology has allowed small scale manufacturers to use functional 3D printed parts in the cars at a viable cost compared to traditional manufacturing methods.

Some automotive companies use large scale inkjet 3D printers to produce casting moulds for their foundries to speed up the manufacturing process. Using these 3D printers allows them to produce more complex shapes for the casting process.

Using this technology has enabled the automotive industry to develop and manufacture higher quality parts at a much faster rate. This has enabled them to bring new designs to market faster and at a lower overall cost.

7.2 Investigate the applications of inkjet printing technology with 3D printing

Inkjet printing technology has been implemented in a number of commercial 3D printers in a variety of ways. The main uses of inkjet printing technology in commercial machines are material jetting or binder jetting style 3D printers. These 3D printers use inkjet style print heads to eject the part material onto a print bed. The materials printed in these machines are usually wax and UV cured plastics and rubbers. The other main style of 3D printer that utilises inkjet printing technology uses the print head to deposit a binder material onto a powder print bed. These 3D printers are usually used to produce sand parts that can be used for metal casting or full colour plaster/sandstone type models.

Existing commercial 3D printers that use inkjet technology are large and expensive. They are designed to use proprietary materials and therefore they do not allow much control to adjust printing parameters, meaning it is difficult to experiment with materials and binders. Due to these factors it is not viable to use one of these commercial 3D printers for research purposes.

7.3 Develop a low cost, powder based 3D printer using ink-jet printing technology

The developed 3D printer uses a standard drop-on-demand inkjet print head to deposit a binder onto a powder bed. The tested configuration uses an HP C6602A print head filled with regular black printer ink deposited onto a bed of VisiJet PXL core powder. This powder was donated for the project and is a 3D Systems product used in their ProJet CJP range of inkjet 3D printers.

The total cost to build and develop the 3D printer came in under NZ$2000 for parts. See Appendix C for a full Bill of Materials breakdown.

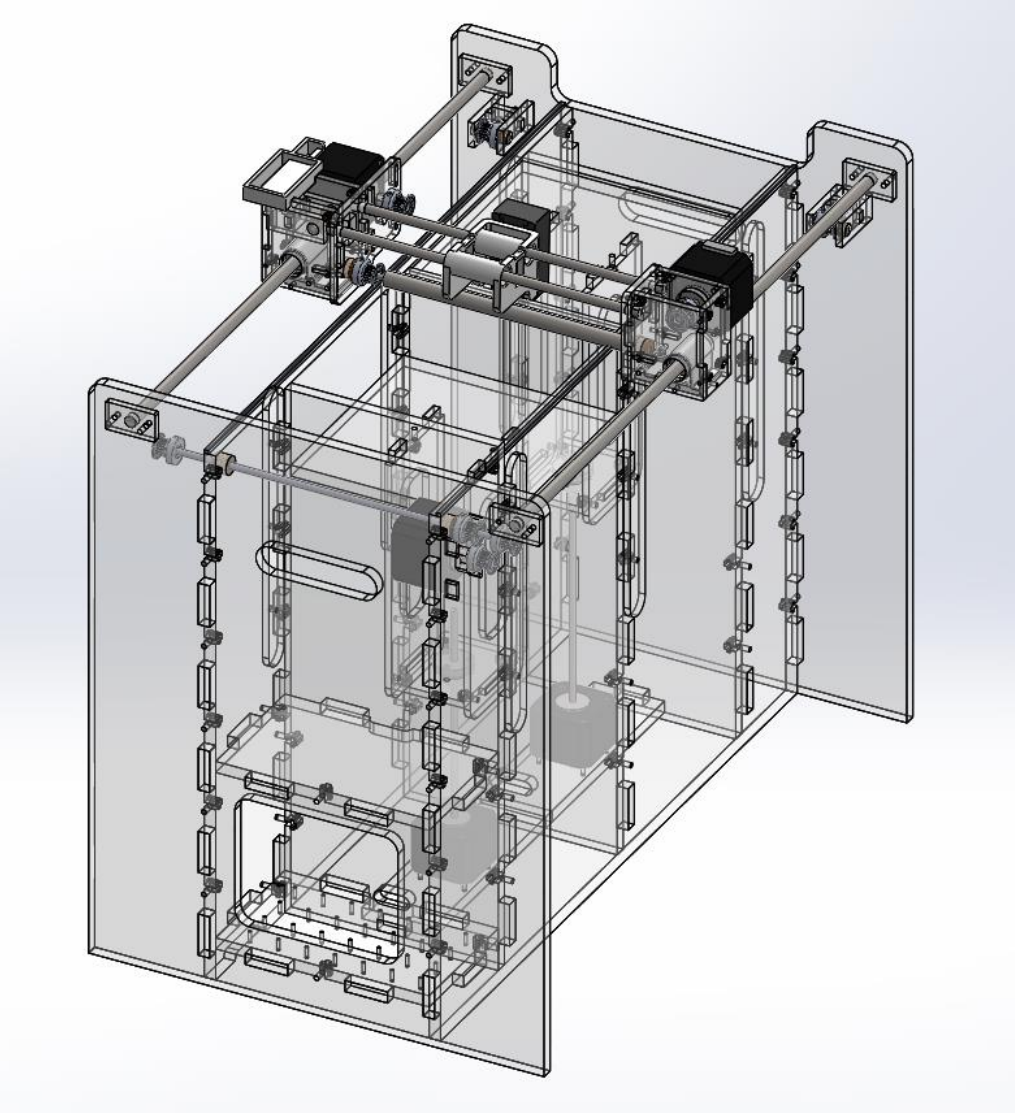


Figure 47 - Final CAD Design

The 3D printer is controlled through an Arduino Mega 2560, a cheap open source development platform that allows for changes to be made easily. The electronic circuits and PCB have been developed to use cheap, readily available parts. Custom parts were 3D printed using the in house FDM and SLS 3D printers.

With these developments done in house, all aspects of the 3D printer can be adjusted easily. With full control over printer parameters the developed 3D printer can be used for research into 3D printable materials and binders.

Figure 48 - Successfully 3D printed part

Using the donated VisiJet PXL Core powder and the standard black ink deposited from the HP C6602A print head, parts were successfully 3D printed. The parts printed were dimensionally accurate and the powder was bonded well enough so that the parts could be removed from the print bed.

7.4 Design future capability into the printer hardware

The 3D printer has been developed so that it can be easily modified for research purposes. With the motor control and print head control using separate power supplies, one can easily be modified without affecting the other.

The Arduino Mega 2560 used to control the 3D printer has a number of unused input/output pins that could be used to control any additional components to increase the capability of the 3D printer.

Extra pins on the Arduino were included into the PCB design with pull down resistors so that they can be implemented easily to add additional functionality to the 3D printer.

Chapter 8. Conclusion

The 3D printing industry is a rapidly growing space with new emerging technologies and machines being released often. This research has investigated the current state of 3D printing technology, including currently available low cost 3D printers and the state of 3D printing in the automotive industry. With the knowledge gained from this research a 3D printer has been developed to further the research capabilities in the area.

The 3D printer was developed to utilise inkjet printing technology to produce 3D parts. The drop-on-demand print head, an HP C6602A print head, deposits regular black printer ink as a binder onto a powder bed. The powder used in the 3D printer for this project is a 3D Systems powder known as VisiJet PXL Core, used in their ProJet CJP range of 3D printers.

Existing commercial 3D printers that utilise inkjet printing technology are not suitable for research purposes as they are large and expensive. This project developed a 3D printer that is suitable for research purposes. All parameters of the printing function can be adjusted to allow experimental research into 3D printable powders and binders to be conducted. The developed 3D printers uses less than NZ$2000 in parts and can easily be replicated as well as modified in house, allowed it to be used for multiple research purposes.

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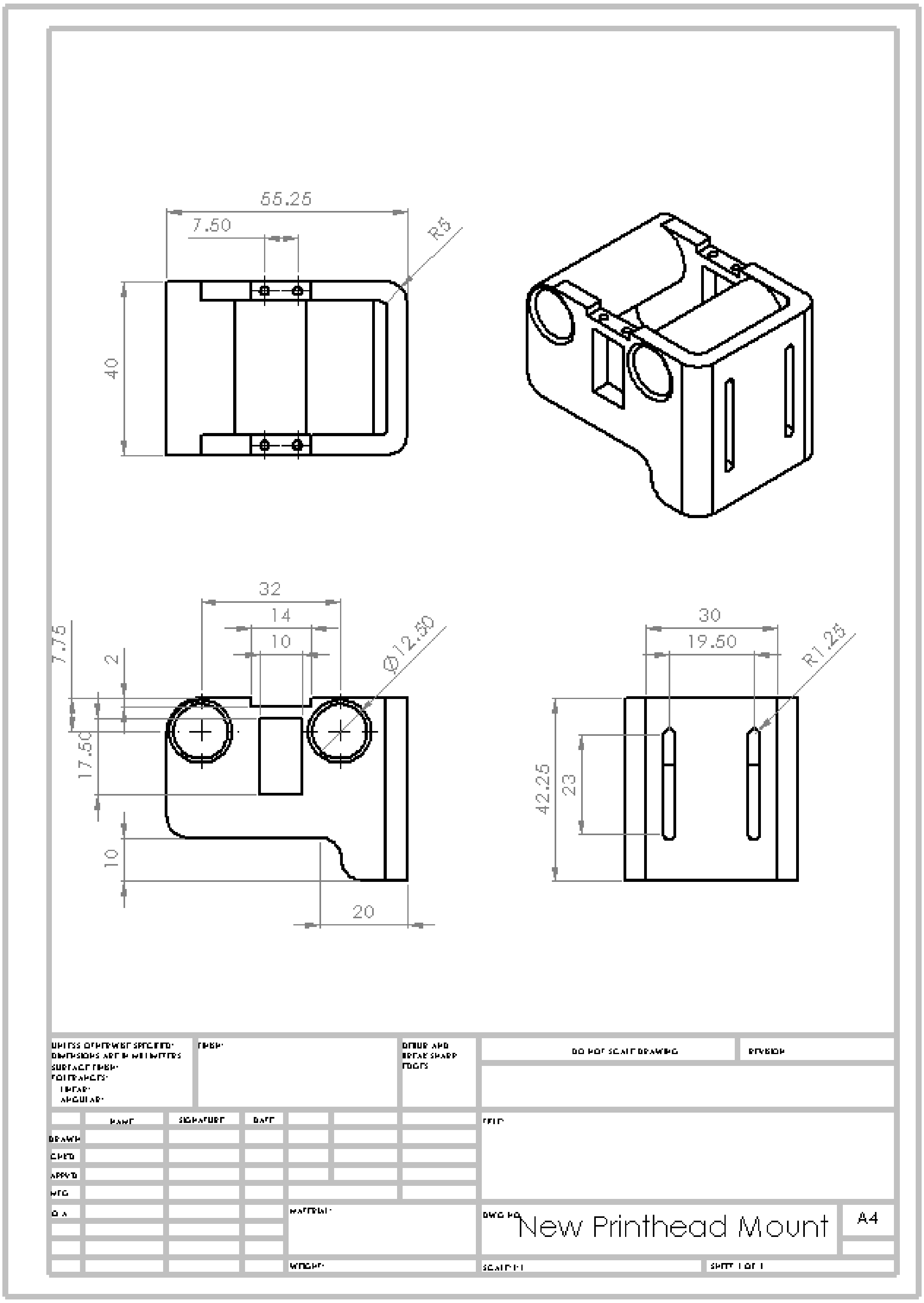
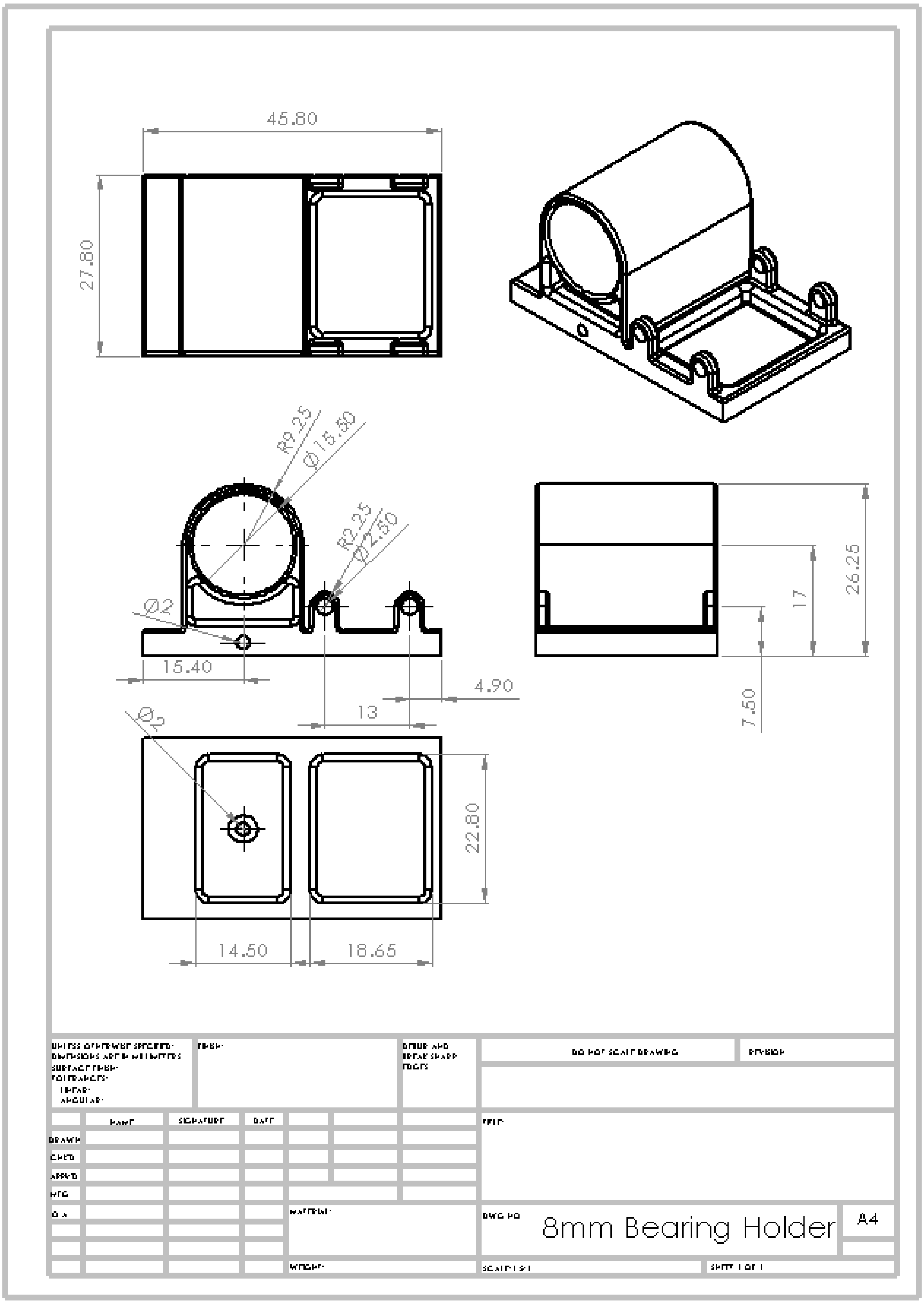
Appendix A – Technical Drawings

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8mm Bearing Holder
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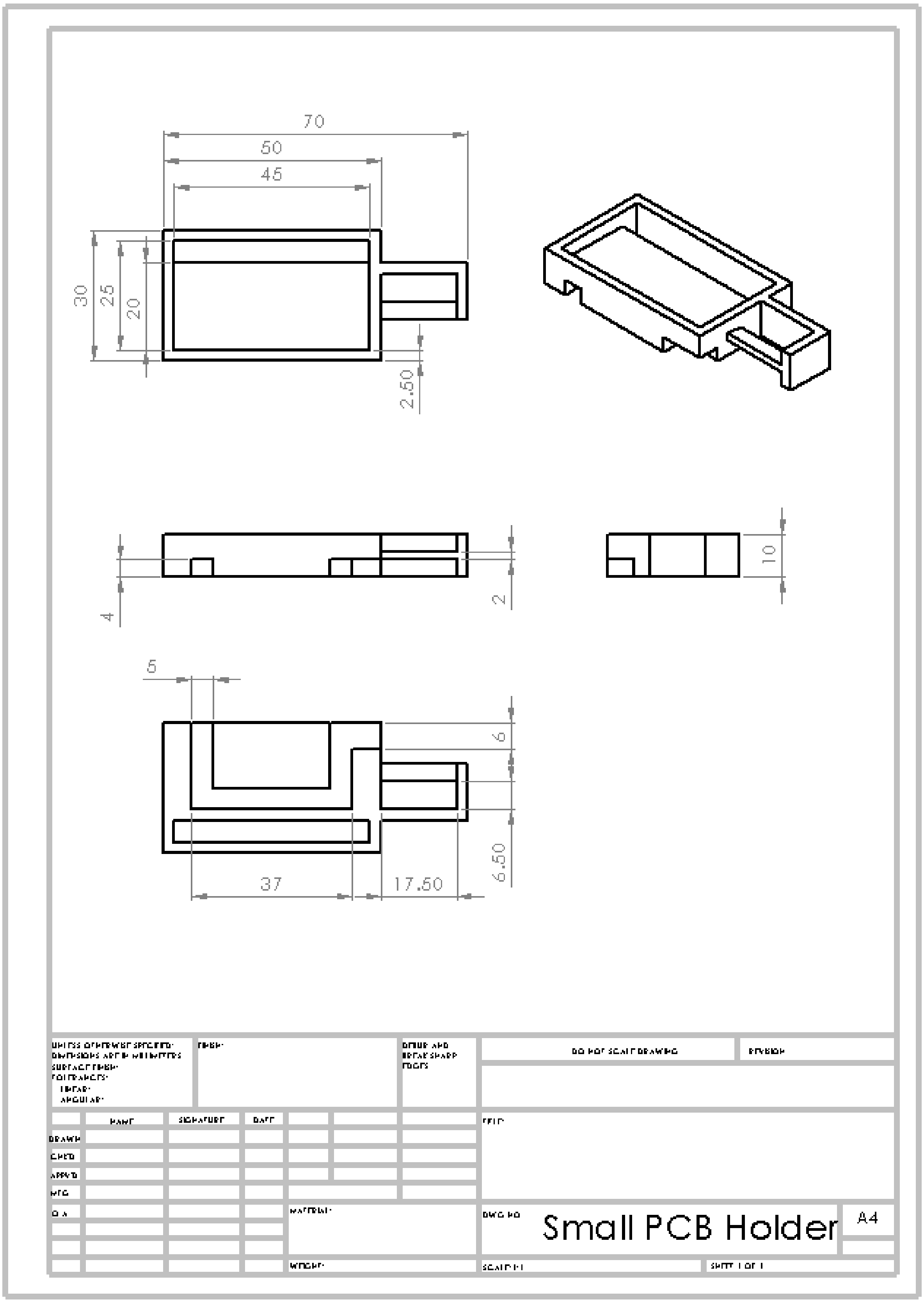
SHEET 1 OF 1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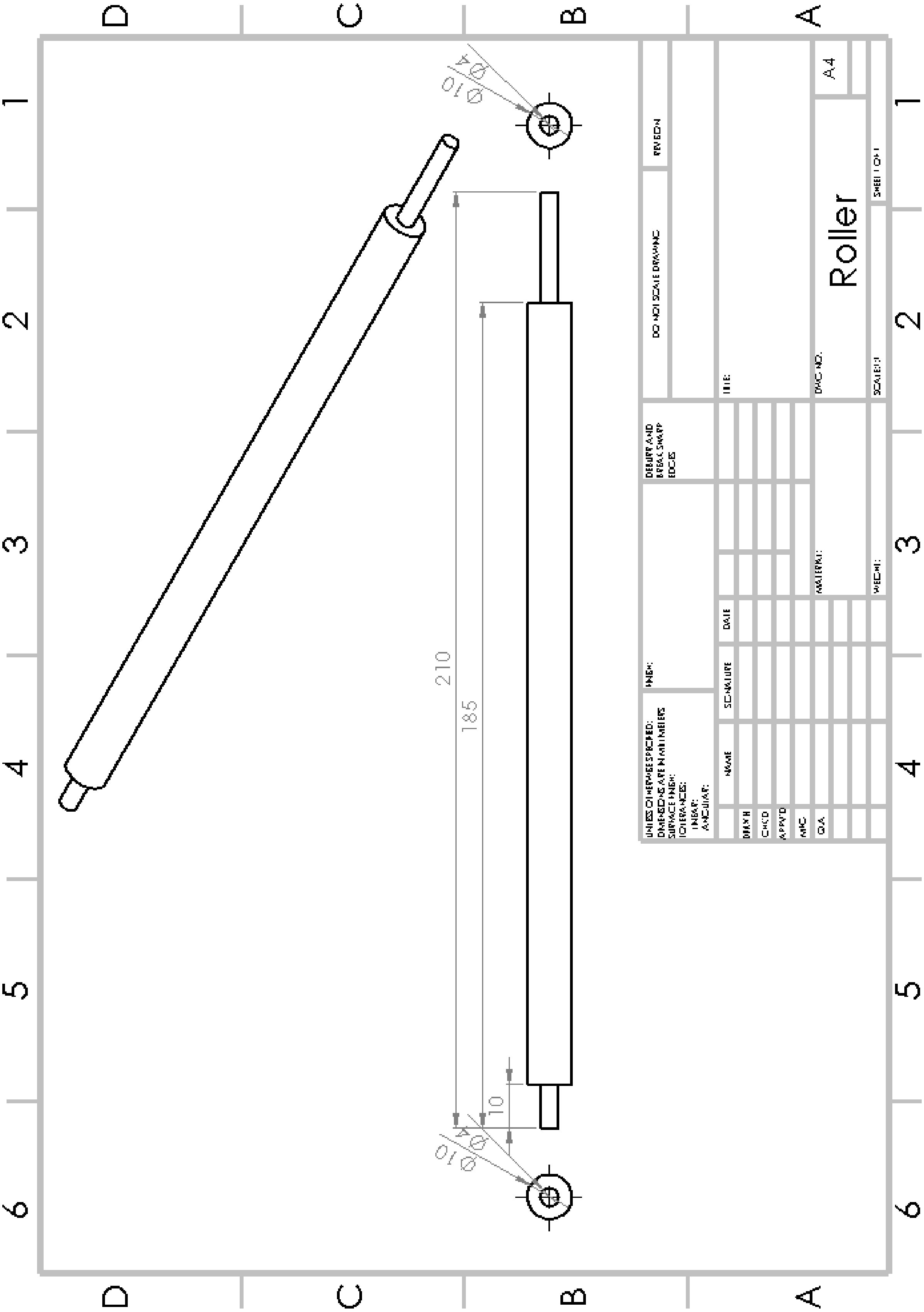
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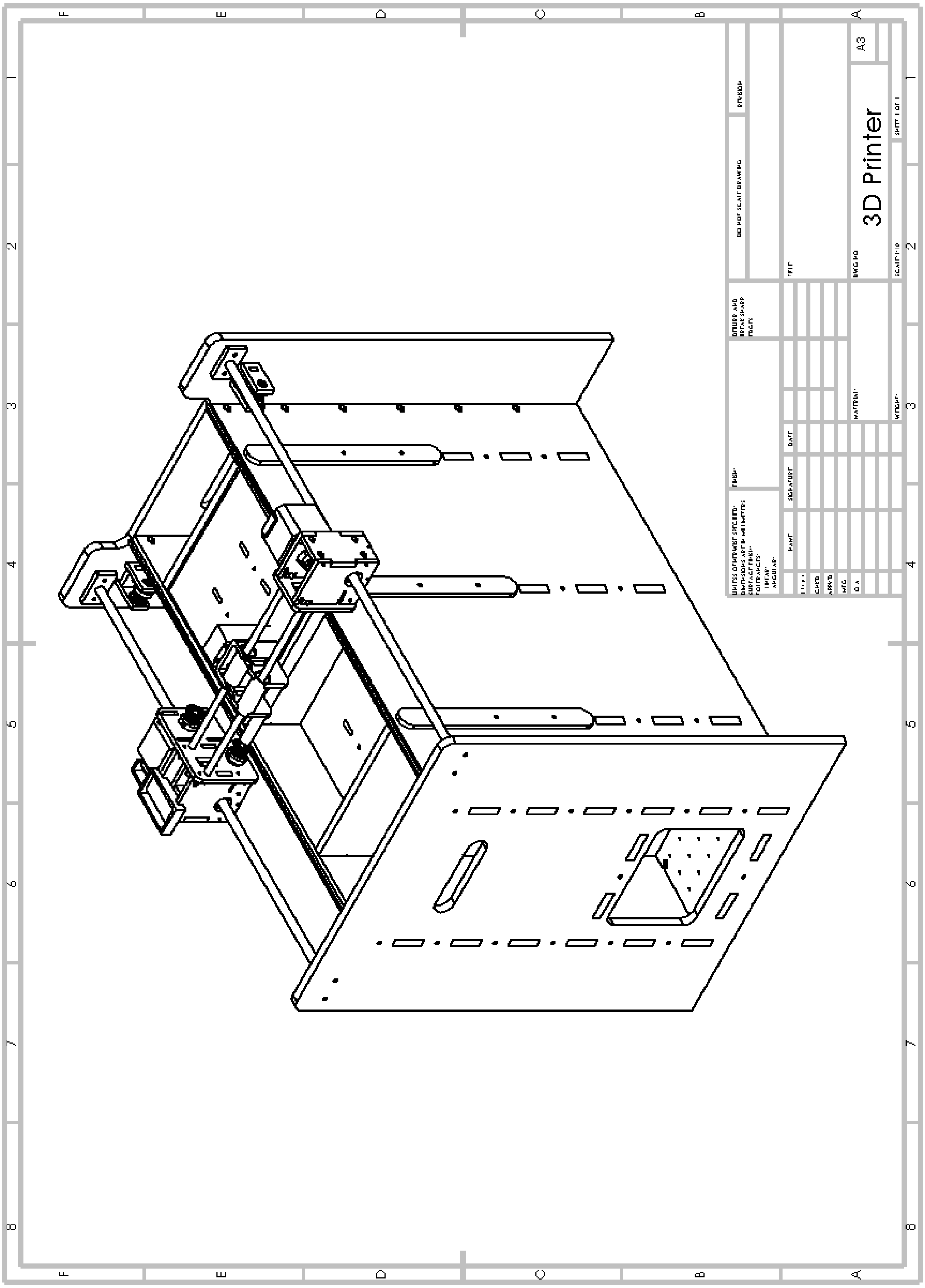
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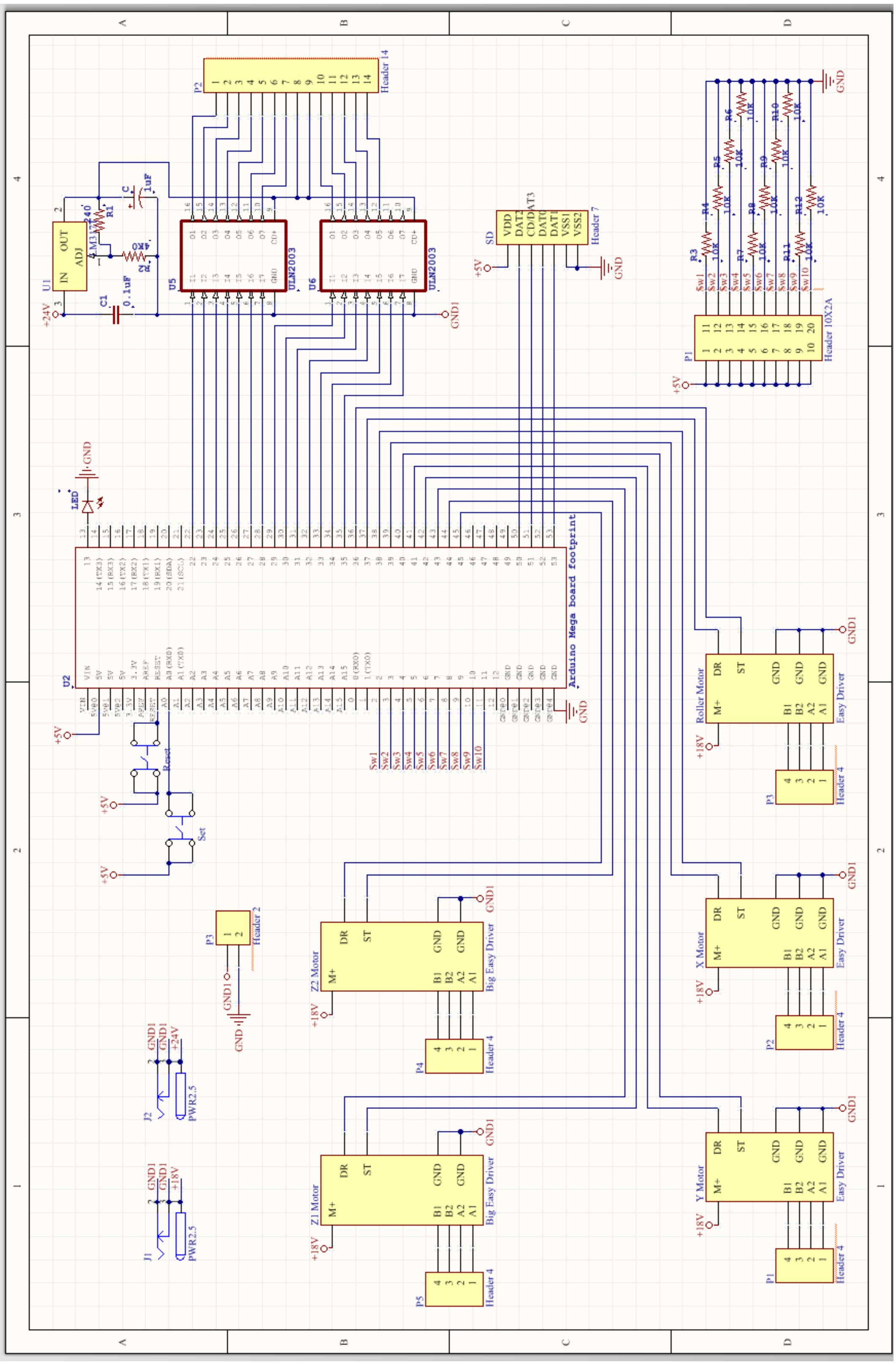
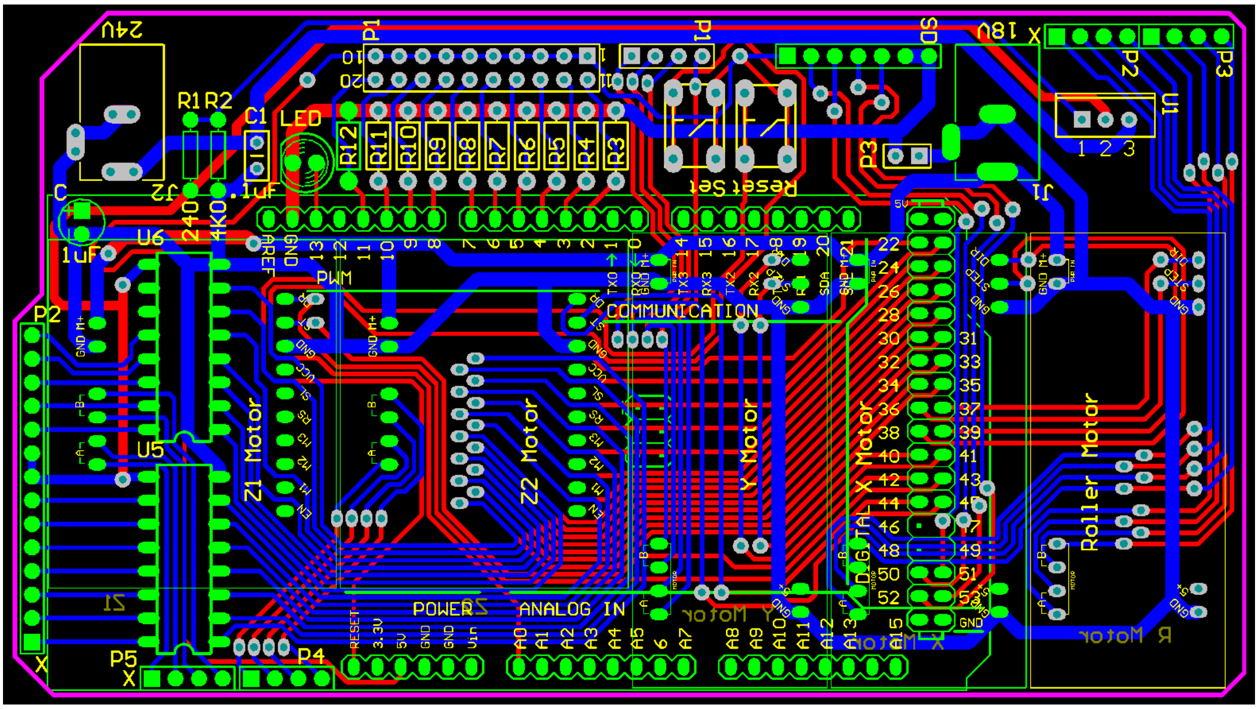
Appendix B – PCB Drawings

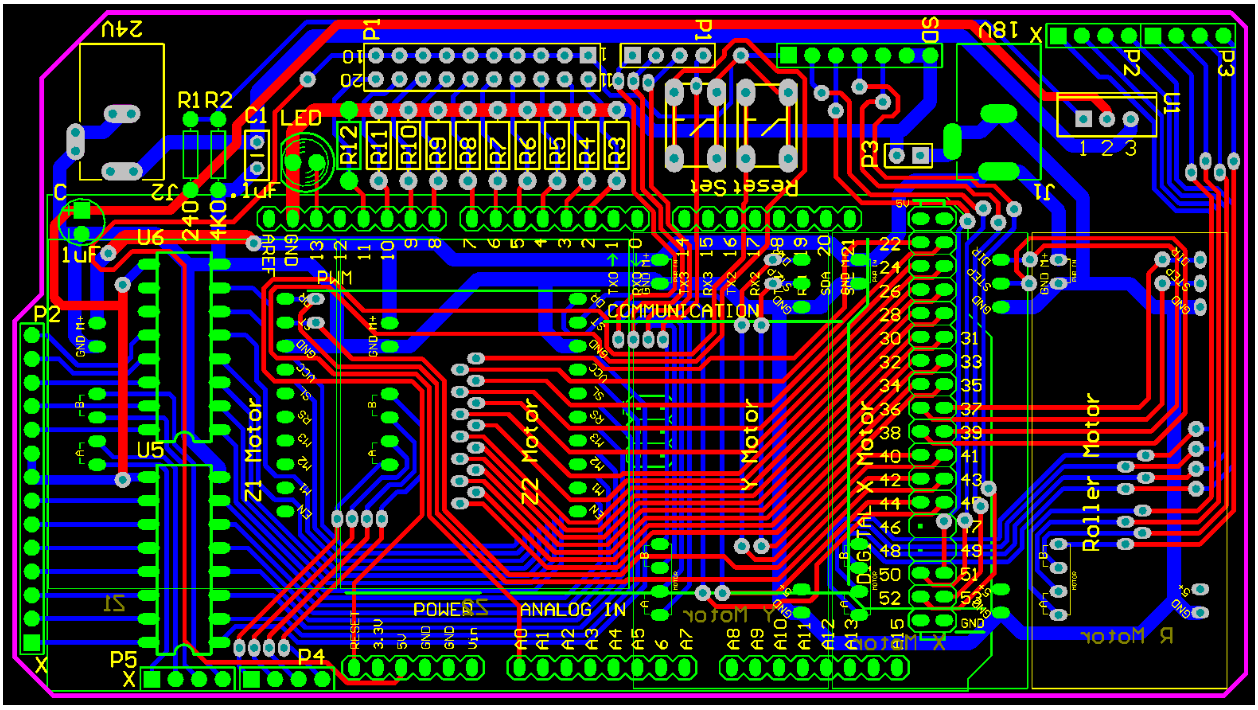
Final PCB Circuit Schematic



Final PCB Design Showing Top Layer Tracks



Final PCB Design Showing Bottom Layer Tracks



Appendix C – Bill of Materials

Mechanical Components

Part	Quantity	Supplier	Total Price
Timing Pulley Ø9.6mm	9	SDP-SI	US$94.86
Timing belt 2218mm	1	SDP-SI	US$12.61
Timing belt 112mm	1	SDP-SI	US$4.64
Timing belt 130mm	1	SDP-SI	US$4.74
Ball Bearing Ø8mm	4	SDP-SI	US$41.00
Silver Steel Shaft Ø4mmx260mm*	1	SDP-SI	US$8.18
Silver Steel Shaft Ø4mmx25mm*	3	SDP-SI	US$15.18
Silver Steel Shaft Ø6mmx220mm*	2	SDP-SI	US$22.58
Silver Steel Shaft Ø8mmx500mm*	2	SDP-SI	US$32.26
Silver Steel Shaft Ø10mmx210mm*	1	SDP-SI	US$12.97
Sleeve Bearing Ø4mm	4	SDP-SI	US$9.52
Linear Bearing Ø6mm	2	SDP-SI	US$39.24
Linear Bearing Ø8mm	2	SDP-SI	US$39.80
Acrylic 8mm*	1	PSP	NZ$120.00
Acrylic 4.5mm*	1	PSP	NZ$80.00

Electrical Components

Part	Quantity	Supplier	Total Price
Arduino Mega 2560	1	Element 14	NZ$89.63

Darlington Array ULN2003A	2	Element 14	NZ$2.00
Voltage Regulator LM317T*	1	Element 14	NZ$1.06
Surface Mount Board Connector 1mmx16	1	Element 14	NZ$2.86
0.1µF Capacitor*	1	Element 14	NZ$0.51
1.0µF Capacitor*	1	Element 14	NZ$0.31
240Ω Resistor*	1	Element 14	NZ$0.24
4kΩ Resistor*	1	Element 14	NZ$2.09
LED*	1	Element 14	NZ$0.46
Push Button*	2	Element 14	NZ$1.45
Stepper Motor with Lead Screw T6x2 150mm	2	Element 14	NZ$310.66
Lead Screw Nut T6x2	2	Element 14	NZ$105.60
Stepper Motor	3	Element 14	NZ$185.16
Arduino SD Module	1	Element 14	NZ$10.00
SD Card	1	Element 14	NZ$14.68
Fan*	1	Element 14	NZ$60.00
Power Supply 18V*	1	Element 14	NZ$58.08
Power Supply 24V*	1	Element 14	NZ$43.95
Power Supply 9V*	1	Element 14	NZ$21.97
EasyDriver Stepper Motor Driver	3	SparkFun	US$44.85
BigEasyDriver Stepper Motor Driver	2	SparkFun	US$39.90
HP Cartridge Assembly	1	Transact Supplies	US$8.25
HP Black Cartridge	1	Transact Supplies	US$15.45
PCB	5**	Seeed Studio	US$22.66

*Sourced in house to reduce costs

**Minimum order quantity

Appendix D – Conference Paper

Conference paper accepted into the 6th International Conference on Automation, Robotics and Applications, also known as ICARA 2015.

Optimisation of Ink-Jet 3D Printing Ceramic Components

Development of Low Cost Ink-Jet 3D Printer

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Abstract— **Three-Dimensional printing technology has developed to be able to produce prototypes quickly and cheaply, and is capable of producing final products. Currently available technologies are discussed as well as the advantages/disadvantages of different Ink-jet 3D printing methods. Ink-jet 3D printing has multiple variables that will affect the strength and accuracy of 3D printed components. These variables are discussed and will be experimentally tested in order to optimise the strength and accuracy of 3D printed components.**

Keywords- Ceramic 3D Printing; Ink-Jet; Current state of techonology

I. INTRODUCTION

Three-Dimensional printing technology, also known as Rapid Prototyping or Additive Manufacturing, has developed from a technology capable of producing rough prototypes to a technology capable of producing final products. There are multiple processes used by 3D printing technologies, these include, but are not limited to, Fusion Deposition Modelling (FDM); Selective Laser Sintering (SLS); Stereolithography (SLA); Laminated Object Manufacturing (LOM); and Ink-Jet 3D printing. (Yan & Gu, 1996)

Rapid Prototyping has widespread use in the industrial and manufacturing sector, and is used by large corporations to improve the development of their products. Rapid Prototyping allows designers and engineers to design parts using CAD software, and then quickly turn them into a working prototype without the need for expensive tools, thus allowing the prototype to be produced at a relatively low cost. This allows the designer/engineer to physically handle the part and find any unforeseen errors in the CAD model. Another advantage of rapid prototyping is the ability to develop tools for part moulds. The rapid prototyped part can even be used as a master pattern in some situations. With the ability to quickly and cheaply prototype parts, it is possible to get higher quality, more complex parts to production sooner and at a lower overall cost. (Yan & Gu, 1996)

As 3D printing technology is becoming increasingly mainstream, there is a higher demand for low cost, optimised 3D printers capable of producing strong and complex parts. This research will use the PWDR 3D printer, a powder based ink-jet 3D printer to produce complex and dimensionally accurate ceramic components. The research will focus on the optimization of this printing process in order to produce ceramic parts that are strong and accurate that will require minimal post processing. This will form the basis for research to be done for use in the automotive industry. Parts such as ceramic brake discs and pistons are currently produced through traditional manufacturing methods. Optimizing this ceramic 3D printer will allow for further research to be done and potentially producing ceramic components for the automotive industry through 3D printing.

Variables from the 3D printing process that will be tested through experimentation include: powder size; powder mixture; binders used; amount of binder deposited per layer; and binder drying time between layers; drying time before sintering; sintering temperature; and sintering time.

II. INK-JET 3D PRINTING

Ink-jet 3D printing technology mainly uses one of two methods to deliver the ink onto the powder print bed. These are Drop-on-demand (DOD) ink-jet printing or Continuous ink-jet printing. Each method has its own advantages and disadvantages. (Ainsley, Reis, & Derby, 2002)

Drop-on-demand ink-jet printing mechanically moves the print head to the required location to deposit the droplet in the desired place onto a bed of powder. For each layer, the ink is deposited into a predetermined location determined by the CAD package. Once the ink has been deposited and the layer completed, the print bed lowers by a set height, the layer thickness or print resolution. A new layer of powder is then spread on top of the previous layer and the process is repeated. After the printing process is completed, excess powder is removed to leave the desired part. After the excess powder is removed, the part can be sintered to achieve the desired material properties. (Windle & Derby, 1999)

Continuous ink-jet printing uses a continuous flow of ink with particles suspended in the ink. The flow of ink is deposited onto a build platform. Continuous ink-jet printing method takes advantage of the Rayleigh instability to break the stream of ink flowing from the print head into droplets. These droplets can then be steered to the desired location by applying an electric charge to them. Any excess drops formed from the continuous flow of ink are picked up and recirculated into the print head. (Windle & Derby, 1999)

The advantage of Continuous ink-jet printing is that it is faster than DOD ink-jet printing due to the continuous flow of ink being able to produce droplets much faster. The disadvantage of Continuous ink-jet printing is that it requires an electrostatic field to control the droplets, thus complicating the mechanism required to print. Another disadvantage is the risk of particle contamination during the process of picking up and recirculating excess droplets, or the print head becoming blocked due to large particles suspended in the ink. (Ainsley et al., 2002)

III. SINTERING OF 3D PRINTED PARTS

In order to achieve optimal strength properties in an ink-jet 3D printed part, the part must be sintered after the 3D printing process. To properly sinter the part and form bonds between the particles, the part must be heated to above half the absolute melting temperature of the material. This bonding is commonly done by solid-state diffusion for metals and ceramics. During the sintering process, pores are removed from within the part due to the particles being attracted to each other while forming bonds. As the pores are removed, the density of the part increases, potentially resulting in the part shrinking. It is common for the density of a ceramic component to increase during sintering. (German, 1996)

IV. CURRENT TCHNOLOGY

Current 3D printers on the market that are capable of 3D printing ceramics include the CeraJet, PWDR, ZPrinter 310 and ZPrinter 510.

The CeraJet 3D printer is made by 3D systems. The CeraJet is a full colour ink jet printer capable of producing complex ceramic shapes that are ready to be fired and glazed. It is capable of producing food safe and watertight objects. Examples of complex ceramic objects 3D printed using the CeraJet are shown in Figure 1. (Cubify, 2014)

Figure 1: Complex 3D printed ceramic objects (Cubify, 2014)

Figure 2: CeraJet (Cubify, 2014)

Powder based 3D printers that use ink-jet technology, such as the ZPrinter 310 and ZPrinter 510 made by ZCorp (now owned by 3D systems) can be used with ceramic powders and binders to successfully produce 3D printed ceramic objects. (Maleksaeedi, Eng, Wiria, Ha, & He, 2014)

Figure 3: ZPrinter310 (3DSystems, 2014)

The PWDR 3D ink-jet Printer. The PWDR 3D printer is an open source design that can be built at low cost. The PWDR 3D printer is designed to use a standard Hewlett Packard (HP) ink-jet print head to deposit standard printer ink onto the powder bed. The use of this ink-jet print head allows custom binders to be used by refilling the cartridge with a syringe, such as a mixture of 20% alcohol and 80% water. The PWDR 3D printer is capable of 3D printing with materials such as Nylon, Ceramics, and Sugar. PWDR 3D printed parts may require post processing such as sintering to achieve the desired material properties. (PWDR, 2012)

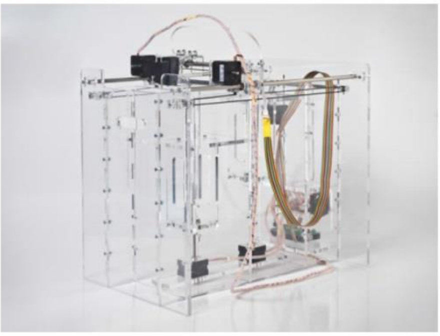

Figure 3: PWDR (PWDR, 2012)

V. DEVELOPMENT OF LOW COST CERAMIC INK-JET 3D PRINTER

This research will be using the open source PWDR ink-jet 3D printer to produce ceramic components of high strength and dimensional accuracy. Various factors will be experimented during the 3D printing process as well as factors during the post processing process. These variables tested will enable the optimization of the properties of the 3D printed components.

Potential variables for the 3D printing process include: powder size; powder mixture; binders used; amount of binder deposited per layer; and binder drying time between layers. Further variables for the post processing process include: drying time before sintering; sintering temperature; and sintering time.

Variables that are expected to have a large influence on the strength and accuracy of the 3D printed component are powder size, binders used, amount of binder deposited, sintering temperature, and sintering time.

- The size of ceramic powder used is expected to have an effect on the strength of the component. This is because smaller particles will be able to reduce air gaps within the component, therefore resulting in a denser material.

- The binder used during the 3D printing process is expected to affect the strength and accuracy of the component as it will determine the initial bond between the ceramic particles. The bond could potentially be different over the x, y, and z-axis.

- Depositing different volumes of binder onto the ceramic powder will result in different levels of bonding between the particles. Depositing too much binder directly onto the powder could result in a strong bond to the previously printed layer; however it could also result in a less dimensionally accurate part. Not enough binder deposited could result in too little bonding between component layers. Depositing smaller amounts of binder two or three times per layer could potentially increase component strength while maintaining accuracy.

- Sintering temperature could affect the strength of the 3D printed component as it will form the final bond within the component. The temperature will need to be high enough to form bonds throughout the entire component, while not melting the outside of the component. Therefore the sintering temperature will need to be balanced with the sintering time. If the sintering time is too high coupled with a high temperature, the outside of the component may soften too much and deform. Alternatively a low sintering time may not allow the component to properly harden the remove any remaining binder inside the component. The sintering process must also be optimised in order to control the level of component shrinkage. In order to produce dimensionally accurate parts, the amount the component shrinks during the sintering process must be minimised. Any shrinkage due to the sintering process that cannot be controlled will need to be accounted for in the original CAD model and therefore accounted for in the initial 3D print.

VI. CONCLUSION

This article has covered the current state of ink-jet based 3D printing methods Drop-on-demand and continuous, as well as the advantages and disadvantages of each method. Also covered were some of the commercially available ink-jet 3D printers. Our project will develop a low cost ink-jet 3D printer that is optimised to produce strong and accurate 3D printed ceramic components.

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