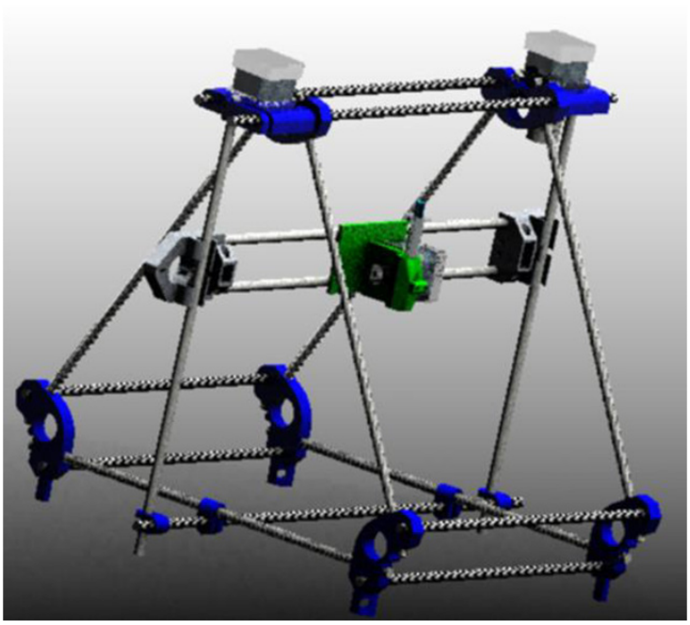
Master Thesis

Innovation in composite additive manufacturing

Euan Muir

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



LUND UNIVERSITY

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

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Preface

I want to thank a few people for their contribution to this report.

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Pernilla Karlsson, my friend that helped me understand the chemical engineering standpoints.

All of the contacts in the industry that took the time to guide me and answer my questions.

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Euan Muir

Abstract

This master thesis contains an overview of existing additive manufacturing methods and considers possible new methods. The purpose being to develop a method for additive manufacturing that can create 3D objects with composite material and/or out of metal. Further this method should work on a low cost additive manufacturing machine. A development process is used in order to select an appropriate method. The method is then divided into parts that are individually analysed in order to produce a proof of concept model.

Initially an overview of existing patents regarding additive manufacturing was conducted in order to see if the devised problem was addressed and how. A patent search regarding both additive manufacturing of composites and of metallic objects was performed.

The next phase was conducting a market overview of existing low cost 3D printers and selecting one model that was appropriate for purchase. The purchased 3D printer was then assembled and tested to build up a general experience of properties and limitations of low cost printers. These properties regard both control parameters, mechanical properties (such as eigen frequencies, resolution) and print limitations (typical errors, materials etc.).

Concept generation took place by brainstorming a wide range of possible ideas to address the project goal. Existing manufacturing methods and processes that inspired the concepts are described in the theory.

The final concept was selected by a process of first concept screening followed by concept scoring and selection. After screening the bulk of four concepts remained. One mainly addressed the goal of manufacturing metallic parts and the others composites. Further literary study of material properties and manufacturing processes relevant to these methods was conducted for the scoring step. Also appropriate retailers of materials and parts and machines were contacted for relevant cost information.

The selected concept uses photopolymers cured by UV radiation. In order to finalise the proof of concept a print head was constructed and several tests were conducted in order to observe possible fill rates and required radiation levels in order to achieve a required flow rate and curing times respectively.

Finally suggestions for further development and studies is summarised.

Keywords:

Additive manufacturing, Composites, Rapid Prototyping

Sammanfattning

Studien har utforskat möjligheter för att utveckla en ny lågpris metod för additiv tillverkning som skall svara mot önskemål från dagens användare. Önskemålen har identifierats till att vara en metod som tillåter att med en enkel 3D skrivare kunna skriva ut detaljer med komposit eller metalliska materialegenskaper. Målet med studien är att ta fram en ”proof of concept” lösning för att visa att metoden går att utveckla och tillverka inom ramarna för kostnad och kundbehov.

Ledande önskemålen och kraven som identifierades var behov av fler material, metalliska materialegenskaper och möjligheten till integrerad ledningsförmåga i designen. Dessa önskemålen togs fram från en samlad undersökning av användarforum, intervjuer från plastindustrin samt testning och användning av maskiner. Önskemålen kompletterades även med kriterier och önskemål som används för utvärdering av framtagna koncept.

För djupare förståelse byggdes en 3D skrivare. En granskning av befintliga maskiner utfördes och en maskin valdes efter pris, öppen hårdvara, öppen mjukvara och mängden användare. Konstruktionen, installation och körning av maskinen gav erfarenhet av användarbehov möjligheter gällande styrning och reglering av processen. Maskinens mekaniska och elektroniska gränssnitt sattes som gränssnitt för konceptlösningen.

En undersökning av existerande metoder för additiva tillverkning och relaterade tillverkningsmetoder utfördes. Existerande metoderna inkluderar Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Three dimensional printing (3DP), Ultrasonicwelding (UW), Metal injection molding (MIM), Microwavewelding (MW) och Injection Molding (IM) med extra granskning på extrudering.

En granskning av ovan nämnda metoder används för att skapa och utvärdera nya möjligheter för tillverkningsmetoder som uppfyllde kraven från användare. Detta resulterade i generering av tolv koncept.

Koncepten utvärderas först enl. de framtagna kraven. Först valdes de koncept ut som klarade alla fastlagda kraven där komplexitet, kostnad, olämplig metod för en novis användare och brist på kunskap och erfarenhet var de avgörande kriterierna.

Fyra av koncept uppfyllde kravställningen. För att avgöra vilket koncept som skulle utvecklas jämfördes de med målen. Målen viktades för att de mest avgörande ska ha störst inflytande.

De fyra koncepten var

1. En matare med förblandad UV härdad vätska/fiber el. partikel
2. En värmd matare för förblandad polymer/fiberkomposit
3. Elektrisk motstånd matare av metalltråd
4. En matare för inbyggd kontinuerlig fiber eller tråd.

Konceptet som bäst svarade på de viktade behoven var mataren för förblandad UV härdad vätska.

En enkel konstruktion togs fram för testning av produkten som svarade till den monterade maskinens gränssnitt. Delar beställdes in för tillverkning och testning inkluderat:

- Gas atomatiserat metallpulver
- Fotopolymer
- UV dioder

En matare konstruerades med en plastspruta, en stegmotor, en rem och en kuggremskiva. En hållare för testning konstruerades (med inspiration från en befintlig modell ”pastruder”) för att passa till projektets ändamål.

Den fotopolymer som beställdes levererades aldrig. För testning användes överbliven fotopolymer från en äldre SLA maskin.

Testning utfördes för att undersöka fiberns fyllnadsgrads och kvantitet av UV dioders inverkan på härdningstid. Utifrån testerna valdes lämpliga komponenter av UV dioder och tillhörande motstånd.

Slutsatsen av undersökningen är att metoden fungerar som additiv tillverkningsprocess och uppfyller kraven på kostnader.

Rapporten avslutas i ett flertal förslag för vidare tester och behov av utveckling av metoden. Däribland föreslås tester av komponenter för ökad ledningsförmåga samt en utveckling av mjukvara för datorstödd tillverknings (CAM) beredning av mer process specifika parametrar.

Table of Contents

Abbreviations and acronyms

Following is a list of commonly used abbreviation. Most of the abbreviations have full descriptions in this report.

3DP	-	3 Dimensional Printing
ABS	-	Akrylnitri-Butadien-styren
AM	-	Additive Manufacturing
CAD	-	Computer Aided Design
CAM	-	Computer Aided Manufacturing
CMC	-	Ceramic Matrix Composites
EVA	-	Ethylene-vynyl acetate
FDM		Fused Deposition Modelling
FDMm		Fused Deposition Modelling of metals
HDPE	-	High density Polyethylene
LLDPE	-	Linear low density Polyethylene
LOM	-	Laminated Object Manufacturing
MIM	-	Metal Injection Moulding
MMC	-	Metal Matrix Composites
PCL	-	Polycaprolactone
PE	-	Polyethylene
PEO	-	Polyethylene oxide
PET	-	Polyester
PLA	-	Poly Lactic acid
PMC	-	Polymer Matrix Composites
POM	-	Polyoximethhylen or acetal plastics
PP	-	Polypropylene
PWM	-	Pulse Width Modulation

RP	-	Rapid prototyping
RRTM	-	RepRap Tricolour Mendel
SL	-	Stereo Lithography
SLA	-	Stereolithography
SLM	-	Selective Laser Manufacturing
SLS	.	Selective Laser Sintering
STL	-	Standard Tessellation Language
UC	-	Ultrasonic Consolidation
UV	-	Ultra-violet

1 Introduction

Additive manufacturing is a technique that allows freeform manufacturing without the need for tools or moulds. In contrast to traditional reductive methods such as milling or lathing which remove material to create a part, additive manufacturing works by sequentially adding more material to build up a part.

Using additive manufacturing methods allows for rapid prototyping (RP) and in some cases can be used directly in manufacturing for small scale production. The method allows manufacturing of complex shapes, otherwise difficult to be made, using conventional methods. It also allows quick and cheap manufacturing of low quantities and allows or iterative changes. For designers this may be invaluable as a tactile sense of a physical object can display characteristics that are hard to interpret from 3D models on a computer screen.

Industrial methods for additive manufacturing were developed in the 1980s. One of the first methods developed was SLA or stereolithography (Hull, 1986). This method uses a photo curable liquid polymer surface that is exposed to a beam of photons in the pattern of the desired parts cross section. Curing a cross section layer by layer a part is created.

The process is controlled by a NC process. A 3 dimensional CAD model can be drawn on the computer. The CAD model is saved in a format (usually standard Tessellation language) and imported to CAM software. The CAM software then slices the object into layers according to the corresponding machines layer height and selects a tool-path for each layer. Machine code is then generated by the CAM software to instruct the additive printing machine how to build the object.

Over the past year there has been an explosion on the consumer market of low cost additive manufacturing machines available for home users. This has brought additive manufacturing machines into focus and interest of the media. Several low cost desktop printers have been developed and the new market segment has influenced a wave of innovation. Another aspect is that consumers now can purchase machines allowing them to create unique precision 3D objects in their own homes that can function as a learning tool and initiative. Either CAD models can be downloaded from the Internet or users can learn how to create their own CAD models.

Another field that has grown substantially over recent years (Hull & Clyne, 2007) is that of composite materials. A composite material is a material that is constructed using two or more materials, usually with the configuration of a matrix material and a fibre reinforcement. The matrix material may be a polymer (PMC), metal (MMC) or ceramic (CMC) as may the fibres, though some combinations are much more common than others. The fibres may also be of varying size from very small to long continuous fibres and of varying shape such as round or edgy particles, short whiskers or long strands. Depending largely on these factors the material may be homogeneous or highly heterogenic.

Composite materials have been used for a very long time and an example is within construction where clay and hay were combined to create stronger building bricks. Composite materials generally work by the fibre reinforcements complementing the properties of the matrix material. In regards to mechanical properties this could entail a ductile matrix material enforced with stiff fibres as to increase the overall stiffness and load-bearing capabilities drastically without losing a substantial amount of ductility. In recent years more advanced composites have become cheaper to make and have found increasingly new uses within industry. A classic example is within metal replacement. Significant reduction in weight may be achieved whilst maintaining required mechanical properties when replacing metals with composites. In the flight industry weight is key as each extra unit of weight in an aircraft requires a large amount of fuel over the course of the crafts lifespan. Thus this industry has been a driving force in developing composite technologies and there have been large increases in the usage of composites in large aircrafts. The ability to tailor material properties on demand has a huge potential and there is still a large potential for growth in the industry.

Additive manufacturing methods are often used for producing prototypes or testing concepts. They allow for fast production of samples that can be used to test limitation and feel of physical properties such as weight, balance, possible thickness and also compatibility with interfacing components. The properties the materials presently used in manufacturing limit the output.

For one-off home production this means limitations in the physical properties available. An example of this may be designing a component with conductive properties in some selected areas integrated into the part or dimension a slim stand or holder that at the same time must support a load without failure.

For concepts intended as prototypes for a component or product that is intended to later be mass produced this may also limit the possibility to correctly represent the properties of the finished product. Additive manufacturing is seldom used in mass production. In all simulations and prototypes there are limitations to the representation of reality and by decreasing the discrepancies a better and more realistic model of the final manufacturing process can be achieved. This can limit risk of over and under dimensioning components along with aiding in identifying possible flaws or achievable improvements in the design.

In summary the availability of a wider range of material properties in additive manufacturing may both allow for more design freedom in manufacturing and may better represent the physical properties of the end component that a prototype is designed for.

This project intends to develop an additive manufacturing method which can print composite or metallic materials for rapid prototyping at a low cost. The development process follows Ulrich & Eppinger's process (Ulrich & Eppinger, 2008). For the development process of this product consideration must be taken to the design of the machine process steps needed and the choice of composite. That is to say the type of composite (short grain, long grain, continuous, laminar etc.) the choice of the fibre material and the choice of the matrix material. These factors are co-dependent in the development process and thus will be discussed in parallel. The literature study intends to cover the theory and practice of existing manufacturing methods that relate to this project. The intent is to develop a new method so an interdisciplinary approach is required, resulting in a literature study observing many fields. Material properties and various manufacturing methods that are not additive manufacturing processes are observed as they contribute to the concept generation. Some of the research for this project is practical. In that stage a common 3D printer is selected and built in order to gain a deeper hands-on knowledge of the technology involved. Knowledge derived from this experience will form a large basis of the selection of concept. Design interface will be based on the printer and it may be used for testing and evaluation.

As this project is an innovation in technology the existing methods and studies function as guidelines for the development process. The general concept selection depends on the possibility for the different concepts to fulfil the customer needs. This final concept selection in turn depends mostly on how well the composite blends succeed in their desired performance during the tests. This project is intended to function as an underlying investigation for continued development of a commercial product and as such aims to show a proof of concept.

2 Aims

Additive manufacturing has long been a technology limited to industry. A change has happened over the recent years and low cost desktop 3D printing technology has been brought to market. The 3D printers that are available are limited greatly to a small selection of materials with limited material property range. The purpose of this study is to contribute to that market and develop a technology that will allow the masses access to an affordable additive technology process that offers a wide range of material and engineering properties.

The main goal of this study is to consider methods for rapid prototyping of composite or metallic materials with a cheap 3D printer.

Other goals are to:

• Develop a method that provides measurable improvements of the physical characteristics of the material (tensile strength, fatigue, and so on) and/or functionality. Specifically creep and deformation due to ultra-violet (UV) light are weaknesses present in most low end 3D printed parts today.

• Build a functioning prototype of the 3D printer

• Develop a process that allows for 3D printing of metal objects or objects with metallic properties with simple “hobby” machines

• Develop a process that allows for 3D printing of objects with controlled local properties, such as conductivity.

• Investigate the limitations of the processes for composite FDM printing.

3 Theory

In this chapter theory is presented that was used during the course of the project. This includes general information about additive manufacturing processes (for metal, plastic and composite materials) and other manufacturing processes used for composite manufacturing. The theory within these fields are largely the basis used in the concept generation stage. Material and composite theory is included here as in large depending on the consolidation method the materials will control and limit the possibility to achieve a functioning result. Also an understanding of what material properties can be acquired depending on the composite components is presented. One paragraph also briefly covers theory regarding conductive properties in design. This is of great interest as it could potentially add another dimension to the values achieved by composite additive manufacturing. This is of interest even if the project does not reach on a proof of concept model focusing on conductive material properties in design as it may still be considered as a component for further development.

The purpose of this chapter is to convey all the necessary theory to understand the generated concepts, selection process and suggestions for further development within the field.

3.1 Additive manufacturing

Additive manufacturing (AM) is an additive process. That is to say that compared to for example a lathe or milling operation material is added instead of removed. A 3-dimensional CAD model created on a computer is saved in a format and imported to CAM software. The CAM software slices the object into layers according to the corresponding machines layer deposition height and selects a tool-path for each layer. The CAM software generates machine code that is specific to the intended additive manufacturing machine. The print is then created by solidifying materials in the cross section layer by layer.

There are different methods for additive manufacturing. Some of the methods for additive manufacturing are SLS, 3DP, LOM, SL, FDM and UC. The methods vary in deposition method and adhesion processes. Some use a powder or liquid bed that is cured by exposure to light, depositions of material or another external energy contribution. Others feed material through a nozzle to deposit it upon the build platform to construct a part. What they all have in common is that they may use numerical control converting a three dimensional CAD model to build up cross sections layer by layer. Thusly build a three dimensional object using additive methods.

SLS

Selective laser sintering uses a laser beam that moves in a controlled pattern to sinter the pattern in a top layer of a powder bed. The bed is lowered by a layer height and new material is deposited to create the next layer. On completion the part is removed from the bed. In some cases only a binder in the powder is sintered so as to create a solid part. The part may then be post treated in a sintering oven to sinter the remaining material that may have much higher energy requirements for sintering. The sintering process may also function for burnout of the binder material. This method allows for construction of many different types of materials, allows for construction requiring support without the need for support materials and allows for high precision.

3DP

3DP or 3D printing is a method similar to SLS in that it uses a powder bed to construct an object. It differs in that instead of adhering the powder particles with heat from a laser a dispenser applies material that functions as a binder. This material is typically a polymer or polymer blend that is curable using UV light. Other materials may also be applied as a binder. As with the bed of plaster powder, water is used as an adherent. The dispenser may apply single streams of liquid or multiple streams as to increase speed.

LOM

Laminated Object Manufacturing uses a sheet of laminate from a spread over a build platform to form a surface. A laser is used as with SLS to cut and fuse the laminate to the layer below. The spool is raised and fed forward so as to supply a new layer and the process is repeated.

SL

SL stands for Stereo Lithography and is one of the oldest modern industrial additive manufacturing processes (Hull, 1986). The process functions by directing a beam of high energy light to cure a photosensitive layer of liquid. This layer is then moved one unit layer height and new material is applied to build the next layer. This is similar to the SLS in design apart from that the material is a liquid instead of a powder and the light emitted does not require a laser and may be UV (Ultra-violet) light.

UC

Ultrasonic Consolidation is mainly used for metal foils to construct MMC (Kumar & Kruth, 2009). It uses Ultrasonic waves to transfer heat, often in association with an applied pressure, from a roller or other tool. This method is used to adhere surfaces together for multi-layer properties and is considered an additive process but not a 3D manufacturing method as it is used for 2D surfaces.

FDM

FDM stands for fused deposition modelling and uses a spool of amorphous plastic fed through a heater and extruded from a nozzle. The material is heated to above its glass transition temperature so that it is partially molten but not fully fluid. The nozzle is mounted on a 2.5 axis NC-machine and applies the heated material in a thin continuous thread to the build platform. For non-continuous patterns of the cross section of the printed object the extruded material thread is cut by some means such as a rapid movement of the nozzle in relation to the build platform. Once the layer is complete the height between the build platform and the nozzle mount is increased with one layer height and the next cross section is extruded. The previous layer is generally still not fully solidified as to improve adhesion between the layers. The material is then cooled in a more or less controlled fashion and solidifies. To decrease uneven cooling as it may lead to errors, a heated build platform may be used and/or the build area may be enclosed inside a temperature controlled chamber.

In recent years there has been a large development of low priced FDM 3D printers directed to design hobby enthusiasts and smaller design offices. These provide an affordable option to create rapid models of 3D objects and in many cases finished products. This has led to a huge market and an explosion in the 3D-printed world as the technology has become affordable to large numbers.

Many of the methods above have been used to some degree with different composites and each method is limited in regards to composite composition selection due to process specific functions. An example is the challenge presented in introducing fibres to SLS due to mechanical factors. For SLS difficulties occur in applying new layers. The layer height is greatly affected by varying particle shape, size and weight.

3.2 Metal injection moulding

Injection moulding is a manufacturing method used in the industry. It is appropriate for large series and complex shapes. The steps used in metal injection moulding commonly look like the following (Porter, 2003):

- Mixing of materials of create a feedstock.
- Extrusion of feedstock to pellets
- Melting of pellets in extruder
- Injection into mould
- Debinding of material from the green body
- Sintering to a solid body

In injection moulding a polymer or polymer blend is granulated. It is then mixed and heated in an extruder screw. The screw builds up a reservoir in a chamber beyond its tip and then may rapidly force the liquefied polymer or polymer blend into a mould through an extrusion nozzle. The mould may be heated in order to control the behaviour and cooling of the polymer.

Metal injection moulding, or MIM, is a technique similar to injection moulding. MIM differs in respect that the feedstock added to the extruder contains a compound of polymers and a fine metal powder. After the extruder has filled the form it is slowly cooled. The polymer is removed and the metal is sintered in a sintering oven with a controlled atmosphere to avoid oxidation of the metal. Removal of the polymers is done either by solving in a liquid, burning out or by the use of a catalyst. In the case of solving or using a catalyst that is generally used to remove some of the binder and the rest is later burnt out. Burn out may be done separately or during the sintering process.

Akron discusses the water de-binding process, rheological and thermal properties looking at binder/metal microstructures. Including metal content, binder and process. Uses stainless steel, gas atomised with POM, PP and PE (Both high and low density PE) (Adames, 2007).

3.3 Mixer and Extruder

Mixer selection is done from an array of existing mixing methods. A wide range of existing mechanical mixers exist today. These include but are not limited to Screw extrusion systems. Example of different screw extrusion systems are single screw, dual screw, z screw and boden screw. Mixing may take part entirely in the extrusion process or may also take place in two steps as with the typical MIM process described above.

(Ashby, 2011) (Calluster, u.d.)

Extrusion process is when material in the form of granules are put into a hopper. The hopper allows material to enter a long heated screw chamber with a rotating screw that mixes and feeds the material forwards (*Figure 1*). Extruder dimensioning depends mostly on the feedstock. The functions of the extrusion is heating, feeding, kneading or transition, mixing and metering. Heating is needed in order to bring the materials to an appropriate temperature above their glass transition temperature. The material is generally forced forwards through a rotation of one or multiple large screws. Mixing takes throughout the chamber, though some screws have special adaptations to increase mixing. Kneading or transition takes place mostly between the screw helicoil thread and the chamber walls. The purpose is to achieve desired material properties after expulsion. Metering is a zone with channel depth even throughout the zone allowing the mixture to reach uniform temperature.

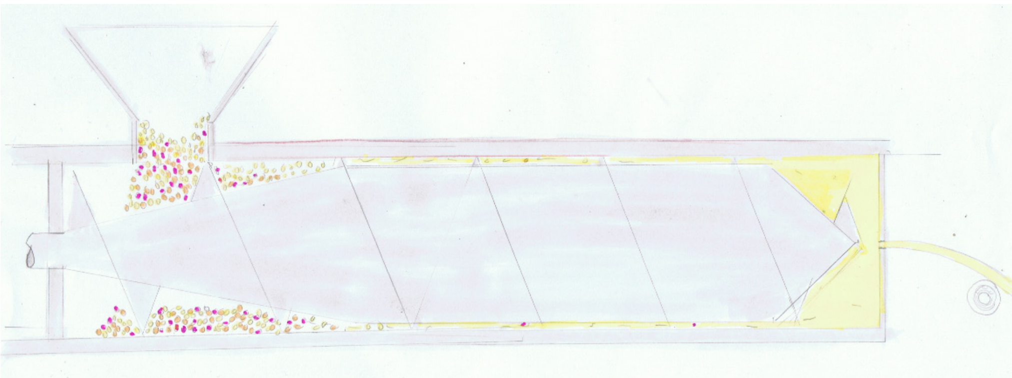


Figure 1 Extruder

There are several types of screws. To begin with there are single or double screws. The advantages of double screws are much better mixing of the materials as the screws that are next to each other increase kneading of the material.

A typical screw is the PVC or PE/PP screw. These are characterised by long slim screws with a length-to-diameter ratio depending on factors such as the material and whether a screw is a single or double screw. For instance PVC with a single screw may have a L/D ratio 18-22:1 and with a double screw 16-18:1 whilst PE/PP typically has a L/D ratio of 24-33:1.

There may also be adaptations on parts or throughout the whole screw to enhance some machining properties. For example increased mixing may take place or increased kneading.

A barrier screw has two helicoil threads that overlap at the ends such as to create one path for material entrance that is closed off at the other end and one path that start off closed and ends in an opening (see *Figure 2*). This forces the material over the threads and thus ensures that the material expulsed from the extruder is thoroughly mixed.

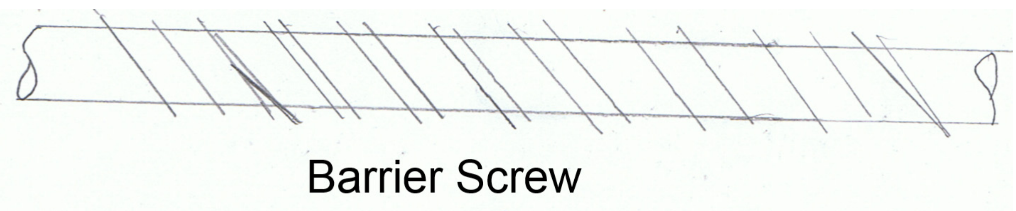


Figure 2 Barrier Screw

The same function may be achieved by a zone of the screw. Three examples of barrier zones are Maddock, Egan and Pin zones on screw (see *Figure 3*). Egan and Maddock are very similar differing in that Maddock has multiple axial channels parallel along the radii forcing the material over axial barriers whilst Egan has helicoil tracks like the barrier screw. The pin mixer is mostly used to increase general mixing of the material. (Product Application & Research Centre, u.d.).

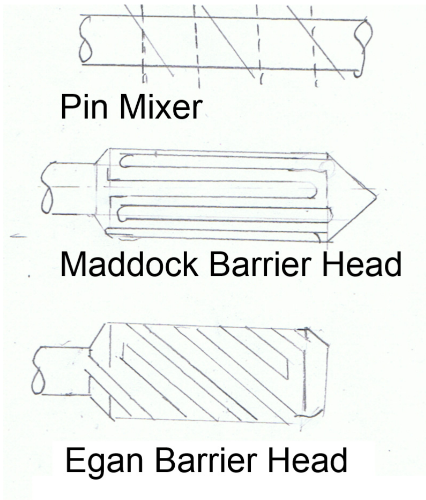


Figure 3 Mixing heads

In some cases the material may place special strains and requirements on the extrusion equipment. For instance during MIM it is common that hard metal particles such as gas atomised stainless steel may be mixed in fill weight ratios as high as 60%. The wear due to these particles requires extra strengthened screws with strong surface areas. To achieve sufficient mixing a dual screw solution or pre mixing may be required.

It is also very common for other features such as multiple temperature areas, pressure control and areas allowing for additives or material to be added in different orders such as to select what materials/additives are exposed to different stages of the extrusion process.

3.4 Materials and composites

3.4.1 Composites

Composite materials consist of two or more materials. One is a matrix material and one is a fibre material. The fibre material enforces the matrix material with its properties. An example of this is a ductile matrix material reinforced with a fibre material with load bearing properties. "Central to an understanding of the mechanical behaviour of a composite is the concept of load sharing between the matrix and the reinforcing phase." (Hull & Clyne, 2007). Typical manufacturing methods for composites depends on the matrix material. A schematic overview for PMC is shown in *Figure 4*, CMC in *Figure 5* and MMC in *Figure 6*.

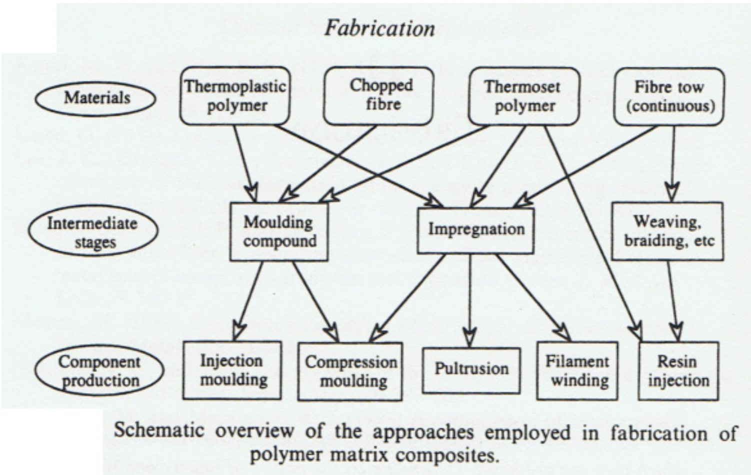


Figure 4 Polymer matrix manufacturing (Hull & Clyne, 2007)

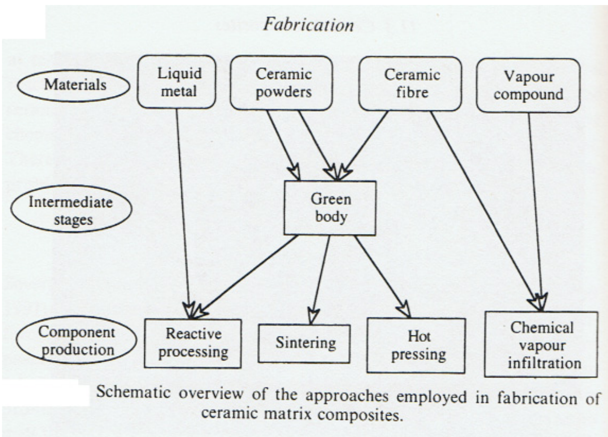


Figure 5 Composite matrix manufacturing (Hull & Clyne, 2007)

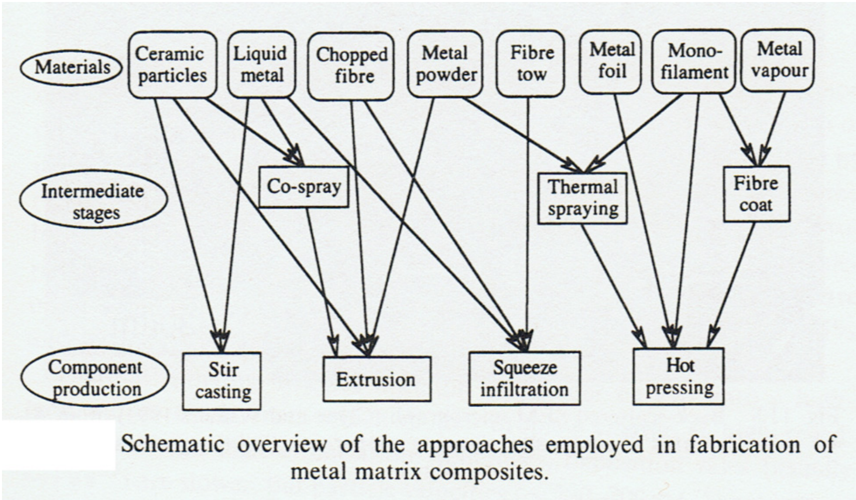


Figure 6 MMC manufacturing processes (Hull & Clyne, 2007)

3.4.2 Metal fibres

For this study metal particles are observed. Specifically gas atomised particles. These are observed as they may:

- be introduced to many of the rapid prototyping methods
- contribute to a large variety of material properties
- be sintered to construct a solid metal part (depending on amongst other things the binder material)
- and are commonly used in tests allowing for benchmarking from experience.

Gas atomisation is a process in which the metal is heated. The heated metal is forced through a small orifice to produces a liquid metal stream. The stream is divided and cooled by jets of gas. This produces small spherical metallic particles of varied size. The particles can then be sieved to remove small or large particles in order to have particles of a determinable diameter. In a similar way rough particle shapes may be made using water jets instead of gas jets for separation. The rapid cooling causes sharper shapes.

3.4.3 Polymers

Polymers are built up by many monomers connected in a long chain. Their characteristics are defined by their constituent part, chain length, intermolecular interaction and chain shape which depends on the order and types of bindings within the molecule. Polymers can be sorted into two categories.

Thermosets are polymer chains that upon hardening create cross-links (see *Figure 7* below). These cross-links give the materials their properties. Once cross-linked the chains are hard to re-form.

Thermoplastics are polymers without cross-links between the chains (see *Figure 7* below). They can be heated and remoulded which makes many of them suitable for manufacturing methods using heat as a moulding or shaping tool. Thermoplastics may often be recycled by shredding down to granulate and re-formed using heat.

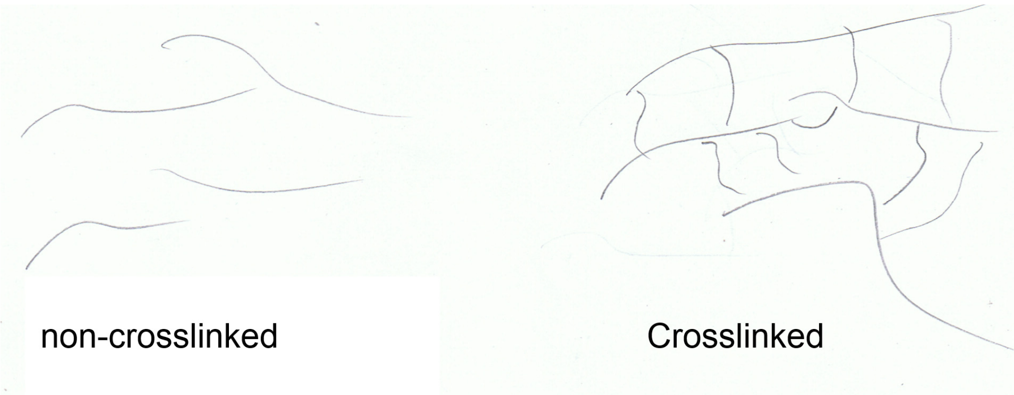


Figure 7 Non-cross-linked polymer chain to the left, cross-linked to the right

Thermoplastics have two subdivisions depending on their microstructure. On solidification some are semi-crystalline and some are amorphous. The level of crystallinity can vary amongst the materials. For additive manufacturing methods using heat to form a solid amorphous materials are generally used. This is due to the transition properties of amorphous properties when heating. A crystalline material has a set temperature at which it transforms from a solid to liquid state. Amorphous materials have a transition range in which the material gradually increases viscosity as its internal energy is increased (see *Figure 8*). This property leads to materials of high crystallinity to contract and/or warp a lot more than amorphous during cooling. In a related manor, the property serves to increase the adhesion between layers of an object build up layer by layer as heat will transfer from the newly applied layer to the previous layer.

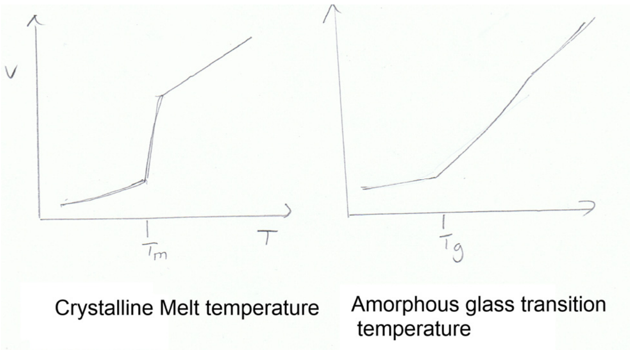


Figure 8 Temperature vs viscosity table. Melting temperature of crystalline properties to the left, Amorphous to the right with glass transition temperature

3.4.4 Composites in additive manufacturing

Previous attempts to introduce composites to various rapid manufacturing methods have been conducted. The composition of the materials depends to a large extent on the method used. Restrictions in fibre material may be due to spreading of the material (size) adhesion method or matrix material (Kumar & Kruth, 2009). Restrictions on the matrix material are generally set to materials previously used in the technology (Nkzad, et al., 2007), (Mireles, et al., 2012). Other factors limiting material selection are purpose of investigation, function of the final part, additives and combinatorial factors of the materials.

With powder-based methods such as SLS a restriction is the fibre size (Kumar & Kruth, 2009). This is due mainly to the application of a new layer. When the new layer is applied it is smoothed out so as to lay flat above the surface below. Large particles may disturb this process. Apart from that SLS can combine a large selection of materials such as different metal alloys.

With extrusion-based methods such as FDM limitation in material selection are both dependent on the matrix material ability to form due to the applied heat, heat absorption of the fibres, change in rheological properties due to the added fibres and stiffness of the material depending on fill-factor of the fibre. As mentioned above amorphous materials are suitable for FDM manufacturing due to their semi-solid properties in a temperature. In regards to metal matrix material this could be seen as non-eutectic alloys as they will have similar properties. For metallic matrix materials in FDM the technique is limited to materials with low melting temperature (Mireles, et al., 2012). In the case of polymer matrix with metal fibres consideration has to be taken to the energy absorption in the fibres. This will affect the properties as metals with high heat capacity may slow the heating and cooling rate of the composite. Rheological properties of the material are greatly affected by added fibres and small variation in the ratio of fill material may greatly affect the materials overall properties (Adames, 2007).

It is also important to note that in nearly all modern manufacturing processes using polymers multiple additives are added to improve manufacturing and end material properties. Theses may be stabilisers, anti-oxidants, additives to increase surface quality, viscosity, flame resistance and many other properties. It is also common practice to blend multiple polymers to achieve improved material properties for specific applications. This is a large field of research but will not be investigated in depth in this report as the focus is on composites (mainly larger particles as they set clearer limitation on the manufacturing process).

3.4.5 Polymers tested with fibre reinforcement in previous studies

Several different polymer compositions are used in the aforementioned techniques. Below is a list of some polymers enforced with fibres in referenced tests. (Kumar & Kruth, 2009), (Porter, 2003), (Leigh, et al., 2012), (Adames, 2007)

PE - Polyethylene

PET - Polyester

PP - Polypropylene

HDPE – High density Polyethylene

LLDPE – Linear low density Polyethylene

POM – Polyoximethhylen or acetal plastics

PEO – Polyethylene oxide

EVA – Ethylene-vynyl acetate

PLA – Poly Lactic acid

ABS – Akrylnitri-Butadien-styren

PCL – polycaprolactone

Some polymers have been tested to be selected singularly as the matrix material in the desired compounds with fibre material. Amongst these ABS has been tested with atomised metal fibres. But in most tests a combination of polymers is common for some applications.

Compositions used in studies are described below:

1. LMW-PP, PW, CW, SA
2. EWA-A, PW, CW, SA
3. HDPE, PW, CW, SA
4. PP, PW, CW, SA
5. PEO, POM
6. PEO, POM, PVB
7. EVA-C, PW, SA
8. PW, HDPE, SA
9. PW, PP, SA
10. PW, EA, HDPE, SA

These lists served as guidelines in the study for appropriate materials for composite use in thermoplastic additive manufacturing methods.

3.4.6 Carbon black (CB)

Carbon black is mentioned in a few of the RP applications. Carbon black is an amorphous form of carbon. CB is a successful filler material for incorporation of conductive material (Sumita, et al., 1991).

3.5 Sintering

Sintering is a process commonly used in manufacturing. “Sintering is the process whereby green compacts are heated in a controlled-atmosphere furnace to a temperature below the melting point but sufficiently high to allow bonding (fusion) of the individual particles.” (Kalpakjian & Schmid, 2006). The atmosphere may be controlled by removing unwanted gases (vacuum) or by filling the chamber with desired gases. The purpose of this is to prevent unwanted reactions such as oxidation.

3.6 Conductive properties in design

A manufacturing technology that can produce integrated conductive materials in one step, a wide range of possibilities are made available. In principle this means that a part can be manufactured with selective properties varying within the material. In regards to electrical conductivity this can allow for electronic incorporative design. This is not primarily intended to compete with circuit board manufacturing, but to allow for transport of current or integration of sensors directly into the part.

This is a recent technological possibility and thus there is exploration to be done in the applications. But simple examples have been investigated and tested.

Some examples that have been investigated are:

- Conduction of electricity to electronics component (diode)
- A “flex sensor” that registers elongation of a material to change resistivity
- Capacitive buttons
- Smart vessel

Printing with CB filler in RP conduction of electricity through selected paths was achieved. By connecting a power source to nodes in a printed part and connecting a light emitting diode (LED) to another part. When the power source is turned on the LED is supplied with power and turns on emitting light. The direction of print plays a large part in the conductivity of the materials.

Flex sensors use piezo resistive properties to register elongation of material. Piezo resistive effect is the change in resistance of a semiconducting material when applied upon by mechanical stress (such as tensile stress caused by elongation of the material). A glove shaped print was made to register movement fingers. By closing the hand embedded fibres were elongated and stressed registering an increase in resistivity. When the hand is opened the resistivity is decreased.

Capacitive buttons were achieved by printing a broken circuit on surface. By touching the button surface the circuit is completed. To increase the conduction areas available at touch the two ends of the broken circuit are interwoven so as to increase parallel contact areas (see *Figure 9* below).

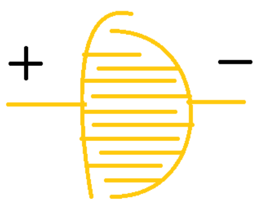


Figure 9 Increased surface design

Smart vessel is an example of an application of integration that serves a specific function. Two conductive wires were integrating in parallel going vertically down the inside of a cup. By then measuring the resistivity level of the connections from the top of the wires the fill level of the can be sensed. Conducting the circuit to the outside allows for a circuit to be attached to the cup. Feedback of the fill level of a cup could be very useful for a person with limited or no eyesight to know how much liquid is in a cup when filling the cup.

(Leigh, et al., 2012)

Conceivable applications of integrated circuitry in design are abundant. Selective integration of local composite materials could also include properties like magnetic shielding, selective heat-conduction, physical properties and many more.

3.7 Standing waves

Standing waves occur when the medium is moving opposite to the source of the waves or due to interference and means that the wave remains in one position. The interference between waves from two sources can be found by combining the formula from the two waves in Equation 1 below. A is the amplitude, s the wave function, t time, T period, lambda the wavelength and n the wave source number.

Equation 1 $s_n = A_n \sin[2\pi \left(\frac{t}{T} .. \frac{x_n}{\lambda}\right)]$

Using multiple wave generators the maximum amplitude can be calculated at each point. The maximum amplitude in the interference path of two waves is at the anti-node where the amplitude is the sum of the amplitude of the two waves. Similarly the waves cancel each other out at the nodes and the amplitude is null.

(Jönsson & Nilsson, 2007)

3.8 Ultrasonic transfer of energy

Sound wave are vibrational propagation of pressure through a medium as longitudinal waves. In solids sound may also be transmitted as transverse waves. Ultrasonic sound is oscillating pressure with a higher frequency than that detectable by human hearing. Higher frequency wavelengths entail larger energy transfer. Ultrasound is used for detection and imaging as with sonographer in medicine which is commonly recognised for its use in observing babies in the womb. It may also be used to transfer energy to a material. An example of this is ultrasonic welding where to sheets are held together and exposed to a high frequency low amplitude source. The materials are locally heated and melts the contact point between the two materials welding them together. (Jönsson & Nilsson, 2007)

Ultrasonic surgery uses ultrasonic emitters to transfer energy to specific places without having to surgically cut into the body (Beaupre, 1999) (Noguchi & Shibata, 1986).

3.9 Microwave transfer of energy

Microwaves are a type of electromagnetic wave, like visible light. Electromagnetic waves propagate transversely. Unlike sound waves that require a medium as they are pressure waves, electromagnetic waves can travel through vacuum. Microwaves are short and, thus with a small amplitude can transfer large amounts of energy and are thus commonly used in microwave ovens for heating. Microwave emitters may be used to create polymer bonds. Most polymers are insufficient at absorbing the energy from microwaves and thus fillers such as talk, zinc oxide and carbon black (Harper, et al., 2005) have been used to increase the efficiency of heating.

3.10 Rheological properties of plastics

Defining parameters in the detailed concept design will depend on rheological properties of plastic and fluid mechanics. Pressure build-up occurs when a viscous material is being forced through a tube. The quantity of the force required to achieve a speed of liquid depends on the height of the liquid, friction to surrounding surfaces, direction of flow to gravity, surface area of pipe, dimensions of the flow channel (thinning of at the end, entrance flow conditions) and the nature of the flow (laminar or turbulent).

The rate of flow can be calculated using the Equation 2 $Q = VA$ below where Q is the flow, V is the velocity and A is the area. The area is calculated by twice the radius squared times Pi.

Equation 2 $Q = VA$

Reynolds number will be found using the equation below.

Equation 3 $Re = \rho VD/\mu$

Head pressure loss for laminar flow may be calculated using the equation below. hL is the head loss, l is the length of the flow, f denotes the friction, D denotes the diameter of the flow channel, V denotes the velocity and g is the gravitational constant. (Anon., 2004)

Equation 4 $h_L/l = (f/D)V^2/2g$

4 Method

For the product development a generic development process (Ulrich & Eppinger, 2008) will be used to develop and select a method for the mechanical and chemical aspects of the printing process (see *Figure 10* below).

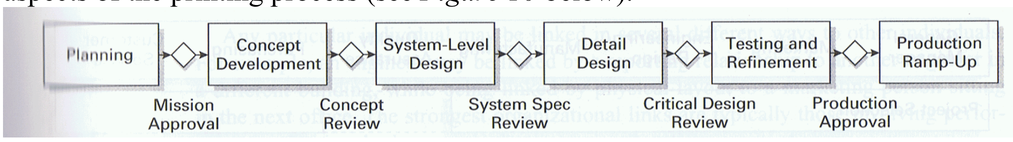


Figure 10 Generic development process (Ulrich & Eppinger, 2008)

The primary step is project planning. This is an essential step in all development projects. The project is broken into parts that are intended to be performed sequentially according to the development process model. A planned time is allotted for each step including a time buffer in the end of the project to allow time to catch up with any delay. The purpose of the planning is mainly two parts. Firstly structuring and managing the project in order to aid in making sure the project does not get stuck and fall behind the time plan. Secondly as a tool for reflection after the project to determine possible improvements and better understanding of time planning for project.

Existing methods for manufacturing composite and metal products are described in the theory. Customer needs are identified. A simple additive printer is selected, constructed, programmed, run and tested. This is then the basis for the target specifications and design interface.

A bottom up approach is used for analysis and concept generation. This is due to the project attempting to develop a new process. Thus a review of existing processes and an overview of appropriate material presents suitable concepts. A top down process is used for the development of testing equipment for proof of concept tests.

A concept generation aims to identify possible processes to achieve the goals. These concepts are then reviewed, screened, scored and the best concept is selected. Due to the complexity and sensitivity of the process quality in relation to the measure of success the selected concept is tested. At this stage equipment and materials for the concept testing will be selected. The result from these tests are used to quantify the requirements and possibilities regarding curing/heating/solidifying mechanisms and mix ratios.

Testing of the concept solution is performed with a simplified electronic controlled solution developed directly for testing of the concept. This is done in a method closely adaptable to the selected printers interface. A simulation model is created in order to verify the design before manufacturing. It is present in Appendix B: Simulation model.

Finally the testing will be the basis of the final concept selection. This will be followed by concept design, detailed design and reflections on limitation, possibilities for improvement and suggested methods for continued development.

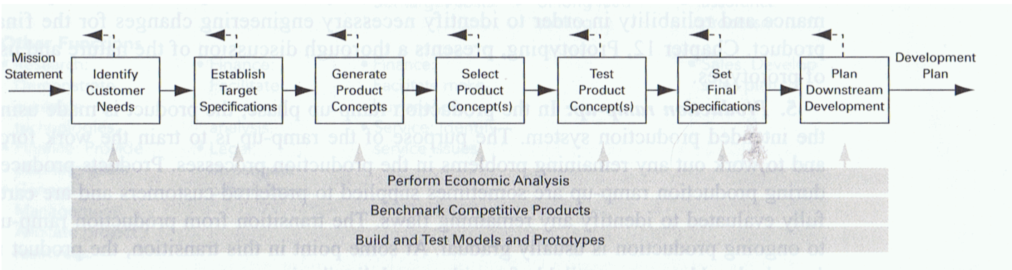


Figure 11 The Front-End Process (Ulrich & Eppinger, 2008)

5 Product planning

This chapter covers the Product planning and the project time plan and is inspired by the structure used in (Ulrich & Eppinger, 2008). The purpose of a product planning is to identify the market, strategy and shareholders and to insure that the product falls in line with the needs of the organisation and fits well with the product portfolio. The project planning should reflect this with appropriate tollgates to insure that the project stays in line with the plan and mission statement and to address any deviations from the plan that may occur such as delays or supplier restrictions. The project plan should help insure that a project is completed in time for its launch date with the appropriate resources available at each stage. This project was conducted independently of a company and as such the content of this chapter mostly focuses on the product in the context of the market and users and the plan mainly focuses on the sequential component of the project. No further resource allocation planning was formally done as this was a single person project. This project was conducted in parallel with work at the additive manufacturing lab at LTH in order to improve the knowledge and understanding of additive manufacturing. This is also presented in the time plan.

5.1 Competitive strategy

The competitive strategy used in this project is primarily that of technology leadership. An innovation in technology is the source to develop new products. This allows for an evolution of strategy towards a customer focus in the future by adapting the technology to the demands of the main customer needs and preferences.

5.2 Market segment

The market segment targeted is very clear. This project aims to develop a low cost solution for composite or metallic 3D printing that falls within the price range of the hobbyist, enthusiasts and small scale design office users that own or will purchase a lost cost FDM printer. This concept is not expected to directly compete with either the main exiting methods of metal or composite manufacturing.

5.3 Technology trajectory

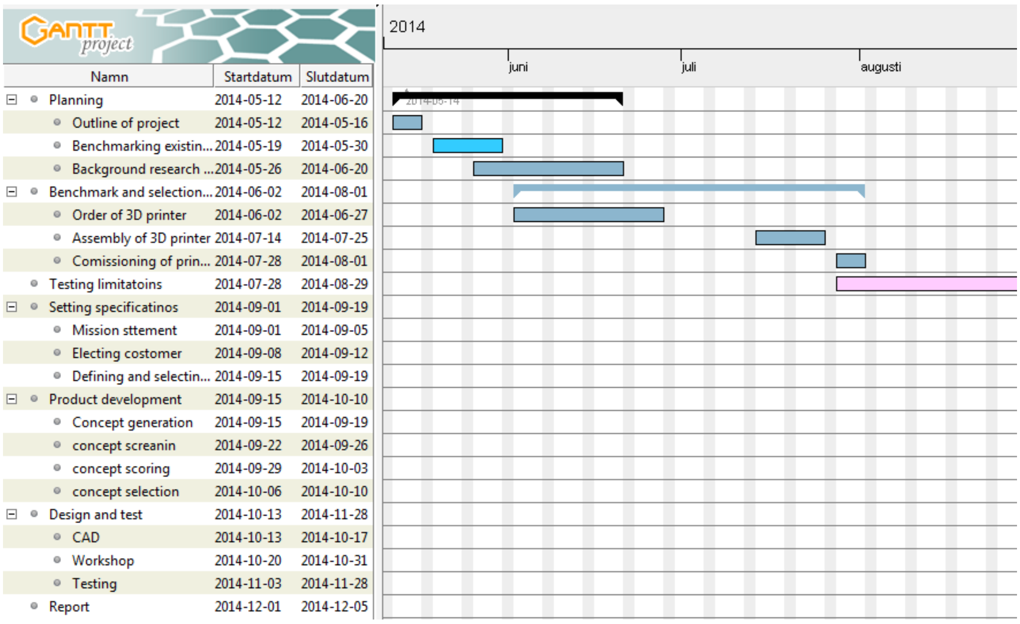
The technological trajectory of this market is hard to assess. There has been a major growth and interest in 3D printing over the past years which in turn has dramatically lowered the prices of both the 3D printing machines and materials. This is largely credited to the patents for FDM printing expiring allowing for several parties to implement an existing technology in an untapped market. The market may continue to expand as it has done over the past years or plateau. In despite of which there is a gap in the market with regards to low priced composite or metallic printing that may only be filled by an innovation of technology. It is of note that within the low price 3D printers there are those that continue to press the prices downwards (such as RepRap, Printerbot and many more) and those who have chosen to have a slightly higher price range and develop a more commercial product with features such as product specific software (as the Makerbot).

5.4 Product opportunities

An evaluation of the product opportunities depends on the results and selected method on a detailed design level. These might be sales of filament or material blocks or containers. It may require the development of a 3D printer with built in functions or a printer head or nozzle specific for the technology. The range and development of the market size may vary from near non-existent to those exceeding the number of additive printers in use today. Potentially solutions may be patented to some degree and a level of knowledge and experience of this technology will give a competitive edge towards other companies wishing to compete in this field. A realistic and conservative assumption is that this concept if brought to market would serve as a novelty solution to those users that want to expand existing methods. A platform approach of development may later be considered using the print head parts from this project and adapting them to multiple existing printers or developing a stand-alone printer. Further platforming may be used if developing different iterations adapted for specializing in different material compositions.

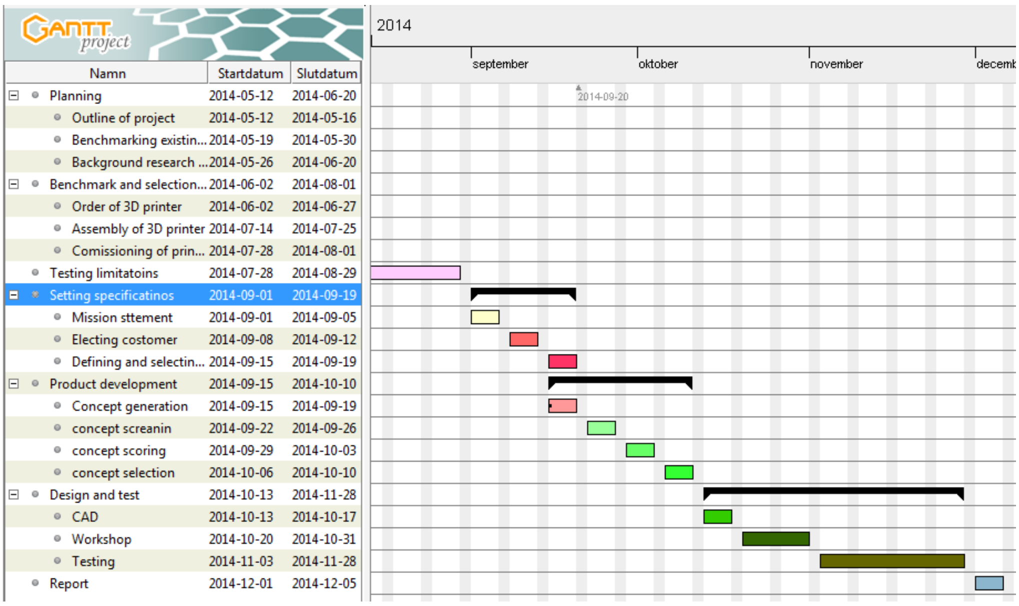
5.5 Project time plan

The following images Figure 12 & Figure 13 show the preliminary planning of the preparation and development process set from the start of the project. It should be noted that the project was commenced early to allow for extra time due to the project size and allowing flexibility for other work performed in parallel with the thesis.



Namn	Startdatum	Slutdatum
Planning	2014-05-12	2014-06-20
Outline of project	2014-05-12	2014-05-16
Benchmarking existin...	2014-05-19	2014-05-30
Background research ...	2014-05-26	2014-06-20
Benchmark and selection...	2014-06-02	2014-08-01
Order of 3D printer	2014-06-02	2014-06-27
Assembly of 3D printer	2014-07-14	2014-07-25
Comissioning of prin...	2014-07-28	2014-08-01
Testing limitatoins	2014-07-28	2014-08-29
Setting specificatinos	2014-09-01	2014-09-19
Mission sttement	2014-09-01	2014-09-05
Electing costomer	2014-09-08	2014-09-12
Defining and selectin...	2014-09-15	2014-09-19
Product development	2014-09-15	2014-10-10
Concept generation	2014-09-15	2014-09-19
concept screanin	2014-09-22	2014-09-26
concept scoring	2014-09-29	2014-10-03
concept selection	2014-10-06	2014-10-10
Design and test	2014-10-13	2014-11-28
CAD	2014-10-13	2014-10-17
Workshop	2014-10-20	2014-10-31
Testing	2014-11-03	2014-11-28
Report	2014-12-01	2014-12-05

Figure 12 Gantt schema week May-August



Namn	Startdatum	Slutdatum
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Order of 3D printer	2014-06-02	2014-06-27
Assembly of 3D printer	2014-07-14	2014-07-25
Comissioning of prin...	2014-07-28	2014-08-01
Testing limitatoins	2014-07-28	2014-08-29
Setting specificatinos	2014-09-01	2014-09-19
Mission sttement	2014-09-01	2014-09-05
Electing costomer	2014-09-08	2014-09-12
Defining and selectin...	2014-09-15	2014-09-19
Product development	2014-09-15	2014-10-10
Concept generation	2014-09-15	2014-09-19
concept screanin	2014-09-22	2014-09-26
concept scoring	2014-09-29	2014-10-03
concept selection	2014-10-06	2014-10-10
Design and test	2014-10-13	2014-11-28
CAD	2014-10-13	2014-10-17
Workshop	2014-10-20	2014-10-31
Testing	2014-11-03	2014-11-28
Report	2014-12-01	2014-12-05

Figure 13 Gantt schema week August-December

5.6 Mission statement

The mission statement below defines the parameters of the project described in this report.

Table 1 Mission statement

Mission statement: Composite/metallic FDM 3D printing	
Product Description	• A device that uses additive manufacturing to create three dimensional composite material objects
Benefit Proposition	• Tensile strength • Printing metal • Anisotropic characteristics • Enhanced material properties • Integrated circuits • Controlled locally enhanced properties • Possibly to sinter
Key Business Goals	• Proof of concept 2013, platform for further development
Primary Market	• Do-it yourself 3D printers
Secondary Market	• Universities • Design companies • Small scale manufacturing
Stakeholders	• Users Retail • Lund University • Maker community • Researchers • Developers

5.7 Assumptions

Orientation of the material is not prioritized for the proof of concept. This may be addressed in future development. One solution to the control of fibre orientation is by the slicing step in forming a CAD document. Fibre orientation and distribution plays a vital role on the materials characteristics (Fu & Lauke, 1996) .

Many FDM printers are very similar in design principles. This project focuses on one model of additive printers in order to define the specification parameters for the concept design for testing. This is a proof of concept solution and is assumed to work well on most existing FDM printers.

Developing a technology that allows for printing of metallic objects in a simple FDM printer is in large demand. It is a concept that people can easily comprehend and see the function in. Additive printing technology that allows for printing in materials that are entirely or partly metallic and polymer composites may offer as many or more advancements in regards to the innovative opportunities for the end user. This solution is more likely to be underrated.

6 Identification of customer needs

A crucial step in concept development is the identification of customer needs. This is the basis of the criteria that are used for the selection and modification of the concepts. In this project the customer needs are found by identifying the intended customer as described in the planning and defining the expected needs of the customer regarding this project. The raw data is collected through interviews, observations of similar products in use, conversations on blogs and by hands-on experience of existing products.

6.1 Gathering data for customer needs

The sources for customer needs were varied. The large increase in popularity of 3D printing technologies over recent years may be to an extent attributed to hype, word of mouth and anecdotal references. Due to open source and information sharing efforts a new marked segment has been opened for this technology. This market segment is still growing and including new customers all the time. Thus the average customer for this technology is changing. Therefore the source of customer need is selected by users in discussions on dedicated forums with quotes such as “Why hasn't this been done yet???” regarding metal printing and “I'd like to emphasize that 3D metal printers at home ("low cost") will be a huge benefice for everyone, a true revolution. So the open source project MetalicaRap is really great, thank you!” (reprap.org, 2014), personal experience building and testing printers, and interviews from suppliers. A collection of relevant quotes are shown in Appendix D: List of Industrial suppliers and/or contacts.

6.2 Benchmarking

A part of this project was spent on researching existing products and patents in order to observe existing methods and ensure that there weren’t any existing solutions for concluded problem. The patent search was performed through a preliminary patent search using keywords such as “additive manufacturing” in order to survey existing patents within the field. This was later complemented by a patent search at the end of the project to ensure that the resulting solution did not infringe on any existing patent (Appendix H: Approach to patent search).

Also investigation into the thermal dependence of viscosity in short fibre composite materials was conducted. The purpose of this was in order to evaluate the complications in relation to developing composite FDM solutions. The study was conducted by examining several sources where testing had been conducted previously (Porter, 2003) (Anon., 2004) (Fu & Lauke, 1996). This was not formally summarised beyond that included in the theory 3.10 due to the final selection process not using a method requiring solidified material as feed material. Existing methods of composite material manufacturing were examined (see chapter 3.4.1). As were the design of several FDM printers (see chapter 3.1). Finally a large study in material science around polymers suitable for the project was performed and a survey of existing retailers of possible fibre materials such as metallic powder was composed. The relevant result of which is summarised in the theory chapter 3.4. These are all presented in association with the relevance throughout the report and in full in the Appendix C: Material content.

6.3 Interpretation of Customer needs

The target customer for this project, as mentioned in the project planning, is a typical user of a low range FDM printer. The desired result is to develop a process that allows such a user to use the system for printing AM printed parts with minor adjustments to their equipment. This user is not expected to have a large experience of handling hazardous materials. This user is expected to have the basic mechanical skills needed in order to replace parts of the AM printer such as the nozzle or extruder if needed. But this should not require the user to manufacture the parts by themselves. The user is expected to require a reasonable price for the adapted system costs and material costs. The system should not be overly complex as it is expected that some of the users will require the ability to update and modify parameters or control methods.

A bullet list of the customer needs is listed below. The list is a basis of selection for the generated concepts.

- Simple system
- High repeatability
- Compatibility with existing printers (low price range FMD)
- Temperature below ca. 240 °C (in printer, higher temps may be allowed for post printing treatment)
- Environmentally friendly materials
- User friendly materials (example non-toxic and non-corrosive materials.
- If filament preferably around 1.75 Ø mm
- If soluble material preferably water soluble over ex. Ethanol
- Cheap
- Compounds may be rigid and non-flexible requiring alterative solution to filament spool. May also be liquid at room temperature.

7 Establishing target product specifications

The information gathered in customer needs is converted into specifications which the concepts may be ranked in order to select the most appropriate paths. The needs are interpreted and quantified when possible, then ranked in order of their importance. They are then later used in a weighed selection process during the concept selection according to the degree of which the concepts satisfy the specifications. Notably the weighting is higher for start-up equipment and test equipment and the weighting of the cost of material is lower. This is due to the nature and goals of the master thesis. For a long term sustainable process the weighting would be different.

7.1 Target specifications

The target specifications are assembled in Table 2 below. For some criteria a note is added for clarification. The criteria are weighted according to the importance for this proof of concept investigation. As this is a conceptual development project no fixed values are set for the product. Instead a group of measureable qualities related to properties attained are listed. This is mainly due to the fact that the concept generation process is aimed to be wide allowing for inspiration to be applied from many different fields of manufacturing that may be very hard to estimate fixed values or even reasonable ranges. Thus the target specifications will serve the purpose of defining the desired properties to be attained in order to make a qualitative compare in the product selection process.

Table 2 Target specifications

Criteria	detail/note	Weight	unit
Printing speed		2	mm/sec
Solidifying/Curing rate	Controlled hardening is important for resolution	2	sec/mm^3
Matrix solid stiffness		3	N/m
Material ductility		3	N/m
Matrix solid UV sensitivity		1	σ/day sunlight
Cost for raw material		2	SEK
Cost for material treatment		2	SEK

Cost for components		5	SEK
Cost for test equipment		5	SEK
Warp	Resin based materials warp, thermosets warp with uneven cooling	4	Γ
Minimum Layer height		4	mm
Resolution/nozzle diameter		4	mm
Wear of equipment	Extrusion of fibre wears out equipment	2	SEK/year
Simplicity for end user	Ready mixed filament on spool has advantage over active mixing	5	
Switching to normal material	Switching nozzle vs. Cleaning nozzle	1	S
Reliability	Cutting/stopping flow/ Release of part from build platform errors a.s.o.	5	% of prints without fail
Control of mix ratio	On the fly for active control or pre made feedstock solutions	5	
Distribution of mix	The variance of the fibre distribution and orientation plays a vital role in the consistency of the properties	5	Variance
Sinterability	Whether or not the process allows for sintering or otherwise manages to produce metallic objects	4	
Start-up time for print	FDM printers require heating time. For printers with heated build platforms or heated chambers and printing in materials with higher temperature (ABS) the time is quite substantial	5	S
MMP ability	Weather the solution allows for designed variations in printout material	5	y/n

8 Selection of printer platform

In this chapter the process of selecting and assembling a platform which the concept will be designed for and tested on is described. The design interface will be defined based on the properties of the selected printer including physical (assembly and size), electrical (currents, outputs, and sensors) and programming (control, firmware and machine code generator) parameters. The information and experience gained from set-up, calibration and running of the printer, add to the experience gained from additive manufacturing help make the basis of knowledge used in the selection process as "soft" values (not always quantifiable but of the nature of a deeper understanding or preferences and common issues for an end user).

8.1 Selecting printer for development process

In order to decide the customer needs a specific AM printer is selected to define the parameters for primary design focus.

An initial study of existing low range AM printers was conducted. First a study of the available machines was performed with the purpose of gaining an overview of the machines. This was then to build the bases for a selection and purchase of an AM printer. The purchased AM printer would serve the purpose of being the model which the product is primarily developed for.

A list of some of the most commonly available FDM printers was assembled[1]. This would be the main source for the selection of the purchased printer model. The list contained information (when available) on the source of the model information, delivery time from that source, price, whether or not it had a heated bed, if it was open sourced or not and extra details.

Apart from the list, consideration was taken to other factors. One goal of the project is that the process developed should function for as many pre-existing AM printers as possible. Therefore consideration to an overview of which AM printers are most commonly used (Moilanen, u.d.). Another factor that was considered was the type of microcontroller and its firmware used in the AM printer. Arduino based AVR microprocessors, such as those used on RepRap type FDM printers are an example of microcontroller boards that allow for easy adaptation of software and designed as tools to allow reprogramming without expert knowledge. Whether the purchased FDM model was pre constructed or a kit that needed constructing was considered. A kit that required assembling, while taking more time of the project, allowed for

[1] List conducted summer 2013 and may not reflect current market

further exploration of its design factors, characteristics and empirical understanding of its limitations and sensitivity. Finally a criterion which came to weigh in was the availability of extra I/Os and multiple extruders. At the stage of purchasing the 3D printer little was decided about the concept for the projects process. By selecting a printer that contains outputs for multiple extruder motors, extra sources for sensors inputs that may be reprogramed and extra control I/Os the concept generation would be less limited in regards of the complexity of the control parameters available for the extruder system. Dual motor control may be required for separate drive systems of the different materials in the extruder nozzle or a possible mixing process. Sources for inputs may be needed for elements such as PID control of heat measurements. Out ports may be needed for such functions as heating or turning on and of ultra-violet light sources.

A list of low cost 3D printers was assembled listing price, lead time, option of heated bed and if the printer is open sourced (see Table 3 below). The list was used for the selection of a printer.

Table 3 Selection 3D printer

Make	**Website/source**	**Lead time**	**Price**	**Heated bed**	**Open sourced**	**Note**
Makibox	makibox.com	6-10 weeks	200 $	no		
Makibox	makibox.com	6-10 weeks	300 $	yes		
Ultmaker	ultimaker.com	1-3 days	1.194 $			
Printerbot	printerbot.com		299 $	no	yes	
Solidudle, 2nd gen	storesolidoodle.com	2-3 weeks	499 $	no		
Solidudle, 2nd gen	storesolidoodle.com	2-3 weeks	599 $	yes		
3D Touch	cubify.com		450 $			
Reprappromono	reprappro.com	20 days	648 $	yes	yes	
Makerbot	makerbot.com		2199 $	yes	yes	
Reprappro Huxley	creativetools.se	3-4 weeks	3 775 kr	yes	yes	Meltzi circuit board
Reprappro Mono mendel	creativetools.se	3-4 weeks	4 872 kr	yes	yes	Meltzi circuit board
Reprappro Tricolour Mendel	creativetools.se	3-4 weeks	7 137 kr	yes	yes	Meltzi circuit board

The model selected was the RepRap Tricolour Mendel (see Figure 14 below). This machine will henceforth be mentioned as RRTM. The main reason for its selection was the availability, source of extra I/O and motor control, Arduino controller, Open sourced and the fact that RepRap models are closely built upon one another and together are one of the dominating FDM printer models. It should also be noted that during this research some access was arranged to another FDM printer, Makerbot 2 that was already available at the institute. This allowed for comparison which contributes to detailed experience mostly used later in the concept selection process. For the circuit board the model chosen has two Melzi circuit boards. One master and one slave. They allow reprogramming and interact with several models of software. The software used during the project to control the system was pronterface and slic3r.

Figure 14 RepRap Mendel

8.2 Assembling, programming and testing printer

The assembly of the printer was carried out according to the methods described on the RepRap homepage (repraphomepage). One of the thermistors was damaged a replaced by a generic thermistor with similar properties from ELFA Distrilect. Datasheets for the replaced thermistor are found in Appendix F. The controller board was flashed with a firmware for dual Melzi circuit boards (one master, one slave) called Marlin. Before flashing the board, corrections were made for the resistance and alfa values for the replaced sensor component according to Appendix F. Calibrations for errors in movement were also made.

Testing of the RepRap gave a qualitative experience of the experience of a simple 3D-printer user issues that aren't necessarily quantifiable. But some of the user experience can be put into words. Empirical knowledge gained from the build, programing, booting and running of the RepRap 3D printer follows.

- An understanding of the limitation and problems connected to the 2.5 axis motor drives and the build platform.
- An experience of factors that may influence the print in such a way that some or all of the material may not stick to the build platform during the first layer print
- General limitations of the FDM printing technology. Such as resolution, level height, speed, surface quality, critical angles and size and shape relations to torsion of the material.

From this empirical knowledge some quantitate criteria is developed for the continued evaluation of the selection process.

In regards to resolution and layer height the limitations in the RRTM are defined mainly by the nozzle diameter on the hot end and not by the electronics, programming, motor or mechanical resolution, which allow for higher precision. This seems to be in general occurrence with other 3D printers as the limitations in the diameter of the printed plastic thread is set by the nozzle diameter. This in turn is limited by fluid properties of the material used in extrusion. Limiting factors may be temperature, pressure and varying viscosity of the material. Another valuable note is that some competing models seem to achieve slightly higher resolution both in the x-y plane and in the layer height by using a direct drive system. This is the solution applied in the Makerbot 2 and it is also available as a mod for the RepRap models. Whilst limiting speed of the print it appears to allow added control of the flow of material leaving the nozzle. This is an intuitive conclusion as the drive system is closer to the extrusion and this there is less length of material between allowing for build-up of elasticity during extrusion.

A notable difference between the RRTM and Makerbot is reliability and ease of use for the operator. Whilst both had similar errors and limitations, the user experience with the Makerbot is more pleasant. The machine is more robust and reliable. The CAM software provides much less options for the user. This limits the user settings but the pre-sets seem well tested for the machine parameters and thus give are reliable experience. This along with a more graphical user interface and drag and drop functions makes the product a consumer product with a high consumer value. These factors are not intended to be emulated in the proof of concept stage but serve as selection criteria and guidelines for future development.

8.3 Interface

Technical target specifications for the print head, nozzle, sensors and actuators are that they are connected and handled by available ports on the controller board. The printer selected above has two circuit boards, a master and a slave, of the type Melzi (*Figure 15*).

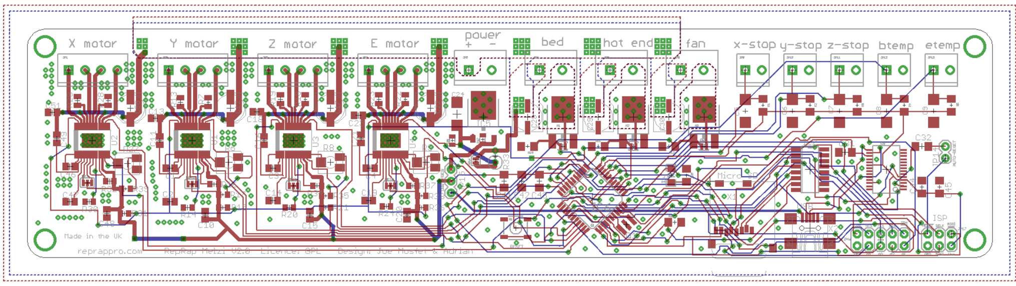

Figure 15 Melzi Circuit board (Reprap wiki, u.d.)

The Melzi circuit board allows for analogue sensor inputs. Outputs for a heater with 5 V and stepper motor control. The actuators available on this drive system are stepper motors and head control with pi control (*Figure 16*). Thus the process developed at this stage should be adjusted to the interface available and stepper motors are appropriate for controlled movement. Multiple stepper motors are available for multiple feed control due to the slave circuit board.

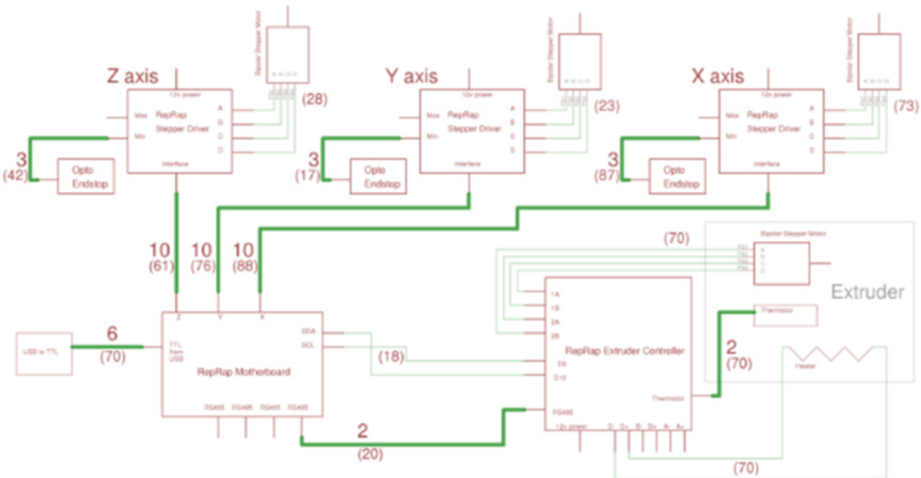

Figure 16 Stepper motor controller Melzi

The sensors used in the project are limited to sensors that can be introduced to the ports available on the Melzi circuit board (*Figure 17*).

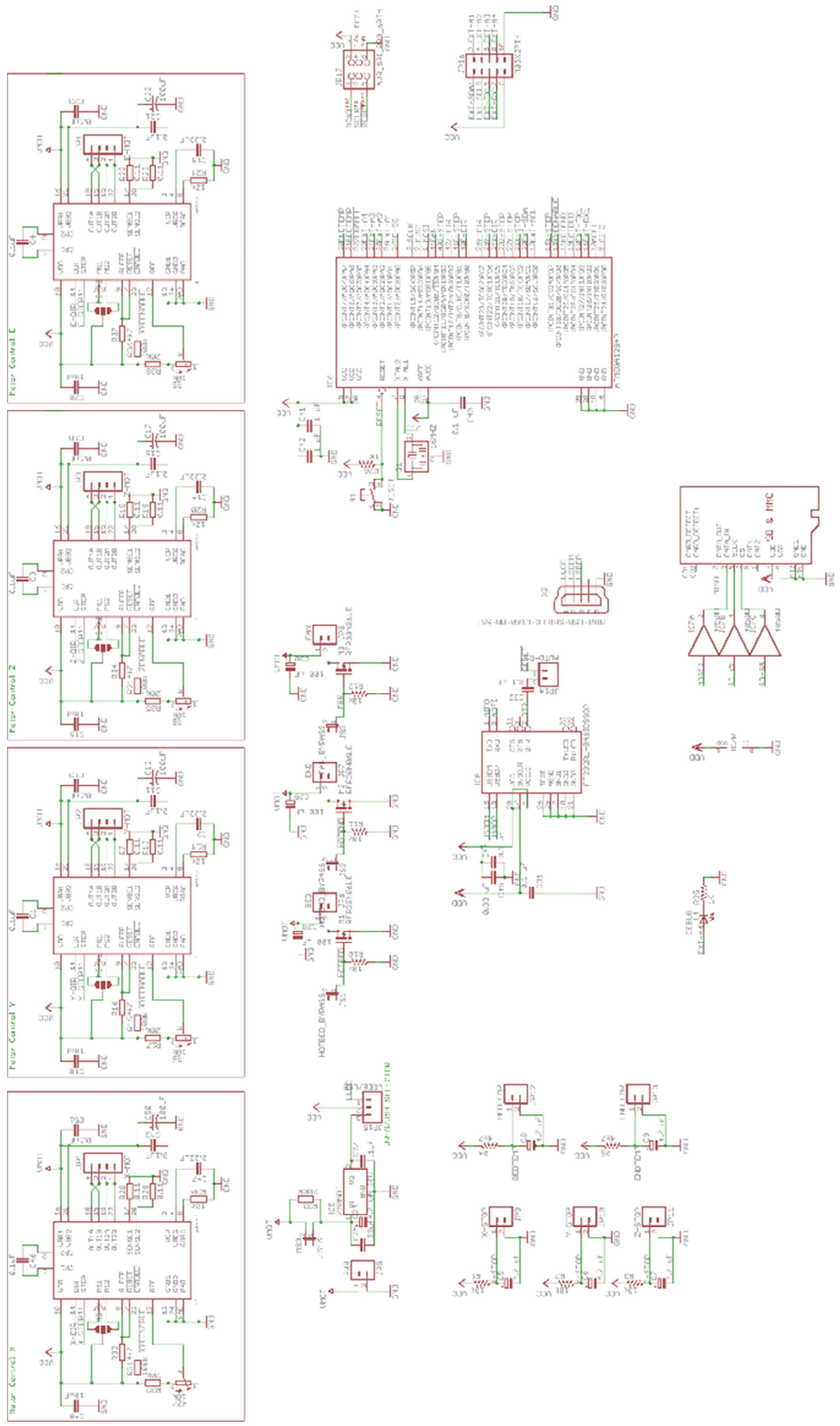

Figure 17 Component ports Melzi

A print head developed in this project should adapt to the hole-interface available on the x-carriage mount on the RepRap Mendel. The four holes are arranged in a rectangular shape with holes for M5 screws (*Figure 18* & *Figure 19*). Further mechanical specifications used for defining the interface are resent in Appendix E: RepRap Mendel Tricolour Specifications.

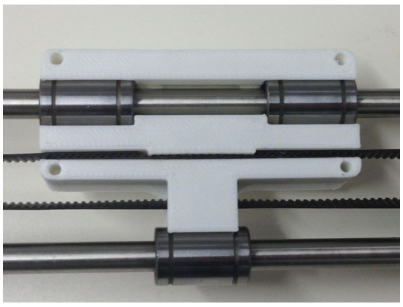

Figure 18 X-carriage mount (Reprap wiki, u.d.)

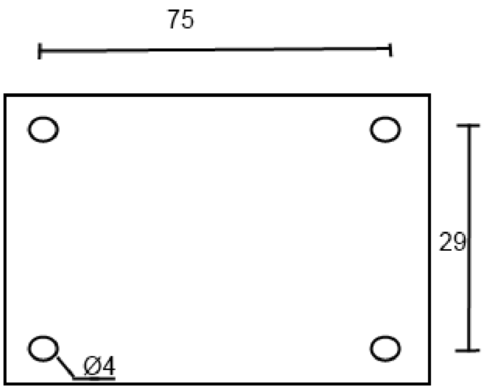

Figure 19 Hole interface RepRap Mendel

9 Concept generation

In the concept generation stage conceptual solutions are generated and described. First the problem is identified as to ensure focus is placed on the correct issues. A bottom up approach is used meaning that each separate state in the process is looked at separately for similar manufacturing processes. Then existing solutions externally and internally are observed (internally looking at existing low end 3D printers and externally looking at other manufacturing methods). Concepts are then generated and presented aided by the external and internal search.

9.1 Identifying the problem

The problem that the project aims to solve is how to create a low cost additive manufacturing process for rapid prototyping that allows for a selection of materials not present in the existing product. The focus is on finding a solution to rapid prototyping with composite or metal (alternatively metal composites that can be sintered). Desired material properties may increase physical properties (such as tensile strength, creep and ductility), conductive properties, heat resistive properties, manufacturing properties (such as warping) or magnetic properties. As the goal of this thesis is to reach a proof of concept with a platform that allows for further development, the concept generation focused on solving the problem of how to mix and orientate the composite materials and how to deliver them to the appropriate position. Furthermore any necessary post processing processes are described in association to the processes below.

The general approach used here is a bottom up approach. This entails identifying the steps of treatment of during the manufacturing processes

The steps are material selection, mixing process, liquefying mechanism, hardening mechanism, intermediary forms and post treatment mechanism (including removal of material) and can be seen in Figure 20 below. Not all solutions presented later in this chapter require each stage. For example UV curing of a liquid would not require a liquefying stage.

This allows for the individual concepts to be reviewed individually and easily replaced if proven ineffective. This is a method used for complex processes.

Figure 20 Material transport and treatment steps

9.1.1 Material

For the materials, the main problem is to determine suitable combinations of materials that may with work one or more solutions for a low end manufacturing process. This part of the project was deliberately widely defined including both composites and metals in order to detect as many solutions as possible.

9.1.2 Mixers

Mixing may be needed either in a pre-treatment step for solid compounds or as an active step in the additive manufacturing process. Here the purpose is to find mixing methods for both solids and liquids that can be integrated into the product or performed separately, if required.

9.1.3 Liquefying mechanism

In order to apply material in the additive manufacturing process it is easier if the material is not of a solid state. Depending on the material selected different methods may be used in order to liquefy or consolidate the material. The problem addressed here could be described as determining possible processes to transfer the materials into a state that allows it to adhere.

9.1.4 Hardening mechanisms

Hardening methods refer to methods used to solidify the print once material has been applied. The mechanism depends on the material and process used and may be passive (such as cooling in room temperature) or active (such as cooling with a fan).

9.1.5 Intermediary form

The problem of intermediary forms intends to identify possible intermediary forms that could be produced in order to make a material that could be delivered to an end user with a simple machine. That is to say if an advanced step is required in the manufacturing requiring expensive machinery (such as a large screw extruder) to suggest a form of material that could be delivered to the end used in which the advanced step is conducted separately in order to produce material that is easily supplied. This may also serve as a market advantage as it would allow for both sales of the product and continuous sales of material. Thus the intermediary forms allows for some innovation.

9.1.6 Feed system

The feed system is a mechanical device that in a controlled manner applies material in the additive process. Here suggestions are searched for both solid and liquid materials.

9.1.7 Post print treatment

Post treatment is common for 3D-printing. One desired goal (in general) in additive manufacturing is to create complex 3D objects in short time and thus low cost. If there is a large post treatment time needed for a print (such as mechanical treatment with sanding or other tools) this lowers the desirability of the method. It is of value to know what post treatment is possible and/or required for different materials (or in some cases manufacturing methods). The aim here is to determine possible post treatment methods that may be used in a concept in order to achieve an acceptable solution.

9.1.8 Process

Depending on the combination of matrix materials and reinforcement fibres, the mixing and forming process varies. The purpose here is to conclude the previous steps into possible processes that can be used to combine methods and build a roadmap that can aid in developing concept solutions. This step is not part of the external or internal search, but will be included under the internal search headline.

9.2 External search

Several RP and AM methods are described in the theory (Kumar & Kruth, 2009).
Existing solutions for additive manufacturing processes that can construct products using composite materials may be categorised according to their methodology used to solve the steps described in the chapter above. Some of these methods are:
SLS/SLM works well with MMC (for example is Fe-Cu composites). One of the materials is melted and binds the other fibre. SLS methods may also be used for PMC. SLS may also be used to create a composite with the fibres un-melted that allow for sintering after production. Complexities restricting this method is the fibre size limiting surface layer spread as explained in the theory. Complexity is also prevalent in the energy transfer from the laser to the material. The energy may both be used to overcome activation energy for adhesion of the material and to trigger chemical reactions that may propagate chemical reactions. (Kumar & Kruth, 2009)
As above the problem is divided into steps according to the process and external solutions from manufacturing methods are suggested.

9.2.1 Material

External search for materials for this project was performed looking mostly at methods for composite and metal manufacturing. Methods as MIM often use compositions of materials in order to produce.

Metal injection moulding inspires materials as wax/polymer blends and polymer/polymer blends to allow easy sequential extraction of the polymer to better the results of sintering.

Another consideration is the advancement in bio materials. This is a technology push that is widening the range of waxes including bio-waxes. Bio-waxes may allow for biodegradable materials. They may also provide non-toxic and user friendly materials.

From these technologies some suggestions of thermoplastics for matrix material in the compounds are:

- PLA
- ABS
- PE (several different types of PE such as HDPE and LLDPE)
- PET
- PP
- Water soluble polymers
- Paraffin based waxes
- Bio waxes

The fibre material selection is dependent on the desired properties of the process.

Some inspiration is taken from the MIM process regarding sinterable metals suggesting atomised (preferably gas atomised) metal powder. A range of sinterable metals are available including different types of stainless steels and many alloys allowing for selected material properties.

Other material inspiration is derived from the goals of this project and existing methods for composite material construction. Continuous fibres allow for interesting mechanical properties regarding extreme anisotropy such high tensile strength or directional thermal or electrical conduction. This suggests a large range of continuous fibres from complex polymers, metal fibres to simple sewing thread.

From this suggestions of fibres follows:

- Metal powder that may be sintered (gas atomised vs water atomised)
- Rough metal powder
- Filler material such as sawdust
- Copper wire (high electrical and heat conductivity)
- Sewing thread (cheap solution)
- Glass fibres
- Carbon fibres

9.2.2 Mixers

A wide range of existing mechanical mixers exist today. These include but are not limited to screw extrusion systems. Example of different screw extrusion systems are single screw, dual screw, z screw and boden screw. The mixing system may be separate system to the 3D printer or build in to the extruder. Mixing may also take place in two steps. Further description of the existing screws and how the components are used is found in the theory chapter 3.3 Mixer and Extruder.

9.2.3 Liquefying mechanism

A mechanism in order to lower the viscosity of the materials varies depending on the selected material. One method commonly used within MIM and IM (and FDM printing) is combining heat and pressure. Some materials such as photopolymers may already be liquefied at room temperature and not require heating. For added and improved lowering of the viscosity, additives to the polymer may be used. (These are not explored in detail in this project but are mentioned during the concept generation as they allow for future further improvement of the process.)

Other methods of applying energy to liquefy/adhere materials in existing manufacturing methods are:

- Electromagnetic (microwaves) transfer of energy described in chapter 3.9
- Sounds transfer of energy (as ultrasonic consolidation) described in chapter 3.8
- Lasers for sintering described in theory chapter 3.5.5
- Use of standing waves (magnetic, sound or other) described in chapter 3.7

For some photopolymers, specific wavelengths of light remove the side bonds and transform the solid molecule into a liquid. This may be useful for cleansing of the nozzle.

Water soluble polymers are as indicated by the name soluble in water. This is useful for removal of the material.

9.2.4 Hardening or consolidation mechanism

As with the previous paragraph, the hardening mechanism depends on the material being treated.

Room temperature will function as a hardening mechanism to set the thermoplastic material. However a controlled lowering of the temperature is often used as to improve the quality of the outcome (such as to decrease uneven cooling leading to deformities).

For photopolymers a controlled radiation of light of a specific wavelength functions as a hardening mechanism. This could be generated from one or multiple narrow or wide-angled light-emitting diodes placed somewhere on the 3D printer. This could also be achieved by larger UV lights lighting up the entire build. This may be done from the sides, from above or from the bottom of the build platform (which would need to be transparent).

9.2.5 Intermediary forms

Intermediary forms for manufacturing methods of metals and composites can be vast. For MIM a pre mixed material compound can be used. Metals can be created in rods or spools for additive processes (such as welding). Composite sheet material may be weaved in layers before assembled to a sheet. Pre mixed liquid composites may also be considered. No further detail is described here as for this section the main interest is of intermediary solutions for additive manufacturing and thus is continued upon in chapter 9.3.5.

9.2.6 Feed system

The feed system will vary depending on the material properties. The material used may be solid or liquid, rigid or flexible. It may have varying properties for different states during the feed process.

Existing solutions are pumps and syringes for fluids and a multitude of solutions for solids (this will be extended upon in the internal search).

9.2.7 Post print treatment

Some materials allow for post manufacturing treatments to improve the material properties or geometry. These include mechanical treatment (sanding, lathing, milling, cutting and so forth), vapour treatment (such as acetone on ABS), liquid solubility, UV treatment and sintering.

9.3 Internal Search

For the internal search in this project technologies from existing 3D printers are looked at. Extra focus is put upon the low cost solutions.
The concept generation first approached the modular base observing the possibilities and limitations of the materials, mixing, liquefying, curing, feed, delivery and breaking systems individually as in Table 4 below. This is an approach to describe the mechanical solutions for the separate modules of the process.

9.3.1 Material

The materials observed in this project are based on the deduction of similarities to other processes such as injection moulding, metal injection moulding and FDM printing as mentioned in the literature study. Initially the matrix material is discussed.

FDM printing suggest usage of amorphous single polymer thermoplastic material. PLA and ABS are common materials used. Amorphous materials have the advantage of even cooling and adhesion between layers at varying temperatures. The materials available for FDM are similar and may be derived from injection moulding.

3DP can print composites by dispensing liquid droplets of UV curable liquid in a pattern onto a powder base and curing layer by layer.
FDM composite printing has been researched to achieve enhanced material properties. ABS filled with 10% and 20% iron powder intended to improve mechanical properties resulting in lower Tensile strength and higher stress at break retrofitted to a Stratasys FDM3000 FDM machine (Nkzad, et al., 2007). The same equipment was adapted to produce Fused Deposition Modelling of metals (FDMm). Tests were conducted to further determine the adaptation of eutectic and non-eutectic materials (Mireles, et al., 2012).

9.3.2 Mixers

FDM printers today use spools of material that are extruded to the correct diameter. These are performed by external industrial extruders in advance and the material is delivered. A mixing step is included in the extrusion for additives and colouration of the material.

9.3.3 Liquefying mechanism

For existing FDM printers heat and pressure from the nozzle of the printer is used to liquefy the material. For STL printers the material used is in a liquid state when applied (liquid UV resin). SLS uses heat as in FDM but applied from a laser to liquefy or sinter the materials. Other 3D printing methods apply a separate liquid adherent such as glue or water (for plaster 3D printing) in order to adhere the materials together.

9.3.4 Hardening or consolidation mechanism

Hardening methods used in 3D printing methods today consist of cooling (passive and active) such as in FDM, UV exposure such as with STL and separate sintering process such as some SLS that sinter a binder material in the additive manufacturing machine and then sinter the part in a separate sintering machine.

9.3.5 Intermediary forms

The most common forms used within FDM printing is filament on a spool with a diameter of roughly Ø1.75 mm.

Another existing model is that used in Sintermask’s machine Fabbster (Sintermask GmbH, 2009) (AB, 2013). There toothed racks are linked together and fed into the extruder. The toothed racks allow for more control of the extrusion rate. Variations of this principle could include solid blocks or blocks that have other shapes to improve functions such as control of extrusion rate or geometric adaptation for better extrusion. These parts could be manufactured using methods similar to MIM. This principle allows for solutions to cases where the high fill rate of metal creates stiff materials which aren’t suitable for filament or that require other dimensional characteristics for their intermediary phases. An intermediate form for the material is also a market opportunity. Machines can be produced and sold for a low price and the material for the machines allows for profit.

These concepts are presented in *Figure 21* below.

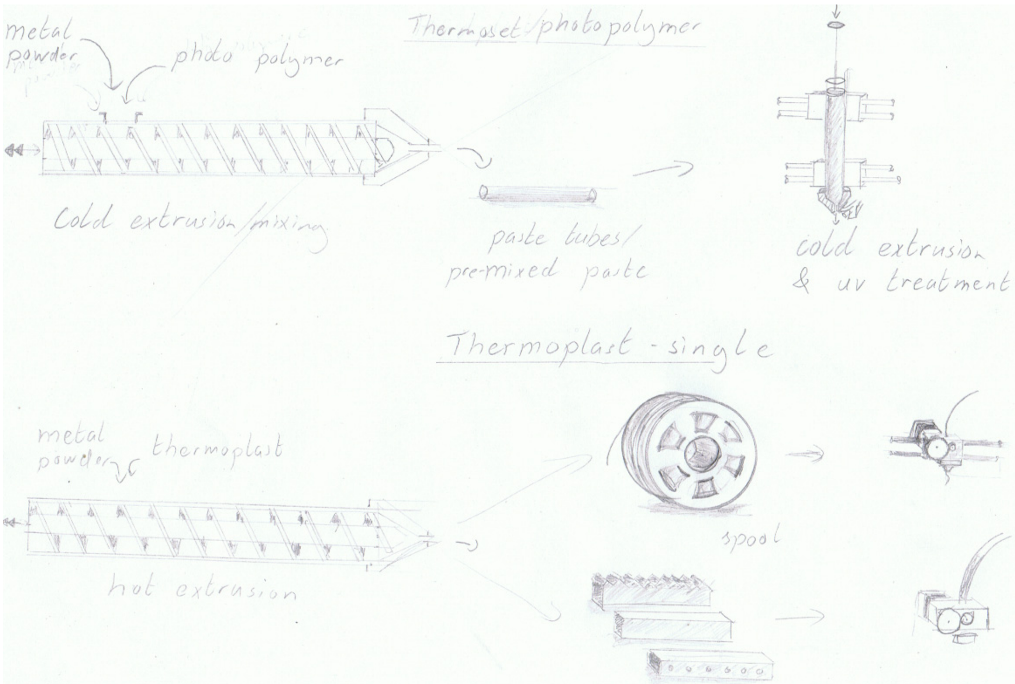

Figure 21 Possible intermediate states

9.3.6 Feed system

In most FDM machines a polymer is fed as a solid form (for example a filament on a spool or as linking toothed racks as in the case of Sintermask's machine Fabbster (AB, 2013) into an extruder that grips the filament or rack and forces it through a heated nozzle.

For liquid systems the material is often applied in a liquid bath that is topped off after each layer. For SLS and other powder based materials new material is applied by a rising bed and material is rolled out onto the build surface witch is previously lowered a layer height.

One common issue is whether to have a centralised feed on the nozzle only, to also have a reservoir or to have a decentralised reservoir with a constant feed. Another issue is the placement of the feed drivers. These may have a significant weight and their placement will have an impact on the result. Whether they are placed on the nozzle carriage or decentralised. These are extra factors to take into consideration when selecting the system.

9.3.7 Post print treatment

Same as in chapter 9.2.7.

9.3.8 Process

A hierarchy of the possible processes is described below (*Figure 22*). The figure is used to map required steps in association with the associated fibres and process. The premade filament describes a process in which the goal is to develop an extrusion process that produces a filament that may be used directly in an existing 3D printer and has integrated fibres. The mixing print process refers to the concept of an extruder solution that mixes the fibres during the printing process.

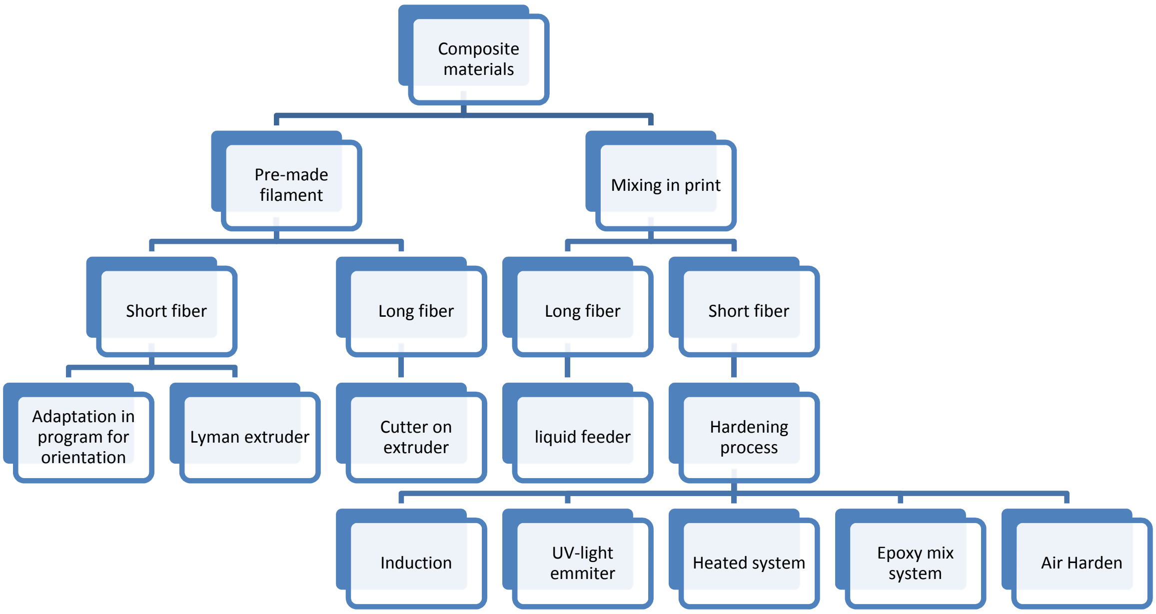

Figure 22 Composite construction family tree

9.4 Combining external and internal components

The steps observed externally and internally were then combined to form a selection of possible concepts.

Table 4 Modular concept generation

Concept development generation modular process

Step	Matrix container	Fibre container	Feed system	Mixing system	Viscous system	stop/cut/break system	Delivery system (nozzle)	Hardening system	Post hardening system (optional)
		Spool	belt extruder	open tubes	heat (electro resistance)	single blade	sharp nozzle	cooling fan	UV light treatment
	beaker	Bricks	food extruder	spray application	liquid from start	dual blade	open tube	UV-light	Sintering oven
	syringe	Tubes filled	geared wheel	brushed mix	magnetism	squeeze end	needle	room temperature cooling	
	open top container		Screw	mixing tube	Ultra-sonic sound	none	blunt nozzle		
			Gravity	mixing screw	micro-waves	external tool			
			post extrusion pull (ex. spool)		pressure				

The specific modules may be combined to create concept solutions. The defining factor of the concept is the liquidation, adhesion and blending systems. Adhesion may be done using electrostatic properties or by inducing heat by contact, in order to reach a melt zone, which then will adhere when cooling or by selecting materials that have liquid properties and may be cured by external an stimulant.

For the concept generation material curing/liquefying and the fibres are the predominant factors. An overview of possible concept combinations is presented in Table 5 below. The curing method is described in the top and fibre is described in the coulomb to the left.

Table 5 Overview of possible fibre and curing/liquefying combinations

Fibre\Curing	UV	Thermal	Epoxy	US	Laser
Particle					
Short					
Long					
Continuous					

Further variations in the concept generation are considered on if the material is premixed or mixed during printing. Also if the print uses a surface for selected curing/hardening as with SLS or SL or if the material is fed through a mounted dispenser that moves in relation to the build platform like with the FDM prints. 3DP is a combination but will be categorised as a layered bed construction.

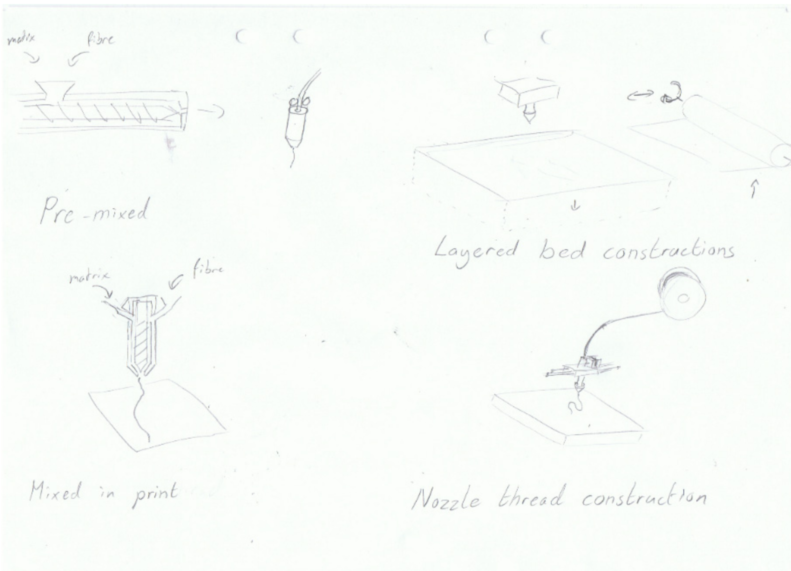

Figure 23 Printing techniques. Upper left pre-mixed, lower left mixed in print, upper right Layered bed & lower right nozzle thread construction.

9.5 Generated concept description

Concepts were generated using combinations of the process steps described above. Some of the concepts are assumed to work with composites, some with metals and some potentially with both. For an overview a table of this is included in the end of this chapter.

The concepts were categorised as follows:

1. UV Curable liquid dispenser premixed with powder
2. Curable liquid with powder mixed in dispenser
3. UV Curable liquid dispenser coating continuous fibre
4. Continuous fibre coated with thermally liquefied polymer
5. Ocular Radiation sintered powder
6. Light radiated melting binder material
7. Controlled microwave sintering
8. Ultrasonic compounding
9. Pre-mixed thermoplastic PMC FDM using heat
10. Thermoplastic PMC mixed with fibre in dispenser curing/liquefying with heat
11. Electric resistance head
12. Embedding continuous fibres or wires with parallel nozzle in FDM

Concept 1 UV Curable liquid dispenser premixed with powder

The first concept uses a liquid polymer blend that is curable using Ultra-violet light mixed with a powder reinforcement fibre. This is pre mixed and added either to a container (like a syringe) mounted on the print head or fed from a filled tank. The mixture is fed through a nozzle and a liquid stream is fed onto a surface or layer of the printing part. The liquid is cured using directed Ultra-violet light emitting diodes as it is printed. There may also be further light sources directed towards the build surface.

This concept is illustrated schematically graphically by the image (*Figure 24*) below. The beaker represents the liquid polymer, the powder represents the powder reinforcement. The light bulb represents the curing process by UV.

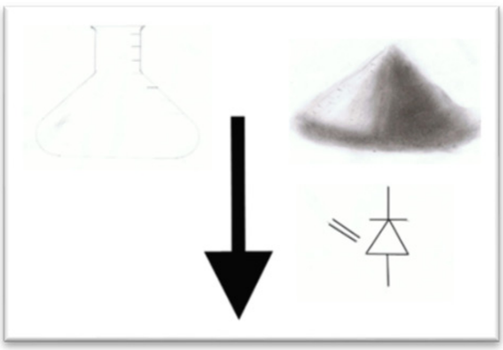

Figure 24 Concept 1 illustration

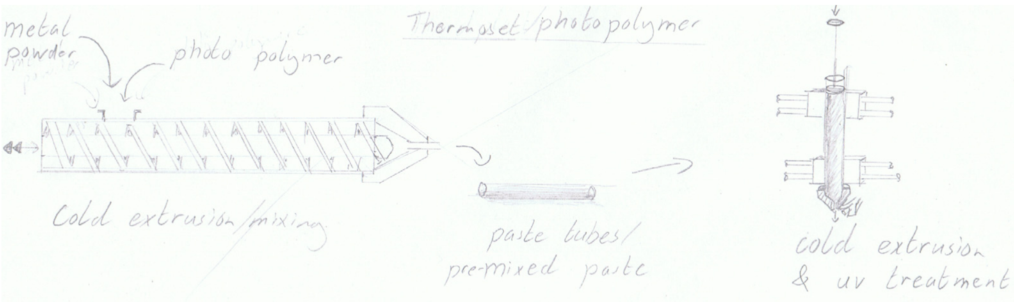

Figure 25 First concept schematic sketch

Concept 2 Curable liquid with powder mixed in dispenser

The second concept is similar to the first concept. The difference being in the supply of matrix and fibre material added separately to the print head. The two are then mixed in the print head and the mixing mechanics function as a feed force. An illustration is found in the image below where the syringe on the left represents a feed system for the UV curable polymer. The container on the right represents a container for the matrix material and the screw in the middle is intended as a generic representation of a mixer.

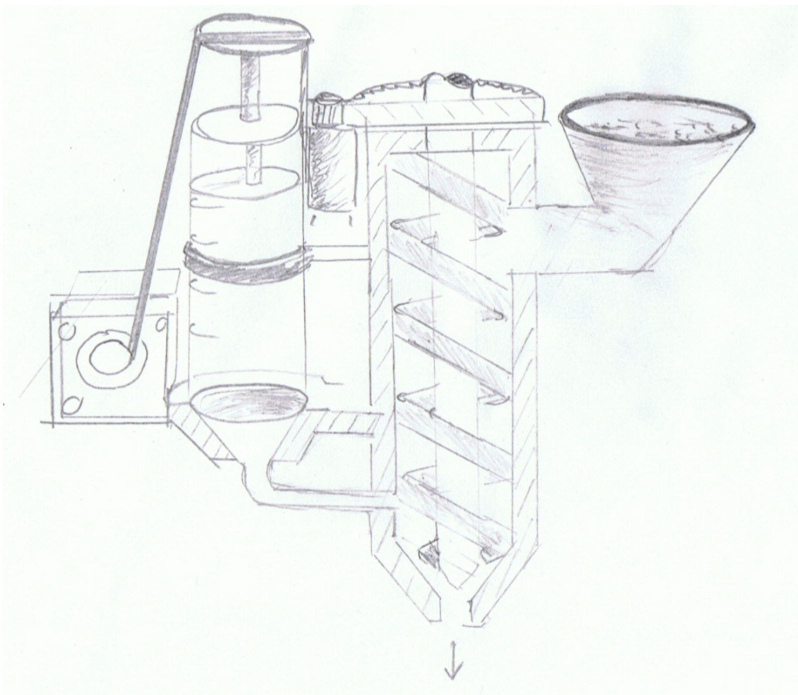

Figure 26 Second concept mixing fibre and polymer separately in print head.

Concept 3 UV Curable liquid dispenser coating continuous fibre

The concept regards coating a continuous fibre with a curable matrix material. This is then cut when the nozzle enters fast movement. The matrix material is cured using Ultra-violet light. An illustration of this process is found in *Figure 27* and *Figure 28* below.

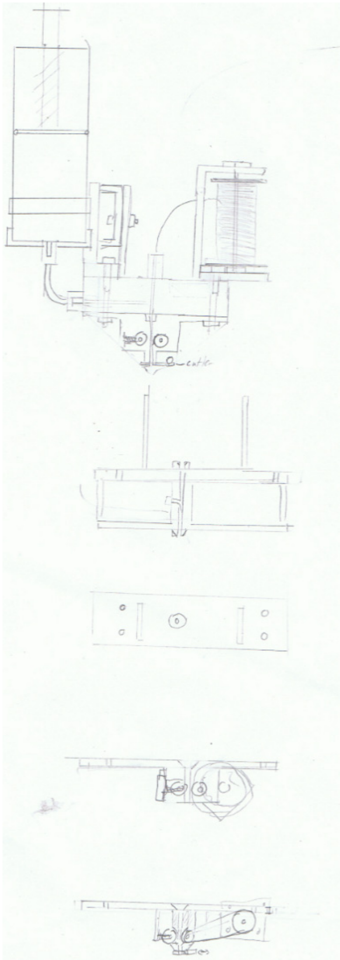

Figure 27 (Above left) Sketch of continuous fibre coating print head

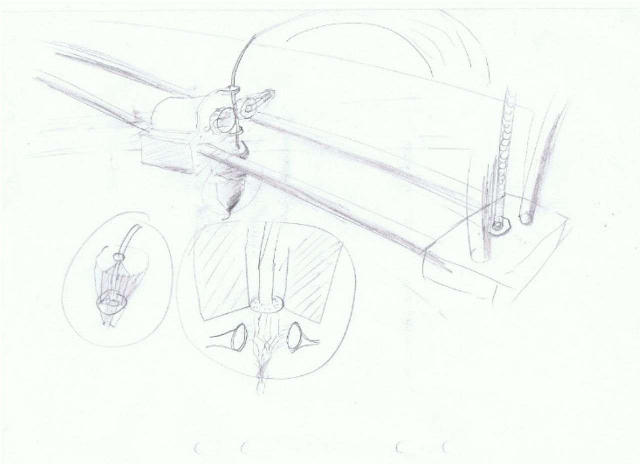

Figure 28 (Above right) Concept sketch coating continuous fibres with curable polymer

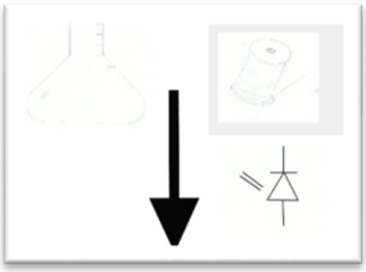

Figure 29 Concept 3 illustration, curing of liquid matrix with spool of fibre

Concept 4 Continuous fibre coated with thermally liquefied polymer.

The fourth concept is similar to the second concept, in that a thread is coated with a liquefied polymer coating. The material is liquefied using an alternative method. For example heat, then cured by cooling. Cooling may occur by active or passive cooling. Active cooling could be by directing a cool air flow.

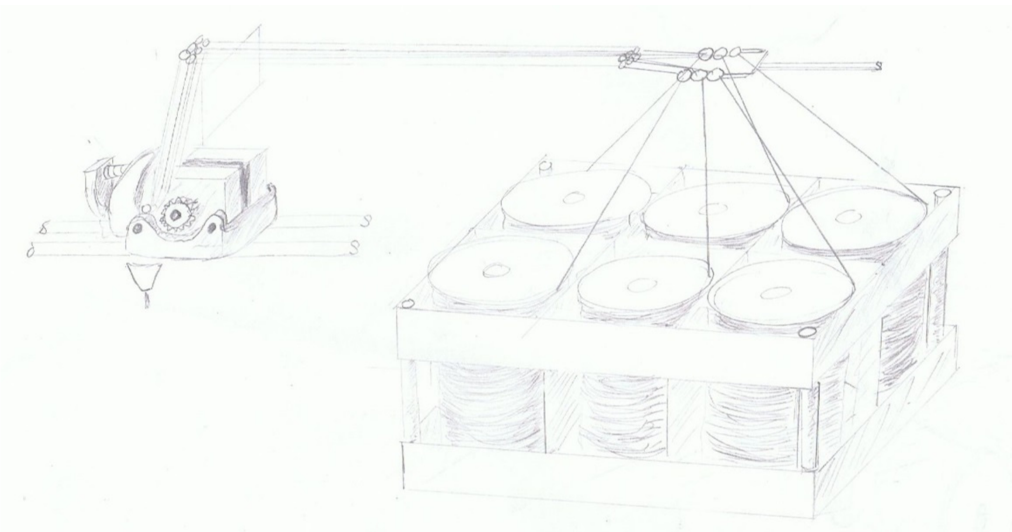

Figure 30 Coated continuous fibre with thermally treated polymer

Concept 5 Ocular Radiation sintered powder

The fifth concept uses radiated light to sinter material powder to adhere particles together and form a part. This concept is based on the direct SLS method and suggests finding a particle solution for reducing the costs for this expensive method. Limitations being restrictions due to patents and cost of high power lasers required for sintering.

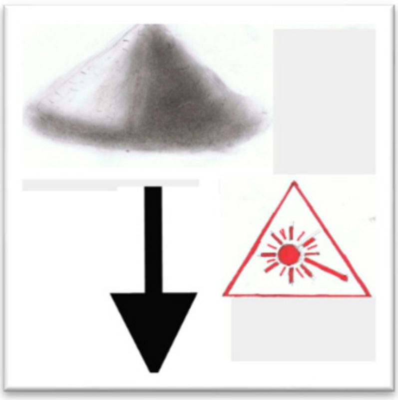

Figure 31 conceptual overview of fifth concept

Concept 6 Light radiated melting binder material

The concept radiates light onto a compound such as to heat the matrix material selectively and create adhesion. This solution only sinters the binding material and not the fibre material. This concept may be followed by a post print treatment to sinter or otherwise treat the fibre material. This method is as above an existing method and limited by requiring a high powered laser, and in when desired solid metal parts, a post-print sintering process. As only the binder material is heated for adherence the required energy transfer from the ocular radiation emitter source is lower than with concept Ocular Radiation sintered powder. Advantages with this concept is that it can both produce composite parts and parts that can be sintered post print for fully metal parts. Limitations are as with the current SLS methods in regards to large fibre and fibre orientation.

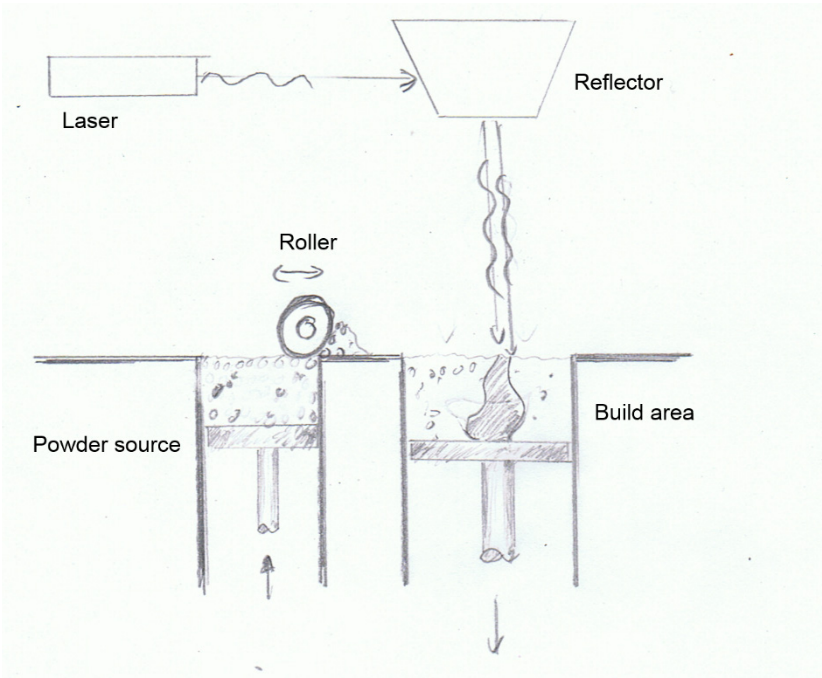

Figure 32 Concept sketch SLS method

Concept 7 Controlled microwave sintering.

The seventh concept uses microwave emission from a singular or multiple microwave emitters using standing waves. The waves transport energy to fuse or sinter particles. This treatment may both be applied to a single, dual, three or four dimensional approach of conduct. By fusing a material flow from a nozzle, a two dimensional cross section on a surface, a three dimensional construction on a volume of material or a multi-dimensional approach using varied time and wavelength intensity. Potential advantages with this method is a highly controlled process. A process that may work directly in three dimensions increasing manufacturing rate. A process that can continuously be measured during run-time in order to implement closed loop control. Potentially a volume may be filled with a material and the process could conduct heat to the volume of material in multiple places at once, including moving in a non-planar manor or even non continuous path. Thus not limiting to the construction technique used today in all previously mentioned patterns. That is to say that instead of creating one cross section at a time and then proceeding to the next cross section, this method may create adhesion throughout the material in a point selected manor without requiring continuous transfer between working area. This could potentially address the large inhomogeneous properties between print direction and layer to layer existing in most additive manufacturing methods. Another advantage with this method of applying energy in a non continuous path is that residual heat build-up may be decreased locally and potentially decrease defects due to uneven cooling of the part. Limitations with this method are primarily material, control and development. Material limitations will relate to the materials uptake and interference of the emitted microwaves. Control is vital for this system and it is a very complex control problem. The method is non-existent and could require a lot of development.

Concept 8 Ultrasonic compounding

The eighth concept uses one or multiple ultrasonic emitters. The ultrasonic emitters create a standing wave that induces energy upon the material. The energy creates a solidification of the material. This concept has similar potential advantages to the method described above. The main differences may be in the material requirements. For this method the material must transport ultrasonic energy in a way which can be controlled, suggesting that uniform characteristics may be suitable. One solution for this may be to have the material submerged in a liquid with dominating properties that is later removed.

Concept 9 Pre-mixed thermoplastic PMC FDM using heat

Granules of matrix material and fibres are heated in a container and mixed. The material is then extruded to a filament, injection moulded into a loadable brick or formed by another method to an easy to handle form. The filament or brick may then be extruded using an adapted 3D print head. The material has thus fibres mixed into the material matrix. This method is the same method used in the literature study presented in the theory. Limitations they described included stiffness in the material due to the fibre re-enforcement. So as to allow for high fill factors filament may not be an option and thus bricks may be used instead. These bricks could be interlinked and could also be formed in a shape that makes even feed easier. An example is the shape of rack. An illustration of this process including a few examples of shapes of bricks is presented in the *Figure 33* below.

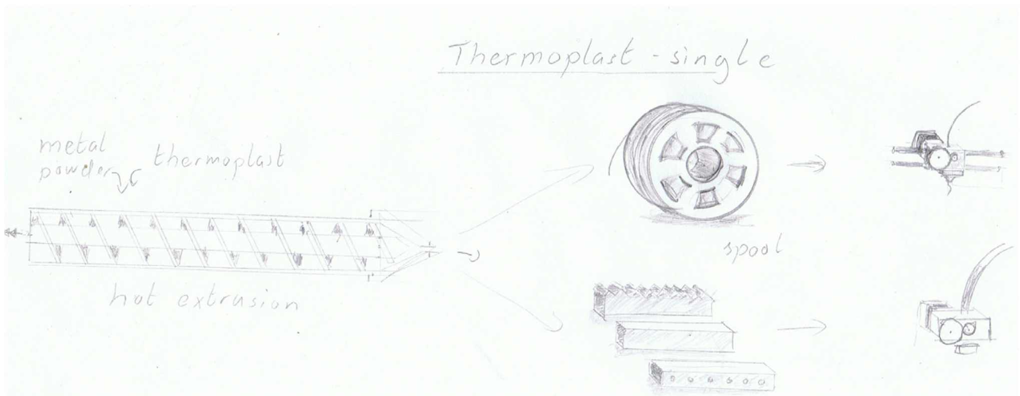

Figure 33 Conceptual sketch. Pre mixed thermoplastic solution

Concept 10 Thermoplastic PMC mixed with fibre in dispenser curing/liquefying with heat

The tenth concept describes a method mixing thermoplastics with a fibre in a dispenser mounted on the printer carriage. The liquefying/curing factors are heat and a mixing mechanism is required. Matrix material and the fibres may be added separately and mixed in a controlled manor in the mixing chamber. The matrix material and the fibre may also be pre mixed in granules and added as a single material to the heating/mixing chamber. An illustration of this process is shown in *Figure 34* to the right. The image is of a solution for the printing material to be added separately allowing for on the fly control of mixing ration. By only using one intake the heat could use the premixed granules. It may prove that the premixed granules place a lesser demand on the mixing process in the nozzle and thus have an advantage over the on the fly solution.

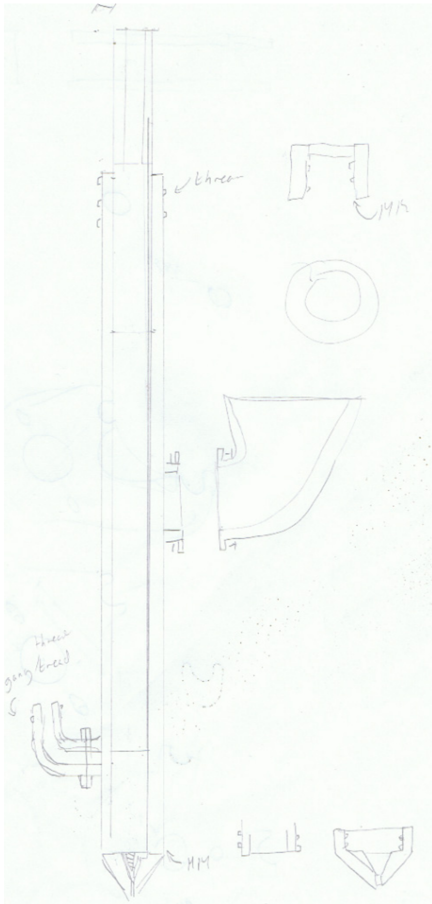

Figure 34 Sketch of mount that allows for mixture of two powder materials in the print head.

Concept 11 Electric resistance head

This concept is an approach to additive manufacturing for metal FDM. By supplying a specially designed head with a spool of metal wire and heating it, deposition of the material is achieved. The method of heating the thread in this example is by exposing the metal thread to a current which heats the material through electric resistivity. Ordinary FDM print heads that heat the nozzle using electric resistivity in a heating element which transfers the heat through conduction first to the nozzle, then to the material. In contrast to that this concept creates the heat directly in the material used for printing. The advantages with the method are many including direct control of heating energy and temperature by direct application of energy and measurement in electrical flow. It also reduces waist energy as the energy is directly transferred to the material, generating less heat. In terms of control engineering this solution transforms the heating process from a three state system to a single state system. The heated material is also in the process of leaving the system and thus less heat exposure is subdued to the print head. These factors allow for much better control of temperature and also allow greater temperature ranges to be achieved with limited power. The material is not fully liquid and can be applied as with plastic FDM. According to the literature studies presented in the theory non-eutectic alloys display this characteristic.

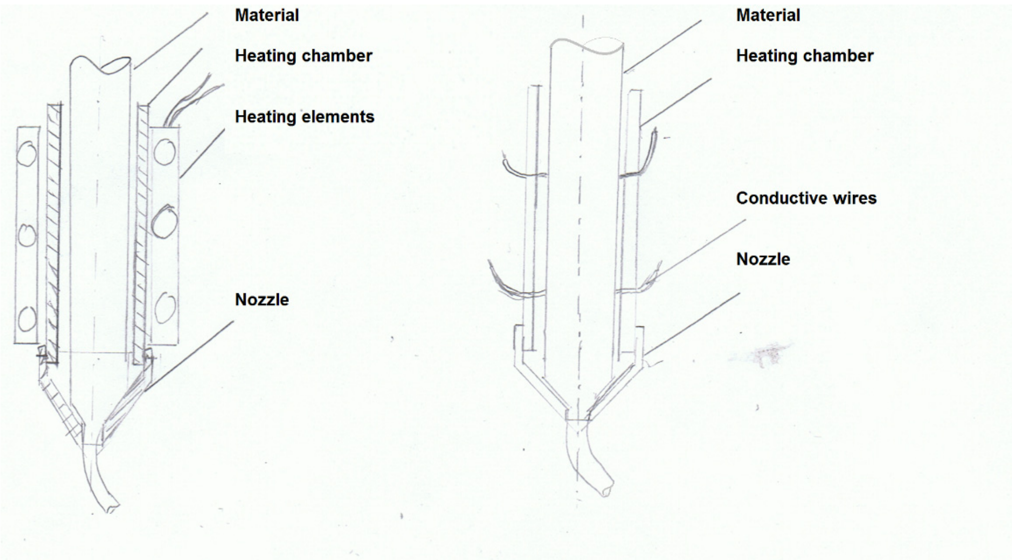

Figure 35 Concept heating nozzle, FDM on left, Electric Resistive Head on the right

Concept 12 Embedding continuous fibres or wires with parallel nozzle in FDM

A simplistic design that uses an existing FDM technology parallel with a simple thread feeder that embeds the continuous fibre by applying while the matrix material is fluid. This provides continuous fibres within a plane. The fibres could have multiple purposes including conduction of heat or increase in tensile strength. An illustration of this concept is shown in *Figure 36* below. For this to work a solution for the cutting of the continuous fibre is required.

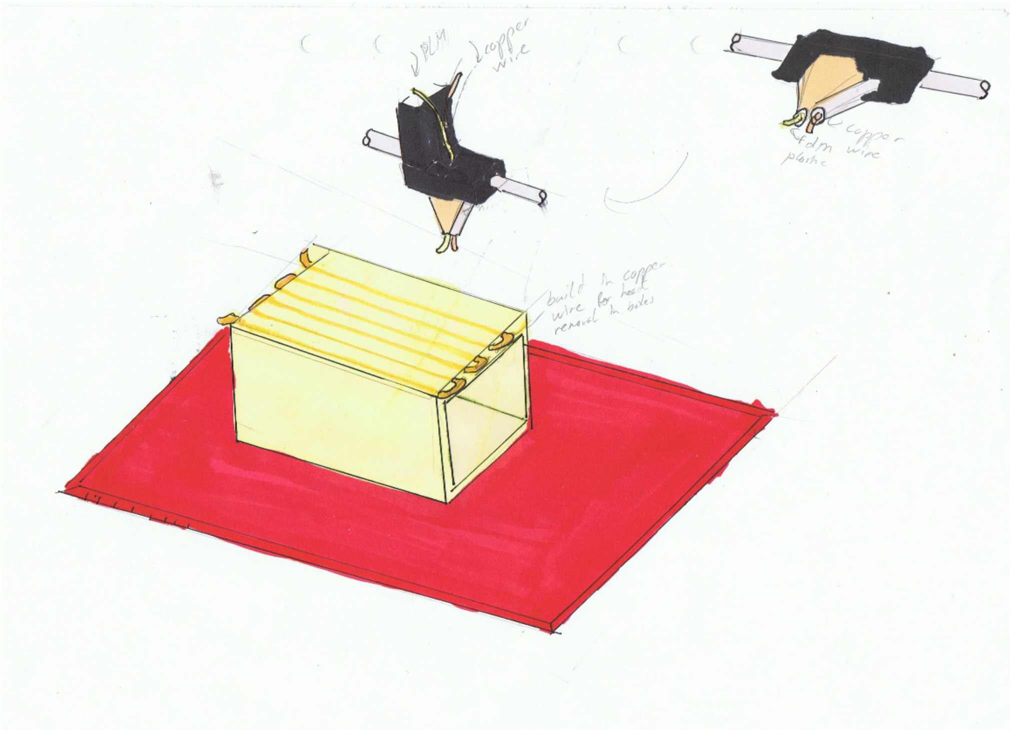

Figure 36 concept of embedded continuous thread with thermoplastic deposition

9.6 Material properties

As this project has an open and somewhat ambiguous target of material (composites and/or metals) an overview of the concepts and what combination of composites or metals they are assumed to work with in Table 6 below. “Maybe” is written where it is inconclusive if it would work or if it may be inappropriate (for example burnout of thermosets). “Yes” in post suggest that a further step would be required in order to achieve the desired result.

Table 6 Concept Material combinations

Nr	Name	Brief description	Metal	Cont reinfocem.	Particle reinforcem.
1	PUVD	Premixed UV Curable liquid dispenser	Maybe	No	Yes
2	MUVD	Mixing UV liquid dispenser	Maybe	No	Yes
3	CFCUVD	Continuous fibre coating UV Curable liquid dispenser	Maybe	Yes	No

4	CFCTD	Continuous fibre coating thermoplastic dispenser	Yes	Yes	No
5	ORS/SLS	Ocular Radiation sintered powder	Yes	No	Yes
6	LRBM/SLS	Light radiated melting binder material	Yes, in post.	No	Yes
7	CMS	Controlled microwave sintering	Yes	Maybe	Yes
8	USC	Ultrasonic compounding	Yes	No	Yes
9	PTD	Pre-mixed heated thermoplastic PMC dispenser	Yes	No	Yes
10	MHTD	Mixing Heating Thermoplastic PMC dispenser	Yes	No	Yes
11	ERD	Electric resistance dispenser	Yes	No	No
12	ECP-FDM	Embedding continuous fibres or wires with parallel nozzle in FDM	Yes	Yes	No

10 Concept selection and detailed design

This is a two-step selection process. The concepts described above are first screened in order to define the solutions that fulfil the list of features in generated to aid in eliminating less appropriate solutions. These features are set by the framework of this project. The selection features are the following:

- Too high temperatures for home use. Temperatures beyond ca 250°C
- Expensive mandatory components. Example high energy lasers. Price range limit for entire printer set at 20'000 SEK
- Advanced control, beyond anything testable in proof of concept for this study
- Unsuitable for novice user, dangerous equipment or materials
- Unexplored technology. Unlikeliness to work. Unexplored manufacturing technologies beyond with too many unforeseeable difficulties

The remaining concepts are categorised and ranked according to the target specifications (see chapter 7).
The concept most appropriate for the criteria and limitations of this study is chosen for further study in the following headlines.

10.1 Concept selection

Initially all the concepts are observed and screened. This is done in relation to the target specifications. The entire process chains are screened as well as single steps and options. Concept screening serves to remove conceptual methods which do not fulfil the requirements of their task.

<u>Process screening</u>
The processes screened are described briefly in the table below. They are screened in their ordinance to perform the tasks described in the process section of the customer needs and target specifications.

Table 7 Concept list with description

Number	Name	Brief description
1	PUVD	Premixed UV Curable liquid dispenser
2	MUVD	Mixing UV liquid dispenser
3	CFCUVD	Continuous fibre coating UV Curable liquid dispenser
4	CFCTD	Continuous fibre coating thermoplastic dispenser
5	ORS/SLS	Ocular Radiation sintered powder
6	LRBM/SLS	Light radiated melting binder material
7	CMS	Controlled microwave sintering
8	USC	Ultrasonic compounding
9	PTD	Pre-mixed heated thermoplastic PMC dispenser
10	MHTD	Mixing Heating Thermoplastic PMC dispenser
11	ERD	Electric resistance dispenser
12	ECP-FDM	Embedding continuous fibres or wires with parallel nozzle in FDM

In

Table 8 (below) the screening process is shown. X represents the process fails to fulfil the noted criteria. The criteria that are coloured red are screened out and the remaining concepts are coloured green.

Table 8 Concept screening

Process		Too high temperat-ures	Expensive mandatory component	Advan-ced control	Unsuitable for novice user	Unexplored technology
1	PUVD					
2	MUVD				x	
3	CFCUVD					x
4	CFCTD					x
5	ORS/SLS		x			
6	LRBM/SLS		x			
7	CMS			x		x
8	USC			x		x
9	PTD					
10	MHTD		x			
11	ERD					
12	ECP-FDM					

The four concepts being compared in the concept scoring are the following:

- mixing a UV curable liquid with powdered fibre material
- extrusion and curing with UV compared to pre mixing and curing a feedstock of thermoplastics and powdered fibre material to a material that may be fed and heated for extrusion and then allows for later sintering
- electric resistance heated dispenser
- or the embedding of continuous fibres within nozzle

(see Table 9 Screened concepts).
The remaining concepts presented in Table 9 Screened concepts, are compared in their performance according to the target specifications. The scoring is an adaptation of the method of concept scoring from the product design and development process (Ulrich & Eppinger, 2008) and is presented in Table 10. At this stage contact was taken with suppliers of material and equipment in order to set up a communication and to determine price and properties. This communication proved to be the decisive factor in the final selection.

Table 9 Screened concepts

Number	Name	Brief description
1	PUVD	Premixed UV Curable liquid dispenser
9	PDT	Pre-mixed heated thermoplastic PMC dispenser
11	ERD	Electric resistance dispenser
12	ECP-FDM	Embedding continuous fibres or wires with parallel nozzle in FDM

Table 10 Concept scoring

Criteria	Weight	1	9	11	12
Printing speed	2	-	+	+	+
Solidifying/Curing rate	2	-	-	-	-
Matrix solid stiffness	3	-	+	+	+
Material ductility	3	-	+	+	+
Matrix solid UV sensitivity	1	-	0	+	0
Cost for raw material	2	-	+	-	+
Cost for material treatment	2	+	-	-	-
Cost for components	5	+	+	-	0
Cost for test equipment	5	+	---	0	0
Warp	4	0	0	+	+
Minimum Layer height	4	+	-	0	0
Resolution/nozzle diameter	4	+	-	-	-
Wear of equipment	2	0	-	-	0
Simplicity for end user	5	+	+	-	-
Switching to normal material	1	+	-	-	+
Reliability	5	0	-	0	0
Control of mix ratio	5	-	-	-	+
Distribution of mix	5	+	0	-	+
Sinterability	4	-	++	+	+
Start-up time for print	5	+	-	+	-
MMP ability	5	+	+	-	+
Sum		19	-10	-16	16

10.2 Selected concept

The selected concept of that of the premixed UV curable photopolymer matric. A premixed composition of material is loaded to a specialised rapid prototyping machine. The material is fed forward through a nozzle and applied to a surface. Curing is done by subjecting the liquid flow to beam of light from a UV-light source. The thread of material leaving the nozzle is not entirely cured and will thus adhere to the next layer applied. Every pass of the print head will further expose the previously expelled material to UV and thus cure it further. Multiple dispensers may be attached to one print heat so as to allow for control of locally varying material properties. For example a dispenser with a metallic-polymer compound and a dispenser with a polymer blend may both be mounted on a print head to allow for objects to be built with mixtures of areas with distinct properties. *Figure 37* below shows single material proof of concept design mounted as on a printer.

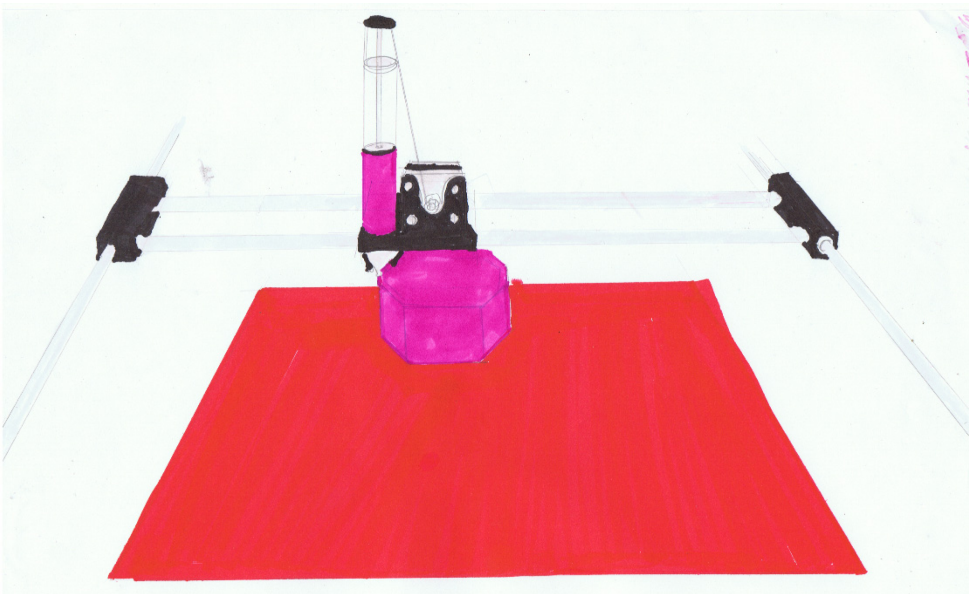

Figure 37 Selected Concept proof of concept of UV curable pre-mixed compound

10.3 Technical review: advanced material and components

In this part the components used for manufacturing and testing of the prototype are reviewed in more detail.

10.3.1 Technical review

A fibre-reinforced photopolymer blend required for this solution must have a low viscosity as to allow for feed with low energy buffers. It must also be cured before flowing out and loosing form integrity during print.

10.3.2 Advanced Materials

10.3.2.1 Liquid Polymer

For testing a UV-curable liquid polymer is required. 1 litre of Clear Resin was ordered from Formlabs (Anon., u.d.), sold as the consumption material for a commercial consumer desktop Formlabs printer. The liquid was selected as it is a commercial product that may be bought in small volumes and is delivered to most countries in the world. The liquid is curable at a wavelength of 405nm according to Formlabs' customer service. The ordered liquid was delayed and not delivered during the time conduct of the report.

In replacement a UV-curable liquid is used. The liquid used excess is material for a 3D systems stereolithography machines VFlash. The contents of the liquid is found in Appendix C.

10.3.2.2 Silica gel

Market research indicated that Silica gel may be a good component in liquid-string curing. The proposed effects of applying silica gel to the polymer blend results in an increased surface tension in the string thus decreasing the viscosity once extruded whilst not negatively effecting the flow properties. This was not applied during testing but supports further investigation.

10.3.2.3 Reinforcement material

Multiple fibre materials were described in the theory and concept generation. Amongst them gas atomised stainless steel particles presented challenges in wear of equipment and are thus selected for this project. The particles used are gas atomised micro melt filtered to an upper size limit of 500 micro meters in diameter. The coarse powder may be sieved to produce a finer powder but for this testing a coarser powder provides a more rigorous test for the testing equipment.

10.3.3 Components

The components required for this solution are primarily those required for flow and feed control and those required for curing. Curing is performed using circuits of UV-LEDs in series with resistors connected to the main circuit board ports for heating. These have a very low power compared to the power requirements for the heating elements used in the melzi standard configuration. At the same voltage (5V) a current is supplied. For the feed system a syringe is used. This is fed using a belt-drive connected to a stepper motor for feed and a mount which holds the stepper motor and syringe in place on the moving carriage.

10.3.3.1 UV-LED

For the curing UV diodes with appropriate wavelengths are required. For the proof of concept test liquid UV-light emitting diodes with the wavelength of 405 nm are used. The power rating of the LED used for curing during testing is 1 mW. The circuit is set up according to *Figure 38*. Atmega 88 microcontroller is used to set the curing time material is subjected to.

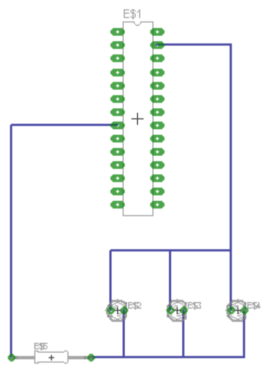

Figure 38 Circuit for LED connection with 100 ohm resistor

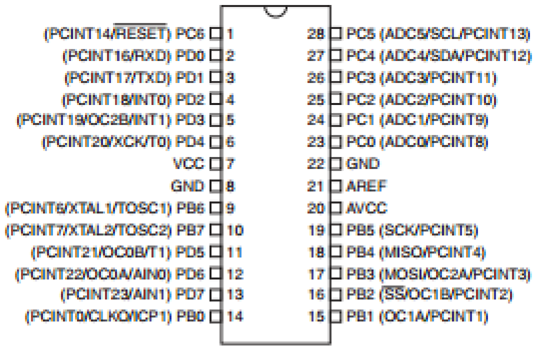

Figure 39 Atmega 88 pin configuration

10.3.4 LED power test

A thin layer (ca 1 mm measured by calliper) of UV curable polymer blend was manually expelled from the syringe on a thin aluminium foil. The polymer was then cured using a UV LED directed at the thread for a selected period of time. This process was repeated with different time periods, multiple diodes and with different concentration of polymer and fibre material ratios. The AVR is controlled from a computer using an optocople circuit for galvanic insulation and inverter connected to a serial port.

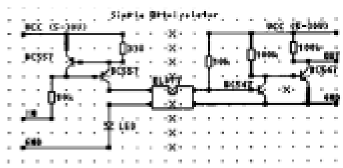

Figure 40 optocple Circuit

A short program was written in java in order to allow transfer of code to control testing. The user interface for the program is displayed in *Figure 41* below.

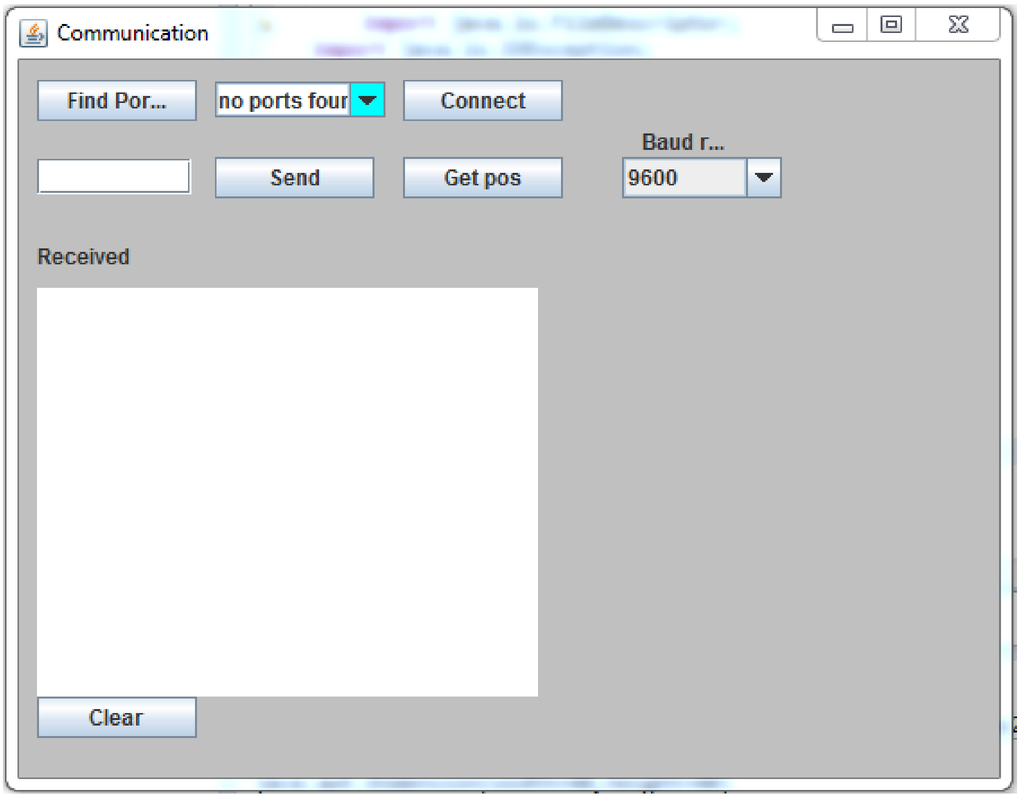

Figure 41 Control program for UV-Led test

10.3.4.1 Feed system

The feed system uses a syringe. The dimensions of the syringe are illustrated in the *Figure 42* below. Using a syringe allows for a small portion of ready mixed material to be loaded to the printer. The syringe is mounted to a mount that also holds the feed motor. The mount is attached to the carriage. The feed motor used is a stepper motor. The stepper motor drives the feed using a belt-drive. This is used as a simple solution. Limitations with belt drive feed is a single direction system that does not allow for reversal. Reversal could prove to be a suitable solution to reducing feed delay control problems due to pressure build up.

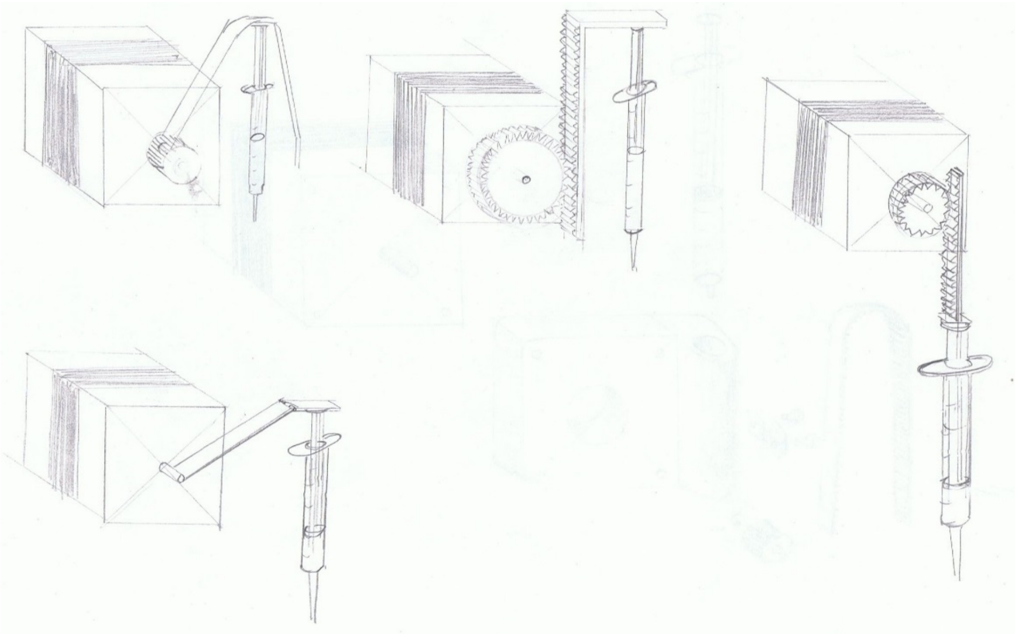

Figure 42 Alternative feed forcing method for syringe

The belt drive used is an excess piece of belt from the RepRap Mendel build assembly. A belt pulley in metal is ordered.
Four screws used to attach the motor to the mount are 12 mm M3 screws. Two 8 mm M3 screws are used to attach the belt fastener. *Figure 46 Mount with motor and syringe*. (to fit with interface in printer see Appendix E: RepRap Mendel Tricolour Specifications).

10.3.5 Firmware updates

Software used for this project was pronterface and the firmware on the 3d printer was a configured and adapted version of Marlin, a firmware developed for Aruino based 3D printers (see Appendix G: Arduino updates for details). Calibrations were made for physical parameters such as heat and movement. Control settings for end-stops and feed-rates were set. Also the firmware was inspected to insure that it could support the functions for both the proof of concept solution and a final prototype. The firmware used for testing is found in Appendix G: Arduino updates.

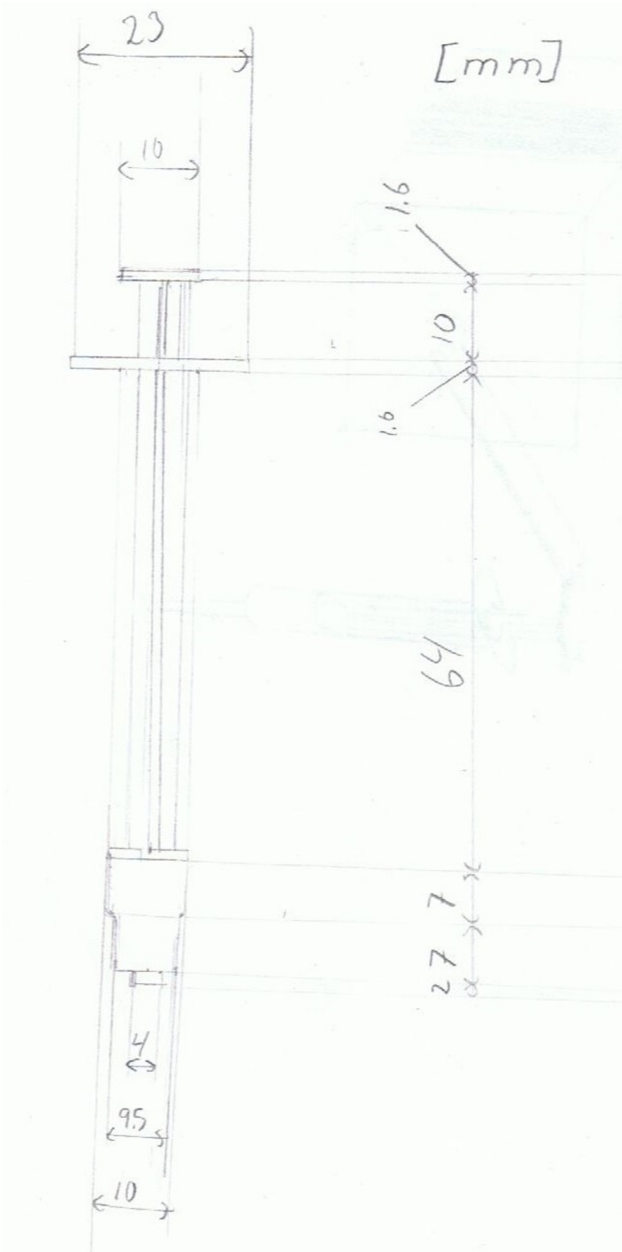

Figure 43 Syringe measurements

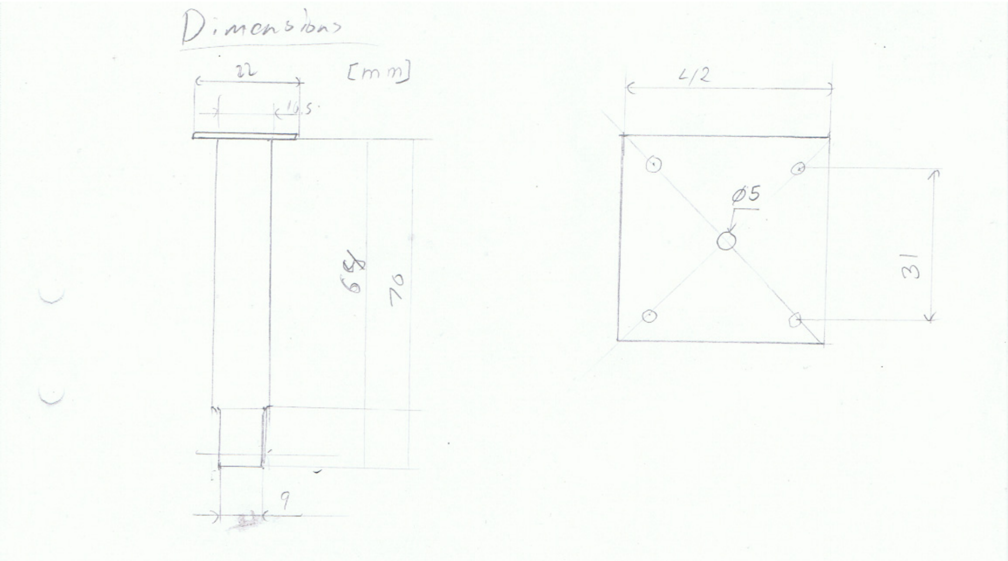

Figure 44 Hole specification for motor mount.

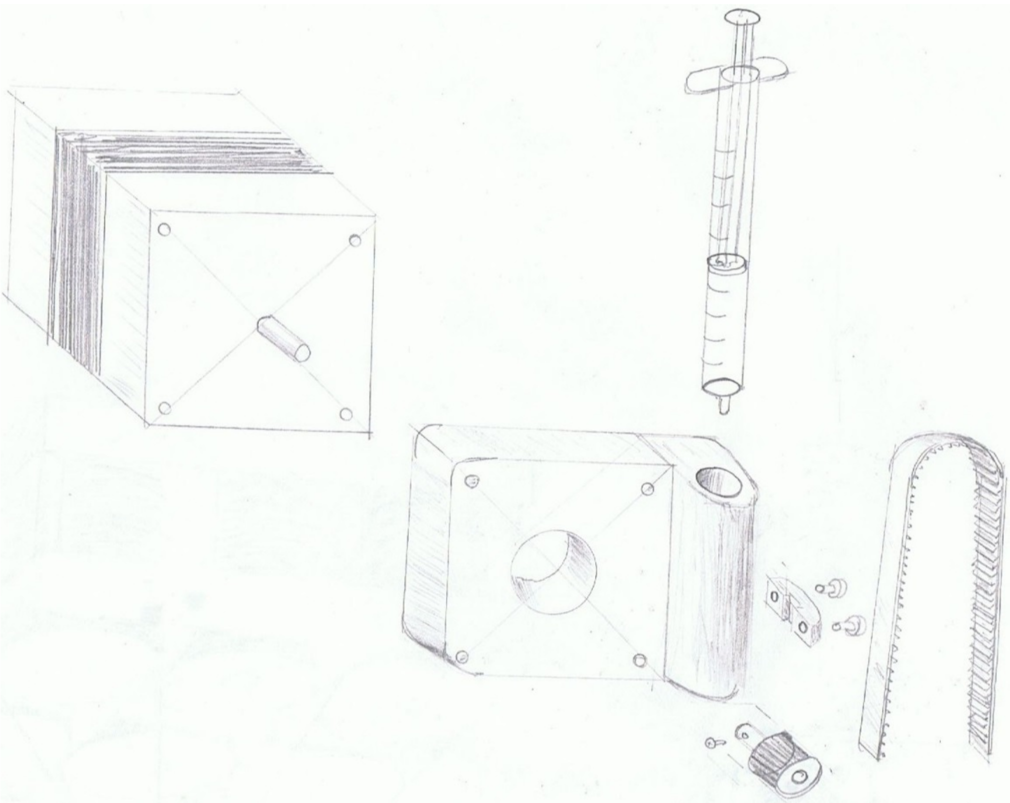

Figure 45 Assembly mount

10.4 Detailed design

The hole-pattern for the motor was measured and is found in the image below along with the size of the belt pulley. The syringe selected had a diameter of 10,5. The syringe hole is set to 11 mm. Depth of the mount is set to 8 mm. See *Figure 46*.

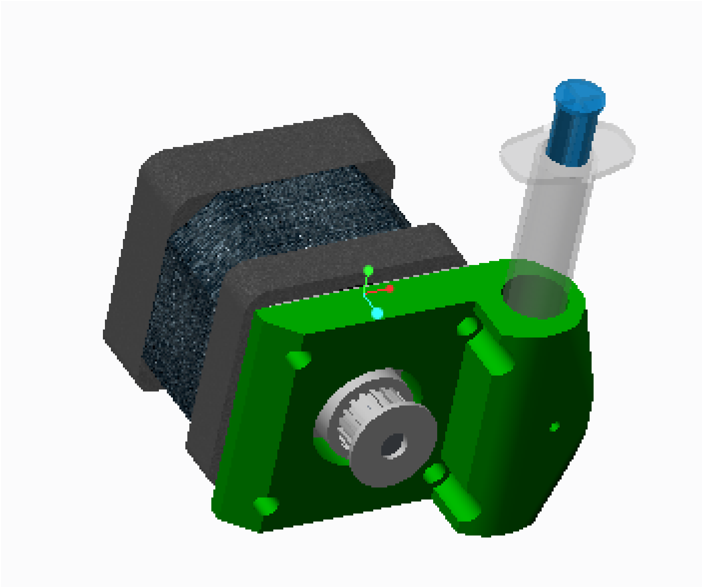

Figure 46 Mount with motor and syringe

The microcontroller is connected to an A4983 DMOS Microstepping Driver with Translator connected to a stepper motor for feed (see *Figure 47 A4983 DMOS Microstepping Driver with Translator connection schematicFigure 47* below). The stepper circuit is connected to four ports on the AVR for control of steps, direction, reset and enable. The circuit is also connected to a reference voltage adjuster, the source voltage, the four stepper motor wires, ground and capacitor. Controlling is done by setting direction and by pulsating the steps using PWM.

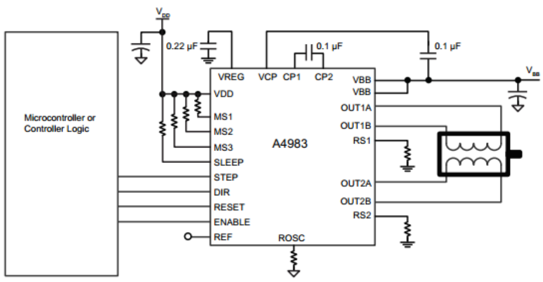

Figure 47 A4983 DMOS Microstepping Driver with Translator connection schematic

11 Final design

The concept selected uses a singular or multiple nozzles in order to feed a thread of material to the build platform or higher layers according to a pre-determined path. This path is devised by CAM software using a 3D image or may be directly programmed using command code.

The thread is cured using directed UV-LEDs at specific wavelengths corresponding to the curing wavelengths of the material. These may be mounted on the nozzle, carriage and/or elsewhere in the chamber.

If multiple nozzles are used or a system allowing a variance of material through the same nozzle, the print pattern may be performed using a variance of material properties. This will achieve varied material properties in the final product. This may be controlled by the command code created by the CAM software and is thus selected in the design process.

The mount is formed as to fit on the RepRap Mendel x-carriage hole specification. It has a large hole for the motor axel to pass through and four surrounding holes for the motor mount screws. The syringe used for material feed is mounted into a long hole in a protruding part of the mount. This hole is nearly closed at on end so as to stop the syringe from passing through but allows for the tip to pass through. A small hole on the side of the mount allows for a screw to be fastened to hold the syringe in place. On the side of the syringe holder a small part is attached using two screws and functions to fasten the belt. To ensure non-slip of the belt a track is below the part shaped as the belt (1 mm square protrusions followed by 1 mm square holes sequentially). A belt-drive cog is mounted on the motor axis.

12 Results

12.1 Prototype

The mount prototype was manufactured using the RepRap Mendel FDM printer. Primarily the mount without x-carriage interface was printed for testing as to reduce material costs in the event of errors. A CAD model was constructed and saved as an STL. The model was converted to print using pronterface. Fill factor used was set to 20% with a minimum of two layers to outer surfaces. Support material was used and removed after print along with grades and rafts.
Assembly was done according to *Figure 48* below and shown in Figure 49 below.

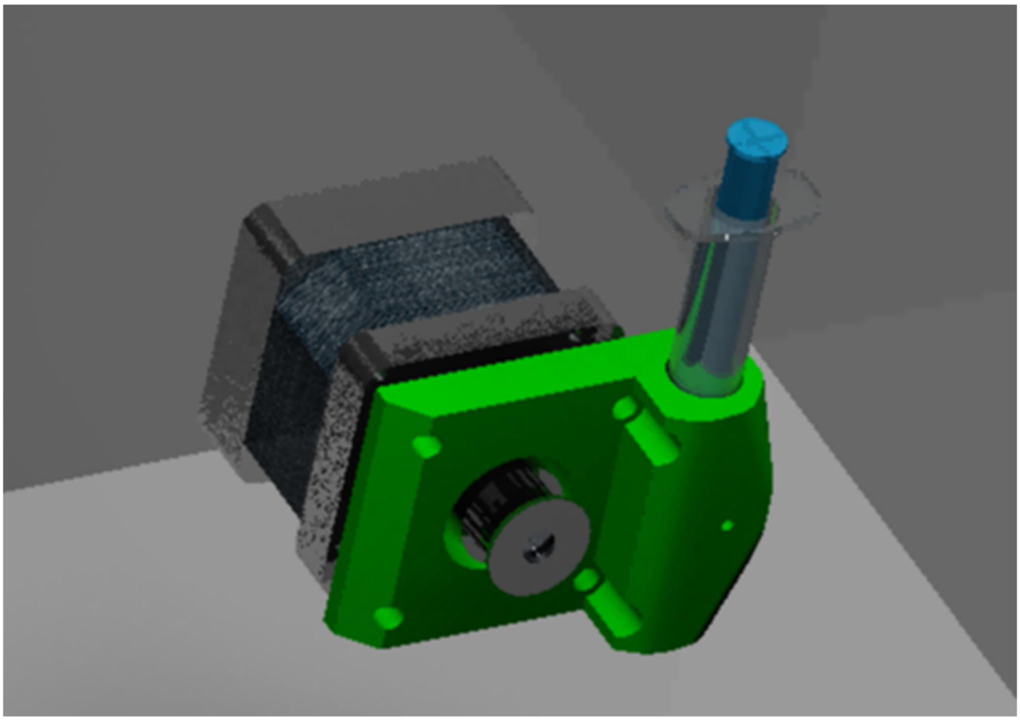

Figure 48 Assembly of proof of concept solution

Figure 49 Assembled proof of concept solution

The assembly functioned without error and a model was printed and allow for assembly to the RepRap Mendel as illustrated in *Figure 50* and shown in Figure 51 below.

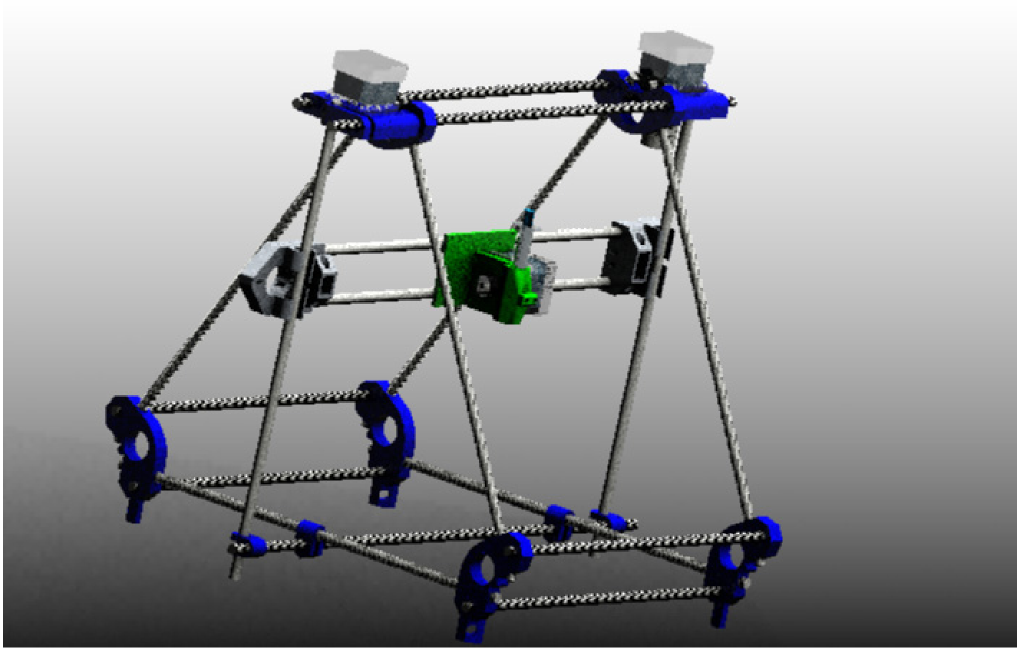

Figure 50 Proof of concept solution mounted upon RepRap frame

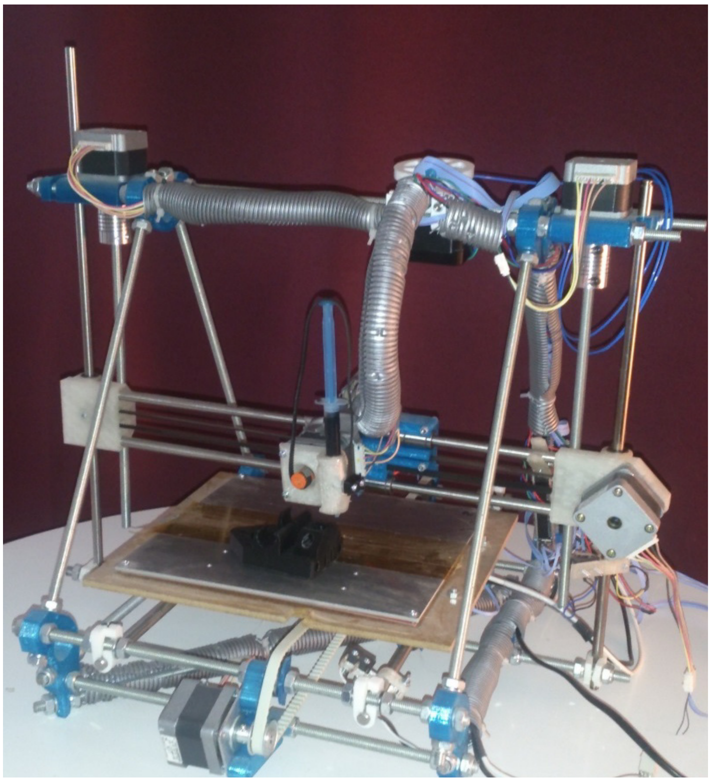

Figure 51 Proof of concept solution mounted on reprap printer

12.2 LEDs

The results from the LED test are presented in the table below. The results indicating fully solid are marked with the letter FS, semi-solid SS and liquid L. This is determined by firmly exposing the cured surface to pressure. Gas atomised metal is noted as GAM in the table. The surface of the thread is cured statically and the diameter of the cured surface is measured and presented below.

Table 11 Polymer curing time test with varying ratio of reinforcement

Nr. Of LEDs	Curing time	Fibre	Weight ratio (%)	Result	Note	Cured diameter [mm]
1	3	-	-	SS	Surface FS	8
1	6	-	-	FS		11
1	9	-	-	FS		12
1	3	GAM	20	SS	Surface FS	8
1	6	GAM	20	FS	Surface FS	11
1	9	GAM	20	FS	Surface FS	12

1	5	GAM	40	SS	Surface FS	6
1	5	GAM	60	SS	Surface FS	4
3	1	-	-	SS	Surface FS	7
3	1	GAM	20	SS	Surface FS	3 x 3

The results demonstrated in Table 11 above indicate higher power requirements for the LED. The results also indicate that there is no clear difference in the requirements of curing power with low fill ratios. A LED from Elfa Distrelec called UV-LED, P8D140 is selected. The specific LED has a power of 200-320 mW. Three of these LEDs are placed in a circle or triangle around the nozzle for multi angled curing. This will then be complemented with multiple UV-LEDs surrounding the build area for further curing.

13 Discussion and suggestion for further development

In this chapter the project is considered and reflected upon. A brief evaluation of the project success is presented. This is followed by a discussion on the patent search allowing for a market launch of a product based on the final concept. Improvements upon the concept design are suggested and finally suggestions for further studies are presented. As the project is a proof of concept project the suggestion for further studies chapter describing both studies to aid in converting the final concept into a product and studies for similar projects that could be undertaken and launched.

13.1 Project success

The project was successful as in its proof of concept and thus leaves many possibilities for further studies. The project time-plan was extended upon mainly due to a supplier delay which was eventually resolved by a replacement material. Despite the delay, the project managed to include all of the planned elements. A proof of concept was developed and further research is required both to detect the appropriate use parameters, possibilities and limitations regarding material results, development of software adapted for the technology. The project is concluded to have attained a new method for additive manufacturing that allows for composite material production. It allows an element of control of the composite material combinations and may be fitted to a low cost 3D printer.

13.2 Patent search

An extensive patent search was conducted in order to determine that the derived solution did not infringe upon any existing patents. This was then verified independently by the help of Lund University Innovation Systems. The patent search is presented in Appendix H: Approach to patent search. The result of the search was a conclusion that no patent infringement was done by this project allowing It to be possible for a product launch.

13.3 Recommendations for LEDs

Improvements of the design concepts were considered after constructions, assembly and testing. These include improvements of the LEDs, improvements of the mechanical properties and a mechanism to allow for relation of downstream flow control.

An improvement from the initial design concept is the selection of appropriate diodes and resistors for curing. A model of improvement of the diodes consists of three parts.

Primarily the LEDs are to be replaced by LEDs with a higher power. This is due to the need to be able to solidify the surface of the existing material before the integrity of the flow is lost.
Secondly the placement of the LEDs are to be considered. For further testing three placements for LEDs are targeted. The first being LEDs mounted on the moving print-head directing the curing UV light towards the syringe nozzle, thus initiating curing before the material exits the nozzle. The second placement for LEDs is upon the print-head directed at the end of the syringe nozzle, thus curing the deposited material as it leaves the syringe and further cure deposited layers below the newly deposited material after contact has been made. Thirdly UV lighting (LED or other) would be placed throughout the printing chamber emitting light upon the entire build area from one or multiple angles. This functions to further cure the part.

The UV lights will be controlled independently. The LEDs directed toward the syringe will be controlled to better determine flow rate and intensity from them (or exposure time) will vary throughout the build along with properties such as feed rate. The LEDs directed at the material exiting the nozzle would be controlled on a separate circuit and may either be controlled in relation to deposition, or permanently turned on during print. The chamber UV lighting may be on during the entire print, in intervals during the print (such as exposure from above between layer deposition) or at the end of print for a set time.

13.4 Further studies of material

Further studies of materials related to the topic of composite additive manufacturing may serve one of three purposes. Developing an array of composites suitable for additive manufacturing, determining perimeters to better the studies in the resulting properties of composites manufactured using additive manufacturing and developing the technology.

13.4.1 Finding more materials

Some suggestions for further studies into further materials are the following.

1. Investigate a catalogue of matrix materials suitable for compounds. The purpose being to have an array of suitable materials to choose from to enable the selection of desired properties. This could be conducted together with testing in order to rank the adaptability of the material o the manufacturing method.
2. Determine suitable fibres for various composite material properties. As above this purpose serves to create a catalogue of materials for the end user to use in order to have a selection of material properties. Fibres that could be of main interest include carbon fibres with electric conductive properties that could potentially easily be introduced to this technology and add another material property to be locally selected using this manufacturing technology.
3. Testing of additives including UV stabilisers and Silica gel. Silica gel could aid in the control of flow within a liquid dispensing print-head and UV

stabilisers could potentially be added to decrease the long term decay of material caused by UV-light.

4. Compounds that could be manufactured using this technology and still allow to be sintered. The study would include critical fill rates and burnout alongside with finding an appropriate matrix material for burnout. The purpose of this would be to allow for creation of metallic parts using the simple printer.

13.4.2 Studying limitations and physical properties

For this project a review was performed of rheological properties for some common materials used in additive manufacturing. What was found is that the properties are greatly changed in relation to additives and more notably with fibres. In order to develop a catalogue of composite materials for additive manufacturing a deeper study into the selected materials rheological properties should be conducted and taken into consideration when dimensioning the print head and liquid currents and so on. This is of interest both for the wear of the machine, flow of material effecting the quality of print and because uneven flow could cause uneven fill rates in the dispensed liquid. Capillary rheological tests could be conducted as part of the further studies and the materials should be tested with various fill rates.

13.4.3 Determining composite properties

Three further studies that could be conducted in order to improve the knowledge of the technology are the following:

- Using an electron microscope (ex. SEM) to better analyse the results of the printouts.
- Investigate changes in heat expansion of polymer with different reinforcements such as glass fibres
- Investigation in user requirements regarding safety of material usage.

13.5 Further studies for hardware

For the mechanical design there are a few aspects that allow for improvement.
These are grouped below as ideas for the project design and general ideas for 3d printers.

13.5.1 Project design

Adjustments from original design are made to allow for the correct diameter of the syringe and the fastening of the belt with correct dimensions including spacing between tracks. The belt did not run smoothly on top of the syringe. Thus a devise for smooth transmission of the belt relieving the syringe of excess radial forces is considered.

To further improve the flexibility of implication, multiple designs should be produced that may correctly interface with other common existing 3D printers.

An issue with fluid transport is flow control. If using a syringe or pump that creates flow by pressurising a liquid which creates a flow in order to even out pressure, when the force applied creating pressure is released there is a delay before the flow is stopped from the nozzle. Two steps may be done to allow for separate regulation of flow control. A replacement system for the syringe and motor is considered using a pump system or path planning flow control. A downstream application for flow control could be a blocker or limiter. That is to say a close or choke function for the nozzle.

Path planning flow control. This would involve decreasing the force in a predictive manor when a path is approaching a part where flow should be turned off. In the same way a force may be applied in advanced to flow being needed in order to induce a flow.

Nozzle closer. Another method is a direct restriction of flow applied at or near the end of the liquid applicator. This may be done using a mechanical flow restrictor.

A common problem with additive manufacturing methods today as well as other printers such as ink jet printers is keeping the print head clean so that it can be used again and again and not get clogged up by the material leaving the nozzle. In order to keep the nozzle clean de-curing possibilities for nozzle cleansing and deconstruction could be investigated. Many UV curable materials can be broken down using specific UV wavelengths. It would be of interest to study the possibility to allow for the print head to move off the print and be cleaned using UV light.

A final point to mention is that the final concept in this project had a very limited source of material in print. Increasing the size of the syringe to include a larger material volume would be detrimental to the performance as the printer would be moving a heavier load at the print head. As such possibilities for continuous supply of materials fed from external source or an in print refill system that allows the print head to fill during printout could be investigated.

13.5.2 General 3D printer improvements

A deeper analysis of the available additive manufacturing hardware and electronics may be conducted in order to further develop the detailed design for this technology. For example the majority of the observed 3D printers in this project use stepper motors for movement, feed and position control. These could be replaced with brushed dc motors with position decoding. The improvement would allow for higher precision and better control of movement including elimination of the loss of position that may occur with stepper motors. This may also be achieved at a lower price and is a technology that is already widely developed and used in for example cheap ink jet printers. The expense of this implementation is a redesign of the control board for the printer and a slightly more complicated firmware design.

13.6 Further studies for software

Software development for the specific application can take note from the popularity gained of a few FDM printers such as Makerbot where the software is simplistic and has a very limited amount of settings. As an engineer one may easily expect that the most popular control software would allow most control. This may be known as next bench syndrome (Jacobson, 2014) where a product would be developed to the desired specification of ones peers but not to the needs of the main users. Thus software development may aim to integrate this lesson and develop a simplistic user interface with only the necessary setting available and good graphic feedback to the user.

Specifically for this project development of software appropriated to control printout of variable material concentrations and orientation are of interest. That is to say design functions that allow for selection and orientation of fibres and/or fibre concentration.

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Appendix A: Interview study

Interview questions were posed to select individuals within the manufacturing industry to better define a priority of needs in regards to material properties achievable using additive manufacturing methods. The questions and answers are found below.

A.1 Interview questions

Metal replacement

Do you believe that metal replacement is a growing need within the industry? How do you imagine this will develop over the next few years?

What are the material properties that mostly need improvement for metal replacement?

Additive manufacturing

In the following questions additive manufacturing methods are referenced to as 3Dprinting and mainly refer to cheap home use 3D printers.

What material properties would you like to see or do you believe would be required for growth of additive manufacturing methods for low cost home 3D printers?

What limitations with 3D printing you see in most need for improvement for you to want to use 3D printing more?

Composites

What in your experience limits the upper bounds of fill factor of short fibre-reinforcement in thermoplastic and thermoset polymers?

Beyond mechanical properties, what material properties have you used as requisites of composite materials?

A.2 Answers from Magnus Ullman, Technical manager at Erteco Rubber & Plastics

Metal replacement

The growth of metal replacement has not jet reach its peak I think we only are in the beginning. In respect of injection molding resins I think we will see more combinations of reinforcement fibres and preformed inserts. The need of higher modulus is main issue.

Additive manufacturing

" Low cost home 3D printers" operate at low pressure and the material properties are therefore limited to a very low level compared to injection molded parts. The heat transfer from the resin to the air is as we know not that good and make the cycle time very long. I think we will see other systems in the future, maybe cross linked materials.

Composites

The wetting of the fibers sets the limit of the loading.

I have had a lot of different requirements on reinforced materials: Color, food and water contact approvals, flame retardant, electrical conductive, thermal conductive, low friction, were resistance, heat resistance, UV resistance, chemical resistance, price and more.

A.3 Answers from Henrik Eriksson from Polykemi

The colours in the following texts represent the questions asked and the answers.

Frågorna är följande:

Metal replacement

Do you believe that metal replacement is a growing need within the industry? How do you imagine this will develop over the next few years?

Metal replacement is certainly growing but it is difficult to say at what rate. However, it is important to remember that the metal industry does it very best to promote new technologies that allow also its products to be used more weight- and cost efficiently. This does not necessarily involve improvements of the inherent properties of the material, but can include new ways of designing a certain function or the process for shaping the material.
Within the automotive industry I see especially how the heat ageing properties of high performance polyamides have improved very rapidly over the last few years. This allow them to be employed in parts of the engine where previously metals were chosen due to the high temperature loads. On the other hand, cheaper polypropylene based materials with improved properties replace the more standard performing polyamides in applications where these have been in use for years, in many cases parts which were originally made in metal.

What are the material properties that mostly need improvement for metal replacement?

Of course metal replacement on its own has no value, but the perception that the approach should allow considerable weight and cost savings is obvious. Let's take for example the strive of the automotive industry to keep weight increase at bay. There I believe that a reasonable strategy for reducing weight in future cars will have to involve a sound balance between step changes, represented by functionality integration and mixed material construction, and straightforward material substitution that take advantage of the properties offered by materials that employ the latest in material science.
The mechanical properties of thermoplastics evolve pretty slowly and within a relatively restricted area. Heat ageing properties have greater potential to make or break the possibility to use a thermoplastic material instead of metal for a parts under the hood of a car for example.

Additive manufacturing

Maybe I'm conservative but I look at it mostly as a toy, so making it more children friendly perhaps?

Composites

I'm not sure I understand the question correctly but for the average engineering thermoplastic (including for example PP, PA6, PA66, PBT, PET etc.) the cost/benefit limit for adding short glass fibre usually ends up between 50-60 wt.%. For other fibres and thermosets I cannot say.

Appendix B: Simulation model

A simple simulation of interference was conducted. A CAD RepRap printer frame was created in CREO. The CAD model of the nozzle was assembled With the syringe full and at its height is the limitation of build height was found to be 120 mm. Another 44 mm build height is available assuming the syringe is emptied (see Figure 52 below). As the container volume of the syringe is so small it is unlikely that this would cause any problems. The RepRap Mendel frame is not ideal for this model of printhead.

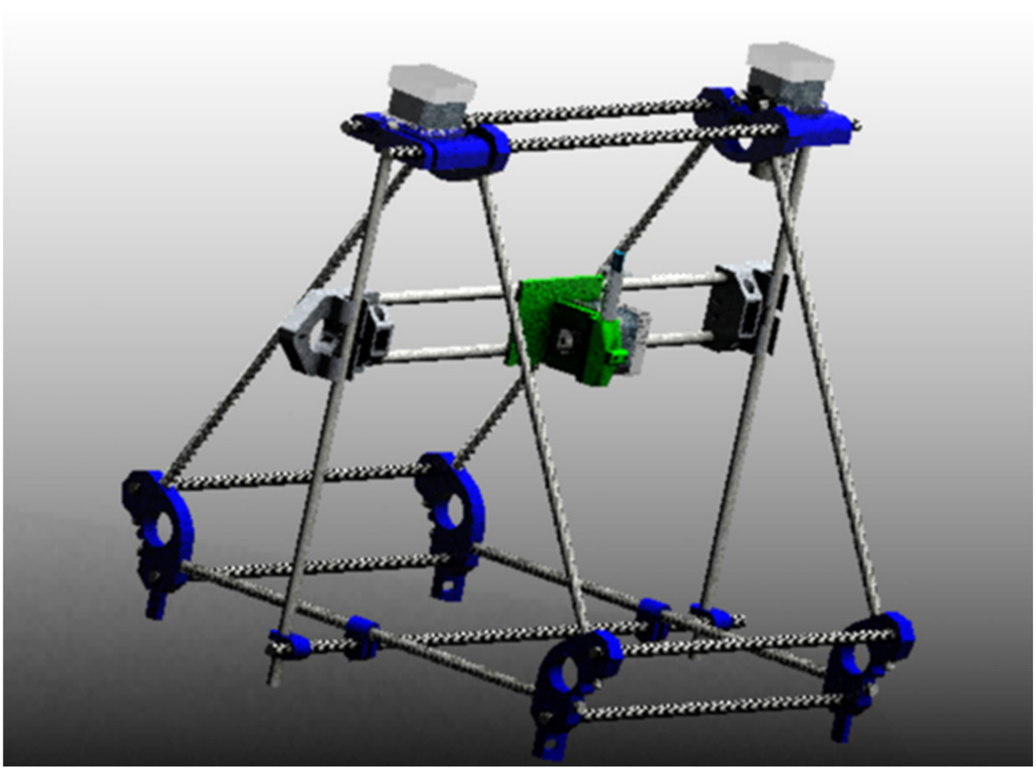


Figure 52 Simulation model assembled with syringe in lower position, build-platform removed.

Appendix C: Material content

The material content of VFlash material cartridge is presented in below.

- Isobornyl acrylate(227-561-6)
- Urethane acrylate(NLP)
- Tricyclodecane Dimethanol Diacrylate(255-901-3)
- Phenyl bis(2,4,6-trimethylbenzoyl)-phosphine oxide

Appendix D: List of Industrial suppliers and/or contacts

Elfa distrelect – Electronical components

AWI Maskin - That company selling the screws

Polykemi – Compounding company

Erteco Rubber & Plastics

Swerea

Carpenter – metal powder supplier

Creative tools- Supplier of RepRap Tricolour Mendel

3D Systems- supplier of photopolymer blend used in testing

Formlabs – supplier of curable UV liquid that wasn't delivered

Appendix E: RepRap Mendel Tricolour Specifications

All references and assembly instructions may be found on the instruction website (Bowyer & Rhys, 2013) and motor specifications reference page (CHANGZHOU SONGYANG MACHINERY & ELECTRONICS, 2011).
Size 500 x 460 x 410 mm (Length x Depth x Height)
Build size 210 x 190 x 140 mm.
Motors nema 17.
Step angle 1.8 degrees.
M8 Threaded rods.
Nozzle diameter 0.5 mm.
T5 belts
12V switching power supply, 300W, 25A, 110 or 220 AC capable
3 Mechanical end stops
MKII Heated bed plate.

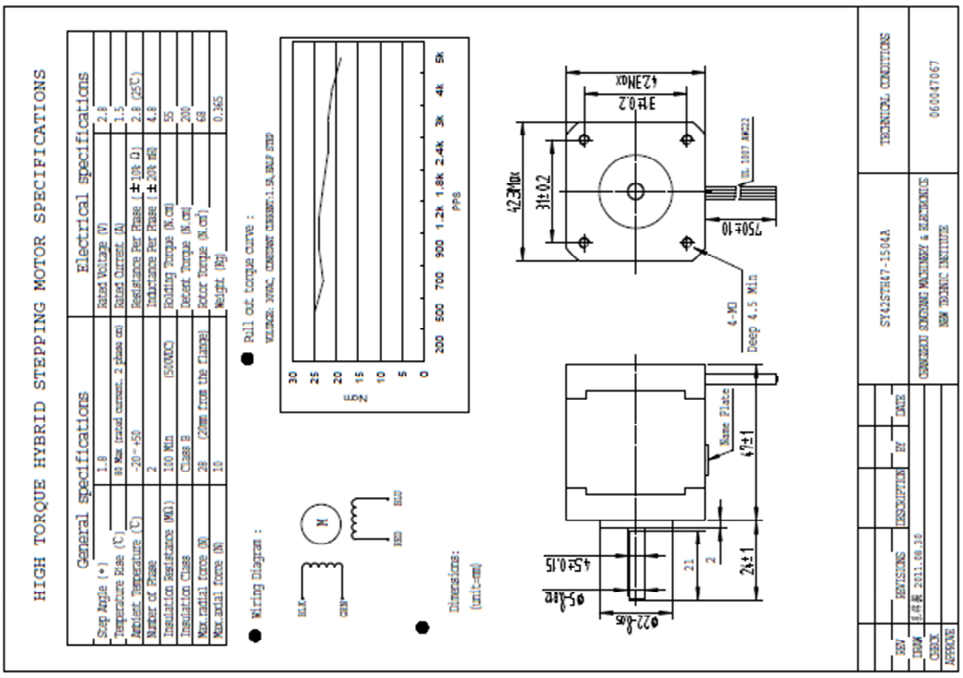


Figure 53 Nema 17 stepper motor specifications (CHANGZHOU SONGYANG MACHINERY & ELECTRONICS, 2011)

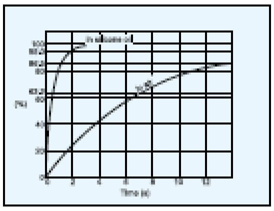
Appendix F: Replacement Thermistor Specifications

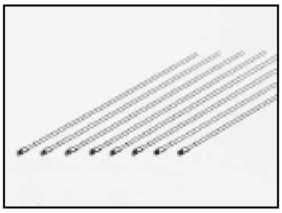
HIGH HEAT-RESISTANCE AND HIGH SENSITIVE THERMISTOR

GT THERMISTOR

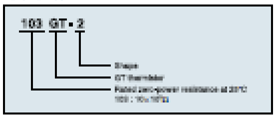
GT thermistor is combined both superior feature of BT thermistor and ET thermistor as fast response time, high reliability, wide category temperature range, high moisture proof, high accuracy and reasonable price.
GT thermistor is made up of a high quality thermistor element and the lead wire is connected to the thermistor element by alloyed technology, and glass coating for the thermistor element.

Time constant

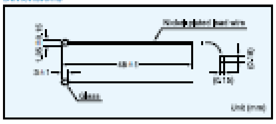




Part number



Dimensions



Specifications

Part No.	R_{25}*1	B value*2	Dissipation factor (mW/°C) Approx.	Thermal time constant(s)*3 Approx.	Rated maximum power dissipation (at 25°C)(mW)	Category temp. range(°C)
102GT-2	1.0kΩ±3%	3305K±2%	0.6	7	3.0	−50 ~ +200
202GT-2	2.0kΩ±3%	3838K±2%				−50 ~ +300
502GT-2	5.0kΩ±3%	3964K±2%				
103GT-2	10.0kΩ±3%	4126K±2%				
203GT-2	20.0kΩ±3%	4282K±2%				
503GT-2	50.0kΩ±3%	4288K±2%				
104GT-2	100.0kΩ±3%	4267K±2%				
104GTA-2	100.0kΩ±3%	4390K±2%				
204GT-2	200.0kΩ±3%	4338K±2%				
504GT-2	500.0kΩ±3%	4526K±2%				
105GT-2	1000.0kΩ±3%	4608K±2%				

Specifications

Part No.	Rated zero-power resistance			temperature (°C)	B value*2	Dissipation factor (mW/°C) Approx.	Thermal time constant(s)*3 Approx.	Rated Electricity mW at 25°C	Category temp. range(°C)
	temperature*1 (°C)	resistance	tolerance						
252GT-2-20185	0	6kΩ	±5%	0/100	3380K±2%	0.6	7	3.0	−50 ~ +300
252GT-2-20197	25	2.5kΩ	±2.5%						
262GT-2-20198	0	8kΩ	±1%	25/50	3745K±2%				
542GT-2-20184	75	0.7331kΩ	±3%	0/100	3450K±2%				
542GT-2-20186	0	15kΩ	±3%						
852GT-2-20156	50	3.485kΩ	±3%						
103GT-2-20196	25	10kΩ	±1%	25/85	3435K±1%				
103GTA-2-20199	25	10kΩ	±5%	25/125	3980K±2%				
303GT-2-20205	25	30kΩ	±3%	0/100	3870K±2%				
333GT-2-20204	125	1.509kΩ	±3%	0/100	3570K±2%				
493GT-2-20157	5	127kΩ	±2%	0/100	3870K±2%				
493GT-2-20159	75	7.214kΩ	±3%						
493GT-2-20188	40	26.05kΩ	±2%						
104GT-2-20201	25	100kΩ	±3%	100/200	4300K±3%				
234GT-2-20194	25	231.44kΩ	±3%	100/200	4537K±1%				
234GT-2-20195	150	3.161kΩ	±3%		4537K±2%				
145GT-2-20203	200	4kΩ	±5%	200/300	5133K±3%				

*1 Rated zero-power resistance at each temperature.
*2 B value : determined by rated zero-power resistance at each temperature.
*3 Time when thermistor reaches 63.2% of the temperature difference. The value is measured in the air.

Appendix G: Arduino updates

The following code was copied from the configuration tab for the marlin firmware uploaded to the Melzi master microcontroller. All changes at this stage were in this tab.

```
#ifndef CONFIGURATION_H
#define CONFIGURATION_H

//
===============================================================
====================

// For instructions on setting these #defines, see:
// Mendel: http://reprap.org/wiki/RepRapPro_Mendel_maintenance
// Huxley: http://reprap.org/wiki/RepRapPro_Huxley_maintenance

// Uncomment ONE of the next three lines - the one for your RepRap machine
//#define REPRAPPRO_HUXLEY
//#define REPRAPPRO_MENDEL //Legacy Mendel
#define REPRAPPRO_MENDEL2 //Tricolour

// Uncomment ONE of the next three lines - the one for your master controller
electronics
#define REPRAPPRO_MELZI
//#define REPRAPPRO_SANGUINOLOLU
//#define REPRAPPRO_DUE

// Uncomment ONE of the next two lines - the one for the series resistors on
your controller
#define SERIAL_R 4700
//#define SERIAL_R 10000

// Uncomment the next line if your machine has more than one extruder
#define REPRAPPRO_MULTIMATERIALS



// ------------------------------------------------------------------------------------
```

```
#ifndef REPRAPPRO_HUXLEY
#ifndef REPRAPPRO_MENDEL
#ifndef REPRAPPRO_MENDEL2
#error Uncomment one of #define REPRAPPRO_HUXLEY,
REPRAPPRO_MENDEL, or REPRAPPRO_MENDEL2 at the start of the file
Configuration.h
#endif
#endif
#endif

#ifndef REPRAPPRO_MELZI
#ifndef REPRAPPRO_SANGUINOLOLU
#ifndef REPRAPPRO_DUE
#error Uncomment one of #define REPRAPPRO_MELZI,
REPRAPPRO_SANGUINOLOLU or REPRAPPRO_DUE at the start of the file
Configuration.h
#endif
#endif
#endif

#ifndef SERIAL_R
#error Uncomment one of #define SERIAL_R 10000 or 4700 at the start of
the file Configuration.h
#endif

//
==============================================================
==================

// Uncomment this if you are experimenting, know what you are doing, and
want to switch off some safety
// features, e.g. allow extrude at low temperature etc.
//#define DEVELOPING

// This configurtion file contains the basic settings.
// Advanced settings can be found in Configuration_adv.h
// BASIC SETTINGS: select your board type, temperature sensor type, axis
scaling, and endstop configuration

//User specified version info of THIS file to display in [Pronterface, etc]
terminal window during startup.
//Implementation of an idea by Prof Braino to inform user that any changes
made
//to THIS file by the user have been successfully uploaded into firmware.
#define STRING_VERSION_CONFIG_H "2013-06-14/2" //Revision number
for all changes
```

```
#define STRING_CONFIG_H_AUTHOR "RepRapPro - AB" //Who made the
changes.

// This determines the communication speed of the printer
//#define BAUDRATE 250000
#define BAUDRATE 115200
//// The following define selects which electronics board you have. Please
choose the one that matches your setup
// Sanguinololu 1.2 and above = 62
// Melzi 63

#ifdef REPRAPPRO_SANGUINOLOLU
#define MOTHERBOARD 62
#endif

#ifdef REPRAPPRO_MELZI
#define MOTHERBOARD 63
#endif



//=========================================================
=================
//============================Thermal Settings
============================
//=========================================================
=================

// Set this if you want to define the constants in the thermistor circuit
// and work out temperatures algebraically - added by AB.

// See
http://en.wikipedia.org/wiki/Thermistor#B_or_.CE.B2_parameter_equation

// BETA is the B value
// RS is the value of the series resistor in ohms
// R_INF is R0.exp(-BETA/T0), where R0 is the thermistor resistance at T0
(T0 is in kelvin)
// Normally T0 is 298.15K (25 C).  If you write that expression in brackets in
the #define the compiler
// should compute it for you (i.e. it won't need to be calculated at run time).

// If the A->D converter has a range of 0..1023 and the measured voltage is V
(between 0 and 1023)
// then the thermistor resistance, R = V.RS/(1023 - V)
// and the temperature, T = BETA/ln(R/R_INF)
```

```
// To get degrees celsius (instead of kelvin) add -273.15 to T

// This DOES assume that all extruders use the same thermistor type.

#define BED_USES_THERMISTOR
#define HEATER_0_USES_THERMISTOR
#define HEATER_1_USES_THERMISTOR
#define HEATER_2_USES_THERMISTOR

#define ABS_ZERO -273.15
#define AD_RANGE 16383


// Extruder thermistor: RS 198-961
#define E_BETA 3960.0
#define E_RS SERIAL_R
#define E_NTC 100000.0
#define E_R_INF ( E_NTC*exp(-E_BETA/298.15) )


#ifdef REPRAPPRO_MENDEL
// Bed thermistor: RS 484-0149; EPCOS B57550G103J
#define BED_BETA 3950.0
#define BED_NTC 100000.0
#endif

#ifdef REPRAPPRO_MENDEL2
// Rapid 61-0446 ; Semitec 103GT-2 All Mendels and Thermistors shipped
after 1/4/13
 #define BED_BETA 3950.0
 #define BED_RS SERIAL_R
 #define BED_NTC 100000.0
 #define BED_R_INF ( BED_NTC*exp(-BED_BETA/298.15) )
#endif


#ifdef REPRAPPRO_HUXLEY
// Bed thermistor: VISHAY BC COMPONENTS - NTCS0603E3104FXT
#define BED_BETA 4100.0
#define BED_NTC 100000.0
#endif

#define BED_RS SERIAL_R
#define BED_R_INF ( BED_NTC*exp(-BED_BETA/298.15) )
```

```
// Actual temperature must be close to target for this long before M109 returns
success
#define TEMP_RESIDENCY_TIME 0  // (seconds)
#define TEMP_HYSTERESIS 10       // (C°) range of +/- temperatures
considered "close" to the target one
#define TEMP_WINDOW     15       // (degC) Window around target to start
the recidency timer x degC early.

// The minimal temperature defines the temperature below which the heater
will not be enabled It is used
// to check that the wiring to the thermistor is not broken.
// Otherwise this would lead to the heater being powered on all the time.

#define HEATER_MINTEMP -1
#define HEATER_0_MINTEMP HEATER_MINTEMP
#ifdef REPRAPPRO_MULTIMATERIALS
#define HEATER_1_MINTEMP HEATER_MINTEMP
#define HEATER_2_MINTEMP HEATER_MINTEMP
#endif
#define BED_MINTEMP 1

// When temperature exceeds max temp, your heater will be switched off.
// This feature exists to protect your hotend from overheating accidentally, but
*NOT* from thermistor short/failure!
// You should use MINTEMP for thermistor short/failure protection.
#define HEATER_MAXTEMP 275
#define HEATER_0_MAXTEMP HEATER_MAXTEMP
#ifdef REPRAPPRO_MULTIMATERIALS
#define HEATER_1_MAXTEMP HEATER_MAXTEMP
#define HEATER_2_MAXTEMP HEATER_MAXTEMP
#endif
#define BED_MAXTEMP 150


// PID settings:
// Comment the following line to disable PID and enable bang-bang.
#define PIDTEMP
#define PID_MAX 255 // limits current to nozzle; 255=full current
#define FULL_PID_BAND 150 // Full power is applied when pid_error[e] >
FULL_PID_BAND
#ifdef PIDTEMP
  //#define PID_DEBUG // Sends debug data to the serial port.
  #define PID_INTEGRAL_DRIVE_MAX 125  //limit for the integral term
  #define K1 0.95 //smoothing factor withing the PID
  #define PID_dT 0.122 //sampling period of the PID
```

```
// RepRapPro Huxley + Mendel
   #define  DEFAULT_Kp 12.0
   //#define  DEFAULT_Ki (2.2*PID_dT) // Time scaling now done in
setPIDValues() in temperature.cpp - AB
   //#define  DEFAULT_Kd (80/PID_dT)
   #define  DEFAULT_Ki 2.2
   #define  DEFAULT_Kd 80

#endif // PIDTEMP

#ifndef DEVELOPING
//this prevents dangerous Extruder moves, i.e. if the temperature is under the
limit
//can be software-disabled for whatever purposes by
 #define PREVENT_DANGEROUS_EXTRUDE
 #define EXTRUDE_MINTEMP 170
 #define EXTRUDE_MAXLENGTH (X_MAX_LENGTH+Y_MAX_LENGTH)
//prevent extrusion of very large distances.
#else
 #define BOGUS_TEMPERATURE_FAILSAFE_OVERRIDE
#endif

//=============================================================
=================
//=============================Mechanical
Settings===========================
//=============================================================
=================

// Endstop Settings
#define ENDSTOPPULLUPS // Comment this out (using // at the start of the
line) to disable the endstop pullup resistors

// The pullups are needed if you directly connect a mechanical endswitch
between the signal and ground pins.
const bool X_ENDSTOPS_INVERTING = false; // set to true to invert the logic
of the endstops.
const bool Y_ENDSTOPS_INVERTING = false; // set to true to invert the logic
of the endstops.
const bool Z_ENDSTOPS_INVERTING = false; // set to true to invert the logic
of the endstops.

// For Inverting Stepper Enable Pins (Active Low) use 0, Non Inverting (Active
High) use 1
#define X_ENABLE_ON 0
```

```
#define Y_ENABLE_ON 0
#define Z_ENABLE_ON 0
#define E_ENABLE_ON 0 // For all extruders

// Disables axis when it's not being used.
#define DISABLE_X false
#define DISABLE_Y false
#define DISABLE_Z true
#define DISABLE_E false // For all extruders

#ifdef REPRAPPRO_MENDEL
#define AXES_MAX_LENGTHS {210, 210, 140}
#define INVERT_X_DIR false    // for Mendel set to false, for Orca set to true
#define INVERT_Y_DIR true    // for Mendel set to true, for Orca set to false
#define INVERT_Z_DIR false     // for Mendel set to false, for Orca set to true
#define INVERT_E0_DIR true   // for direct drive extruder v9 set to true, for
geared extruder set to false
#define INVERT_E1_DIR true    // for direct drive extruder v9 set to true, for
geared extruder set to false
#define INVERT_E2_DIR true   // for direct drive extruder v9 set to true, for
geared extruder set to false
#endif

#ifdef REPRAPPRO_MENDEL2
#define AXES_MAX_LENGTHS {210, 210, 140}
#define INVERT_X_DIR true    // for Mendel set to false, for Orca set to true
#define INVERT_Y_DIR true    // for Mendel set to true, for Orca set to false
#define INVERT_Z_DIR false     // for Mendel set to false, for Orca set to true
#define INVERT_E0_DIR true   // for direct drive extruder v9 set to true, for
geared extruder set to false
#define INVERT_E1_DIR true    // for direct drive extruder v9 set to true, for
geared extruder set to false
#define INVERT_E2_DIR true   // for direct drive extruder v9 set to true, for
geared extruder set to false
#endif

#ifdef REPRAPPRO_HUXLEY
#define AXES_MAX_LENGTHS {155, 150, 90}
#define INVERT_X_DIR false    // for Mendel set to false, for Orca set to true
#define INVERT_Y_DIR false    // for Mendel set to true, for Orca set to false
#define INVERT_Z_DIR false     // for Mendel set to false, for Orca set to true
#define INVERT_E0_DIR true   // for direct drive extruder v9 set to true, for
geared extruder set to false
#define INVERT_E1_DIR true    // for direct drive extruder v9 set to true, for
geared extruder set to false
```

```
#define INVERT_E2_DIR true   // for direct drive extruder v9 set to true, for
geared extruder set to false
#endif


// ENDSTOP SETTINGS:
// Sets direction of endstops when homing; 1=MAX, -1=MIN
#define X_HOME_DIR -1
#define Y_HOME_DIR -1
#define Z_HOME_DIR -1

#define min_software_endstops true //If true, axis won't move to coordinates
less than zero.
#define max_software_endstops true  //If true, axis won't move to coordinates
greater than the defined lengths below.

// The position of the homing switches. Use MAX_LENGTH * -0.5 if the center
should be 0, 0, 0
#define X_HOME_POS 0
#define Y_HOME_POS 0
#define Z_HOME_POS 0

//// MOVEMENT SETTINGS
#define NUM_AXIS 4 // The axis order in all axis related arrays is X, Y, Z, E

#ifdef REPRAPPRO_MENDEL

#define X_MAX_LENGTH 210
#define Y_MAX_LENGTH 210
#define Z_MAX_LENGTH 110
#define HOMING_FEEDRATE {10*60, 10*60, 1*60, 0}  // set the homing
speeds (mm/min)
#define FAST_HOME_FEEDRATE {50*60, 50*60, 1*60, 0}  // set the homing
speeds (mm/min)
#define DEFAULT_MAX_FEEDRATE  {500, 500, 3, 45}
#define DEFAULT_MAX_FEEDRATE          {300, 300, 3, 45}    // (mm/sec)
#define DEFAULT_MAX_ACCELERATION      {800,800,30,250}    // X, Y, Z,
E maximum start speed for accelerated moves. E default values

#else

#ifdef REPRAPPRO_MENDEL2

#define X_MAX_LENGTH 210
#define Y_MAX_LENGTH 210
#define Z_MAX_LENGTH 110
```

```
#define HOMING_FEEDRATE {10*60, 10*60, 1*60, 0}  // set the homing
speeds (mm/min)
#define FAST_HOME_FEEDRATE {50*60, 50*60, 1*60, 0}  // set the homing
speeds (mm/min)
#define DEFAULT_MAX_FEEDRATE  {500, 500, 3, 45}
#define DEFAULT_MAX_FEEDRATE          {300, 300, 3, 45}    // (mm/sec)
#define DEFAULT_MAX_ACCELERATION      {800,800,30,250}    // X, Y, Z,
E maximum start speed for accelerated moves. E default values

#else

#define X_MAX_LENGTH 155
#define Y_MAX_LENGTH 150
#define Z_MAX_LENGTH 90
#define HOMING_FEEDRATE {10*60, 10*60, 1*60, 0}  // set the homing
speeds (mm/min)
#define FAST_HOME_FEEDRATE {80*60, 80*60, 4*60, 0}  // set the homing
speeds (mm/min)
#define DEFAULT_MAX_FEEDRATE  {500, 500, 5, 45}    // (mm/sec)
#define DEFAULT_MAX_FEEDRATE          {500, 500, 5, 45}    // (mm/sec)
#define DEFAULT_MAX_ACCELERATION      {1000,1000,50,250}    // X, Y,
Z, E maximum start speed for accelerated moves. E default values

#endif
#endif


// default settings
// X, Y, Z, E steps per mm
#define DEFAULT_AXIS_STEPS_PER_UNIT    {92.635, 92.635, 4000, 660}


// Defaults changed by the G10 command

#define X_EXTRUDER_OFFSET 0
#define Y_EXTRUDER_OFFSET 0
#define Z_EXTRUDER_OFFSET 0
#define STANDBY_TEMP 0
#define DEFAULT_TEMP 0


#define DEFAULT_ACCELERATION          1000    // X, Y, Z and E max
acceleration in mm/s^2 for printing moves
#define DEFAULT_RETRACT_ACCELERATION  1000   // X, Y, Z and E max
acceleration in mm/s^2 for r retracts
```

```
//
#define DEFAULT_XYJERK              15.0    // (mm/sec)
#define DEFAULT_ZJERK               0.4     // (mm/sec)
#define DEFAULT_EJERK               15.0    // (mm/sec)

//============================================================
=================
//=============================Additional
Features===========================
//============================================================
=================

// EEPROM
// the microcontroller can store settings in the EEPROM, e.g. max velocity...
// M500 - stores paramters in EEPROM
// M501 - reads parameters from EEPROM (if you need reset them after you
changed them temporarily).
// M502 - reverts to the default "factory settings".  You still need to store them
in EEPROM afterwards if you want to.
//define this to enable eeprom support
#define EEPROM_SETTINGS
//to disable EEPROM Serial responses and decrease program space by
~1700 byte: comment this out:
// please keep turned on if you can.
#define EEPROM_CHITCHAT

//LCD and SD support
//#define ULTRA_LCD  //general lcd support, also 16x2
#define SDSUPPORT // Enable SD Card Support in Hardware Console

//#define ULTIPANEL
#ifdef ULTIPANEL
  //#define NEWPANEL  //enable this if you have a click-encoder panel
  #define SDSUPPORT
  #define ULTRA_LCD
  #define LCD_WIDTH 20
  #define LCD_HEIGHT 4

// Preheat Constants
  #define PLA_PREHEAT_HOTEND_TEMP 180
  #define PLA_PREHEAT_HPB_TEMP 70
  #define PLA_PREHEAT_FAN_SPEED 255                          // Insert
Value between 0 and 255

  #define ABS_PREHEAT_HOTEND_TEMP 240
  #define ABS_PREHEAT_HPB_TEMP 100
```

```
  #define ABS_PREHEAT_FAN_SPEED 255                         // Insert
Value between 0 and 255

#else //no panel but just lcd
  #ifdef ULTRA_LCD
    #define LCD_WIDTH 16
    #define LCD_HEIGHT 2
  #endif
#endif

// Enable uM-FPU support:
#define UMFPUSUPPORT 1

// M240  Triggers a camera by emulating a Canon RC-1 Remote
// Data from: http://www.doc-diy.net/photo/rc-1_hacked/
// #define PHOTOGRAPH_PIN     23

#include "Configuration_adv.h"


#endif //__CONFIGURATION_H
```

Appendix H: Approach to patent search

The method describes curing of a material blend containing photosensitive polymer compositions to create a solid object. Thus patents regarding stereolithography are of interest. This is a focus of interest for searching for conflicting patents.

First some preparations were done:

- Describing invention
- Identifying keywords
- Searching for classifications

Steps to search for and find any conflicting patents:

- Check original patent for stereolithography
- Check through all the patents referring to stereolithography (first by title, and if interesting then by abstract and content)
- Keyword search on google database
- Writing patent number of interesting patents and short wording why it doesn't conflict
- Use seven step strategy using keyword search in the abstract & search by category using the US database

The search through all the patents referring to the original Stereolithography is placed last in the document as it is by far the most extensive.

The results from this investigation show no patents with a direct conflict to the desired patent application.

H.1 Concept description

The desired patent covers a method for additive manufacturing. The method can be broken into parts regarding material, feed/delivery, solidification and control.

H.1.1 Material

A feedstock is composed of one or more components. The first component is a polymer or polymer blend. The polymer is in liquid form at working temperature (room temperature). The polymer or polymer bend will contain polymers that may be cured. This process may work by building cross links in the polymer. This will achieve stiffness. This may achieve solidification at room temperature.

The second component is added to the feedstock to change the characteristics of the composite. This may be metal powder for example. The characteristics desired may be such as visual (look like metal), strength, stiffness, inductive, conductive (heat or electric) or magnetic shielding or example.

Other components may be agents to influence viscosity or other flow characteristics. They may also function to introduce or change other material properties.

The concept is to have one or multiple feedstock available. The feedstock may have metallic or carbon particles to allow for the enhancement and control of physical properties (see headline control below).

H.1.2 Delivery

The feedstock is mixed, then fed through a nozzle. This nozzle may be mounted on an NC machine allowing for control of deployment of the feedstock. The concept of additive manufacturing often follows the path of a model designed using CAD software or scanned from a 3D object. CAM software uses cross sections of the model to devise a tool path for the model to be created. This is then generated into machine code in order to control the NC machine. The NC machine follows the machine code and builds the model in 3D.

It is not necessary for the nozzle to be mounted to an NC machine. For example the nozzle may be hand held in order to manually build a 3D model.

The device may have a single or multiple nozzles for material delivery. It may also have a nozzle with multiple heads.

H.1.3 Solidification

The thread that leaves the nozzle is cured using a light source. The light source cures the thread by creating crosslinks in the polymers.

The printing method is similar to FDM printing. But instead of using heating the material into a molten state a viscous material blend is used that is cured whilst leaving the nozzle to form the printed part.

H.1.4 Control

The method described under the headline “Delivery” above describes a generic method for additive manufacturing. What is unique for this concept concerning the delivery is the control system parameters. A control system for this invention may allow for the selection of a range of different feedstock in order to control local material properties within the model being printed. The option may range from only one feedstock to a multiple. This will allow control for paths, walls and other patterns to be build by specific materials in conjunction with the rest of the print.

The desired material properties achieved by this may be but are not exclusive to:

- Strength (ex. tensile strength, hardness, creep)
- visual (example metallic appearance)
- magnetic (ex. Magnetic shielding)
- heat (ex. Conductive, insulation)
- electrical (ex. Conduction ,insulation)

H.1.5 Advantages

The advantages of the concept in regards to other additive manufacturing methods today can be seen in two parts. One is addressing limitations and problems concerning existing methods. The other is regarding innovation in new possibilities achieved by this method.

In regards to limitations of existing methods three mayor properties come to mind

- price
- strength
- warping

What has made additive manufacturing (or 3D printing) so popular in recent years is the development of low cost FDM 3D printers. They are very limited when it comes to choice of materials. Other technologies have wider ranges of materials available. At present day there are few to no commercial versions of alternative 3D printing methods that compete in the same price class as the low cost 3D printers. This may often be due to parts (such as sintering lasers) being far too expensive. This is something that the invention should be able to do as it in principle has even cheaper BOM than an FDM printer.

Strength of FDM parts is limitation that is often mentioned by critics. The materials used are within a limited range in regards to their physical properties. This is directly addressed by the invention.

Warping occurs when a material is cooled unevenly. Due to thermal expansion tensions are created or released within the model or material. This may cause warping which bowing, rooking, kinking, cupping & twisting[2].

In regards to innovation of the invention it allows for a selection of a wider range of material properties. These are described under the headlines “control” above. The main advantage being the possibility to allow for the controlled placement of material properties.

[2] http://en.wikipedia.org/wiki/Wood_warping

H.2 Original stereo lithography

Publication number US4575330 A

Describes clearly that the method cures areas of a surface building up a laminar structure. It also has pics illustrating this.

“"Stereolithography" is a method and apparatus for making solid objects by successively "printing" thin layers of a curable material, e.g., a UV curable material, one on top of the other. A programmed movable spot beam of UV light shining on a surface or layer of UV curable liquid is used to form a solid cross-section of the object at the surface of the liquid. The object is then moved, in a programmed manner, away from the liquid surface by the thickness of one layer, and the next cross-section is then formed and adhered to the immediately preceding layer defining the object. This process is continued until the entire object is formed.”

H.3 Keyword Search

A set of keywords that are vital for the description of the method used in the desired patent is required for an efficient search. An initial set of keywords (“additive manufacturing method photopolymer led metal nozzle thread”) gave 461 results on google patent database. This was then reduced by adding further keywords.

The following keywords were used

- additive manufacturing method
- photopolymer
- LED
- metal
- nozzle
- thread
- continuous
- composite fibre

gave 6 results:

1. Methods and systems for coherent imaging and feedback control for modification of materials, WO 2012037694 A2
2. Methods and systems for coherent imaging and feedback control for modification of materials, EP 2619633 A2 based on WO 2012037694 A2
3. Methods and systems for coherent imaging and feedback control for modification of materials, US 20120138586 A1

4. A curable jettable fluid for making a flexographic printing master, WO 2012175445 A1
5. A curable jettable fluid for making a flexographic printing master, EP 2537675 A1
6. Plasticized pressure sensitive adhesive, WO 2000056830 A1

Patents 1-3 are the same but in different databanks. Abstract is as follows "Methods and systems are provided for using optical interferometry in the context of material modification processes such as surgical laser or welding applications. An imaging optical source that produces imaging light. A feedback controller controls at least one processing parameter of the material modification process based on an interferometry output generated using the imaging light. A method of processing interferograms is provided based on homodyne filtering. A method of generating a record of a material modification process using an interferometry output is provided."

Patents 4, 5, & 6 describe materials.

H.4 Classification Search

Interesting classifications are identified for the different patent databanks. These are then used for a search to identify further patents that are not found by only searching with keywords.

For US databank the following classifications are interesting.

425/174.4

Apparatus wherein electrical energy rays which influence the work are emitted or transmitted by continuous or intermittent radiation or in the form of energy pulses.

264/401

STEREOLITHOGRAPHIC SHAPING FROM LIQUID PRECURSOR:

This subclass is indented under the class definition. Processes directed to the application of electromagnetic wave energy on a confined solidifiable liquid or semi-solid material which results in formation of a solid three-dimensional product.

425/162

WITH ELECTRICAL CONTROL SYSTEM

430/269

IMAGING AFFECTING PHYSICAL PROPERTY OF RADIATION SENSITIVE MATERIAL, OR PRODUCING NONPLANAR OR PRINTING SURFACE - PROCESS, COMPOSITION, OR PRODUCT:

700/120

Stereolithography:

This subclass is indented under 119. Subject matter wherein the building material is a confined volume of photocurable material successively exposed to light.

700/182

Including CAD, CAM, or CIM technique:

425/174

MEANS APPLYING ELECTRICAL OR WAVE ENERGY DIRECTLY TO WORK

H.5 Seven step search

The following search criteria were used in the US patent database.

- additive manufacturing method
- 425/174.4
- 425/162
- 430/269
- 700/182
- 425/174

And they led to the following results:

Apparatus for production of three-dimensional objects by stereolithography, US 4575330 A

H.6 Patents referring to original stl patent

Patents that refer to the original patent US4575330 A were observed. Those whose title don't clearly show there is no conflict with the desired patent are observed in further detail. The conclusion from this is summarised below, often with a quote and an explaining comment. The quote is often from the abstract and helps indicate why this patent is not of interest. The comment explains the quote or notes why this patent is not of interest.

Many of the patents are excluded of interest due to them describing an known method that by its principle is dissimilar from the method described above. An example is stereolithography (stl) using the method of curing selected shapes in a resin bath planar surface (which is standard practice for all stl methods), Fused desposition modelling (FDM) where material is heated, extruded and cooled to form solid or polyjet extruding beads of liquid onto a surface. This is noted briefly in the comment as it is common.

The patents are presented in order of ascending publication date.

Patent: US4707787 *

Quote:

A system and method for forming a model of an underground geological formation is disclosed wherein a quantity of non-solid material of the type which solidifies at volumetric positions impinged upon by preselected incident energy as used.

Comment: Not conflicting

Patent: US4752498 *

Quote:

“The transmittent material is a material which leaves the irradiated surface capable of further cross-linking so that when a subsequent layer is formed it will adhere thereto. “

Comment: The patents describes the method of adhering the print to a surface that is raised.

Patent: US4818562 *
Quote:

“Disclosed is a method of casting a shape. A laser or electron gun is directed at a fusible powder in a fluidized bed. The beam melts the powder and the melted powder fuses and solidifies on a surface to form the shape. Also disclosed is apparatus for casting a shape. The apparatus includes a fluidized bed containing a fluidized powder, a surface within the bed on which the shape is cast, an electron beam or laser directed at the surface, which has an energy sufficient to fuse the powder, means for controlling the level of the powder in the fluidized bed relative to the surface, and means for controlling the horizontal position of the surface relative to the beam.”

Comment:

Similar concept of composition using a laser or electron gun. But the delivery is dissimilar as it uses a fluid bed.

Patent: US4915757 *

Quote:

“ Optical feedback is employed to monotor the actual condition of the model being formed, at each work site”

Comment: Patent talks about visual feedback system and does not conflict with invention.

Patent: US4942001 *

Comment: Describes ratios for polymers suggested for stereolithography

Patent nr US4987044 *

Quote

“A radiation beam used for selectively exposing a surface is moved in a helical path by means of two oscillating mirrors vibrating about axes that are mutually perpendicular. By maintaining a constant product for oscillating frequency and rotational oscillatory mirror deflection, the level of exposure can be made substantially constant.”

Note: describes method for mirror deflection in stl.

Patent nr: US4996010 *

Quote

“whereby a three-dimensional object is formed and drawn from a substantially planar surface of the fluid medium during the forming process, “

Comment: the abstract describes a planar stl curing method.

Patent nr: US4999143 *

Comment: The same as above.

Patent: US5026146 *

Quote

“ The receptacle stores the curable liquid part of which lies in a solidification plane.”

Comment: Method works in a plane.

Patent. US5071503 *

Comment: Images show clearly a plane surface being cured.

Patent: US5094935 *

Comment: Same as above

Patent: US5109589 *

Quote:

"Stereolithographic techniques are preferred for making the mandrels out of polymeric materials."

Comment: Method describes normal stl as a step in other manufacturing process

Patent: US5120476 *

Quote

"This lamina is polymerized by irradiation to form a laminar, two-dimensional polymer layer, then the surface of the carrier liquid is raised and another lamina of the photopolymerizable medium is introduced onto the surface and polymerized to form a further polymer layer which combines with the preceding one."

Comment. Flat surface laminar.

Patent: US5121329 *

Quote:

"Any material, such as self-hardening waxes, thermoplastic resins, molten metals, two-part epoxies, foaming plastics, and glass, which adheres to the previous layer with an adequate bond upon solidification, may be utilized."

Comment: method focuses on other materials whilst referring to photocurable materials used in other methods.

Patent: US5122441 *

Quote:

"An apparatus and method for fabricating integral three-dimensional objects from successive layers of photoformable compositions by exposing the layers of the composition through a semi-permeable film that allows creation of release coatings on the side of said film facing said composition."

Comment. Describes the usual thin film surface layer build method.

Patent: US5135379 *

Quote

“ To decrease drastically fabrication time, whole layer is irradiated simultaneously using masks photoplotted on a roll of film or a matrix of miniature individually controlled components tightly packed similar to liquid-crystal displays, with shrinkage distortion minimized by constraining the irradiated photopolymer surface and/or by solidifying infinitely thin surfaces in continuous mode.”

Comment: normal method of whole surface curing

Patent: US5147587 *

Comment: Describes selective laser sintering (SLS)

Patent: US5171490 *

Comment: Improvement on normal method.

Patent: US5204124 *

Quote:

The present invention produces a three dimensional object with continuous extrusion in a horizontal plane of an instantly ultraviolet cured bead of viscous fluid with the successive beads being placed one on top of or adjacent to the previous bead in a controlled, stacked relationship until the total shape of the three dimensional object is obtained. The nozzle from which the light curable viscous liquid material is dispensed is surrounded by ultraviolet light energy so that the light is not only constantly hitting the properly placed portion of the dispensed bead but is also providing a secondary cure of previously dispensed beads to further cure the object. A light shield located between the nozzle prevents immediate curing of the viscous fluid before it is properly placed. The high viscosity and bead stickiness of the fluid retains the proper bead relationship as the cure takes place. A light observing window, in the form of a cone, surrounds the nozzle in a spaced relationship.

Comment: Similar problem being addressed. Method used is different in such factors as they use a stream of beads instead of a continuous liquid flow.

Patent: US5260009 *

Quote:

A method and process for computer-controlled manufacture of three-dimensional objects involves dispensing a layer of liquid, insoluble material onto a platform at predetermined locations, which then hardens.

Comment: The method described in the patent dispenses a layer of liquid as with normal stl.

Patent: US5303141 *

Quote:

A closed-loop extrusion system (10) includes a nozzle (12) for extruding a material, such as a hot melt adhesive; apparatus (14, 18, 46) for controllably positioning the nozzle in accordance with the specification; and a sensor (60) for generating a feedback signal that is indicative of at least one characteristic of a most recently extruded portion of the material.

Comment: The method describes heated extrusion, which is not relevant.

Patent: US5500069 *

Quote:

The laser light is scanned, from above a tank containing liquid of photosetting resin not yet hardened, outward around a predetermined point of each sectional shape in a manner to trace similar figures to an arbitrary shape, to thereby to set a surface of a resin layer in a shape corresponding to one sectional shape.

Comment: Tank surface curing like normal stl

Patent: US5506607 *

Quote:

The layers are formed by expelling minuscule beads of the substances in liquid or flowable phase onto a platform from one or more jets, the jets and platform being relatively movable in X, Y and Z coordinate system.

Comment: Describes polyjet system.

Patent: US5639413 *

Comment. Describes normal stl.

Patent: US5807437 *

Quote:

A system for producing three dimensional components by bonding together successive layers of a porous material with droplets of a binder material.

Comment: Polyjet

Patent: US5855836 *

Quote:

A novel thermopolymer material adapted for use in thermal stereolithography.

Comment: FDM, uses thermal material.

Patent: US6133355 *

Quote:

“A novel thermopolymer material adapted for use in thermal stereolithography.”

Comment: Normal stl.

Patent: US6146567 *

Quote:

A system for producing three dimensional components by bonding together successive layers of a porous material with droplets of a binder material.

Comment: Polyjet

Patent: US6248504

Quote:

The desired part is generated by applying layers of resin-wetted fabric to the tool, curing the fabric on the tool, removing the tool from the designed part and cleaning, trimming and inspecting the designed part.

Comment: Stl used as a step in a multi-step manufacturing process. No conflict

Patent: US6259962 *

Quote:

Apparatus and a method for three-dimensional printing of a three-dimensional model is provided. The apparatus includes a printing head having a plurality of nozzles, a dispenser connected to the printing head for selectively dispensing interface material in layers and curing means for optionally curing each of the layers deposited. The depth of each deposited layer is controllable by selectively adjusting the output from each of the plurality of nozzles.

Comment: Polyjet.

Patent: US6416850

Quote:

The individual cross-sectional areas are built by using an ink-jet printhead to deliver an aqueous solvent to an adhesive particulate mixture, causing the particles of the mixture to adhere together, and to previous cross-sectional areas.

Comment: Polyjet

Patent US6508971

Quote

A variety of support structures and build styles for use in Rapid Prototyping and Manufacturing systems are described wherein particular emphasis is given to Thermal Stereolithography, Fused Deposition Modeling, and Selective Deposition Modeling systems, and wherein a 3D modeling system is presented which uses multijet dispensing and a single material for both object and support formation.

Comment: FDM, SFMand TSTL

Patent: US6575218

Quote:

A method and apparatus automatically fabricates a three dimensional object from individual layers of fabrication material having a predetermined configuration. Successive layers are stacked in a predetermined sequence and affixed together to form the object. The fabrication material is carried on a substrate to a stacker. At the stacker the layers are stacked together, with each layer being successively affixed to the stack of previously affixed layers, and with the substrate removed from each layer after it is affixed.

Comment: Not similar

Patent: US6658314 *

Quote:

A method and a system for three-dimensional printing of a three-dimensional model is provided. The method includes dispensing a first interface material from a printing head, dispensing at least a second interface material from the printing head and combining the first and second interface material in pre-determined proportions to produce layers for forming the three-dimensional model. In one embodiment, the layers forming the construction layers of the model are formed from interface material having a harder modulus of elasticity from the layers forming the release layers, thereby allowing for the forming complex three-dimensional shapes.

Comment:Polyjet.

Patent: US7004222

Quote:

“The invention relates to a device for manufacturing models layer by layer. The inventive device comprises a frame (**1**), a vertically adjustable and exchangeable workpiece platform (**17**)m and a device for feeding the material comprising a coating applicator (**4**).”

Comment: Heating material, not relevant.

Patent: US7128866

Comment: Polyjet

Patent: US7291002

Quote:

"The invention relates to apparatus and methods for producing three-dimensional objects and auxiliary systems used in conjunction with the aforementioned apparatus and methods. The apparatus and methods involve continuously printing radially about a circular and/or rotating build table using multiple printheads. The apparatus and methods also include optionally using multiple build tables. The auxiliary systems relate to build material supply printhead cleaning diagnostics, and monitoring operation of the apparatus."

Comment: Similar to polyjet

Patent: US7435368

Quote:

"A three-dimensional printer uses inkjet-type printheads to rapidly prototype, or print, a three-dimensional model."

Comment: Polyjet

Patent: US7442643

Quote:

"A conductive element is formed on a substrate by forming an organometallic layer on at least a portion of a surface of the substrate, heating a portion of the organometallic layer, and removing an unheated portion of the organometallic layer. In other methods, a flowable, uncured conductive material may be deposited on a surface of the substrate, the flowable, uncured conductive material may be selectively cured over at least a portion of the surface of the substrate, and a portion of the cured conductive material may be removed. A conductive via is formed by forming a hole at least partially through a thickness of a substrate, depositing an organometallic material within at least a portion of the hole, and selectively heating at least a portion of the organometallic material."

Comment: No heat in the desired method

Patent: US7481647

Quote:

"Systems and methods are disclosed for a platform to form a three-dimensional article from successively selectively solidified layers of a liquid medium which is solidifiable by application thereto of a prescribed energy."

Comment: Normal Stl.

Patent: US7520740

Quote:

“A stereolithography apparatus having a resin vat with resupply containers in one-way flow communication and a leveling container in two-way flow communication, an automatic offload cart to remove and replace build support platforms, an elevator assembly for supporting and releasably retaining a build platform removably attached to the stereolithography apparatus frame such that elevator forks supporting the build platform can be released into the vat and removed from the stereolithography apparatus with the vat, and a recoater assembly and recoater blade for mapping the resin surface in the vat and applying a fresh coating of resin to a cross-section being built in the vat.”

Comment: Resin vat not used. This is normal stl.

Patent: US7597835 *

Quote:

“Inventive machine allowing the simultaneous fabrication of several objects by a method of “rapid prototyping” type, by depositing a succession of layers of heat-fusible fluid.”

Comment: Heat-fusible fluids is a different method

Patent: US7658603

Quote:

“Because the stereolithography (SL) and direct-write (DW) technologies are integrated together, the integrated system **10** of the present invention depicted in FIG. 1, can easily be retrofitted into existing SL systems. The integrated system **10**comprises a preferred SL system **12** with a platform **14** and a vat **16** adapted to vertically traverse along a Z-traverse mechanism **18**. SL system **12** may include a platform **14** that is optionally adapted to rotate about a horizontal axis for angled part and circuitry building. It should be understood by those skilled in the art that although FIG. 1 depicts a single vat system, a multiple vat system may also be employed. It should further be understood that although FIG. 1 does not depict intermediate washing and/or curing units, a system which accommodates intermediate washing and/or curing may also be employed.”

Comment: Method is an adaptation upon exiting SL methods

Patent: US7814862

Comment: Drop on demand, similar to polyjet

Patent: US8155774

Quote:

"A 3D object fabrication method implemented in a fabrication system includes the following steps. A digital object model is retrieved. Sections of the digital object model are respectively printed on plural pieces of plane material. The pieces of plane material are combined to form a physical 3D object of the digital object model."

Comment: Method describes printing out sections of a 3D model for later assembly

Patent: EP0376571A2 *

Quote: " A three-dimensional object is produced by repeatedly exposing successive layers of liquid photosetting resin (3) at the surface of a quantity of the resin (3) stored in a vessel (2) to a light beam (21) so as to change each light beam exposed layer of the liquid photosetting resin (3) into a solidified layer, stepwise incrementally moving each solidified layer downward into the liquid photosetting resin (3) in the vessel (2) so that a new layer of the liquid photosetting resin (3) is coated on the solidified layer, detecting the temperature of the liquid photosetting resin (3), and heating the liquid photosetting resin (3) in accordance with the detected temperature to maintain the fluidity of the liquid photosetting resin (3)."

Comment: Normal SL

Patent: EP0403146A2 *

Quote:

An improved stereolithographic apparatus and method is described. In one embodiment, the improvement comprises immersing at least a portion of a part in a volume of a liquid solvent in a vapor degreaser while subjecting the portion to ultrasonic agitation to substantially remove excess resin.

Comment: SL

Patent: WO1988006494A1 *

Quote:

This invention relates generally to improvements in a method and apparatus for production of three-dimensional objects. More specifically, it relates to a method and apparatus for forming three-dimensional objects by the irradiation of photopolymers that solidify in response to radiation.

Comment: SL

Patent: WO1991012120A1 *

Quote:

"The apparatus includes a fixed support plate (28) disposed in a container (24), the liquid being dispensed to successively higher levels in the container above the plate.

In one embodiment, the liquid is fed from a reservoir (25) below the plate to an upper portion of the container above the plate by an expandable member (150) disposed in the reservoir."

Comment: SL

Patent: WO1994002905A1 *

Comment: Very similar. One of the mayor parts of my idea is the use of composites with fibre materials that may produce certain properties in the printed part. This is not present in this patent.

Patent: WO2013117185A1

Quote:

"To provide a method for the rapid generative manufacture of 3-dimensional objects, in which layers of pourable or flowable material lying one on top of the other are successively applied to a carrier base and the layers are respectively solidified and bonded to one another by the action of electromagnetic radiation or particle radiation, it is proposed that, while material is being applied and solidified, further layers are applied and solidified at a slightly different time, wherein the appropriate number of layers to be created partially at the same time is determined by the length of the carrier base and the rate of solidification"

Comment: SL

Appendix I: Quotes from RepRap forum RepRap.org

The following quotes with referenced links were used to describe the customer need and requirements for this project. They are described with a number, the headline, the web address to the specific thread and the relevant quotes. No further interpretation is described as the interpretation of the quotes with the thread title in the context of this report is assumed to be self-evident.

Thread 1 Metal-print Reprap, http://forums.reprap.org/read.php?2,169046

“Why hasn't this been done yet???”

“You need to ask - When I melt it, what is it's viscosity? Will it maintain the extruded shape during deposition? How quickly will it solidify? Will the heat of new material melt or weaken existing layers? Will layers bond effectively? Can I feed the unmelted material easily enough? and so on”

Thread 2 Conductive filiment, anyone? http://forums.reprap.org/read.php?184,311318

Thread 3 Fibre Core co-extrusion http://forums.reprap.org/read.php?143,255454

I have documented my thoughts on a fibre core extrusion in the Wiki.

The two concepts are winding the thread around the plastic so the correct amount goes into the melt zone so it will exit at the correct nozzle extrusion speed the other is some thoughts on a coaxial nozzle that would work much like a wire insulation machine but much slower.

Thread 4 Fiberglass thread extruder http://forums.reprap.org/read.php?143,37831

Among the many ideas I have already thrown out, and that other people have posted, I still think that the best second non-conductive material to extrude is fiberglass.

Thread 5 Conductive paint extrusion http://forums.reprap.org/read.php?143,114379

Has anyone thought of using conductive paint to create circuits?

Thread 6 Wire and Thread Embedded Extrusion, Introducing a new research project! http://forums.reprap.org/read.php?143,32944

I'm part of a team of three engineering physics students, and we're doing a project course. Our project is to add a new print head to the Reprap, capable of laying wire/thread materials directly from a spool into a printed part. The applications of this would be to print copper wires for cable routing, coils for motors/antennas/electromagnetic components, and connectors; or to print steel reinforcement wires, or (maybe) sewing thread 'living hinges' for flexing parts. We're about 90% done construction of our Darwin base model, and soon to begin on the print head

Thread 6 Major Software Tasks http://forums.reprap.org/read.php?143,39772

Here's a really relevant point when it comes to wire and thread embedded extrusion: The STL file format is highly insufficient.

For our project, we're just going to hand-craft the G-code to print models with wires in them. To do this, we'll start with an STL file, G-codeify it, and then insert the relevant wire G-code by hand.

It's a labour-intensive, machine-specific process that's not fit for the future adoption of this printing technology. You wouldn't be able to upload a G-code file with wires in it to Thingiverse, for example.

What we ideally need is:

- A 3D file format that can support these structures. It could amount to a very simple modification of the STL format, actually; wires could be no more than polylines in 3D space, which would be very simple to represent and process (just a string of XYZ points, really).

- A 3D modelling program that will let you create and store polylines in a model. If you've used SolidWorks, it might be just a matter of creating 3D sketches to represent wires, in addition to the solid part. But we'll need open-source software that can do this, because SolidWorks won't let you reprogram it, and Dassault Systems is not likely to respond to our feature requests. winking smiley

I'd be surprised if Blender could do something like this. Perhaps we'll have to wait on the numerous open-source CAD programs to be released?

- A plug-in for slicing programs like Skeinforge and Host, to generate wire G-code from the polylines.

All three are quite significant tasks. The scope of the SpoolHead project is to create workable hardware and firmware for printing wires into parts. But you won't see parts with wires in them popping up on Thingiverse until these software tasks have been tackled.

Of course, if Reprap is to accomplish multi-material (or colour) printing at all, we're almost definitely going to have to move beyond the STL format. It might be a good idea to start thinking of what's going to replace it. So I, for one, would nominate 3D polylines be considered as an important feature.

Thread 7 iron powder extruder http://forums.reprap.org/read.php?143,59565

Induction heating works with theoretically any material iron is just the easiest to do because you get the benefit of magnetic hysteresis in addition to the eddy currents. The only practical limitation are non-conductive materials. (That goes for directly heating them)

I think the main part would be the function generator/power supply. But once this has been done you could even make your own nozzle using ceramic printing and a induction heated mini-furnace to finish it.

Thread 8 Electroplating ABS prints from Prusa i3 – Problems http://forums.reprap.org/read.php?1,304620

I've recently built (my first RepRap) a Prusa i3 from Maker Farm and have gotten it calibrated and am getting beautiful prints. I'm now experimenting with electroplating these parts and am having issues. I'm plating with Nickel and prior to plating the ABS print is cleaned and then tinned. I'm getting a bright and shiny surface but the adhesion is really bad. The layers of Nickel are literally falling off.

Has anyone experimented with plating ABS and figure out a way to get better adhesion?

Thread 9 Gathering of every information about MetaliRap http://forums.reprap.org/read.php?215,228992

First of all, I'd like to emphasize that 3D metal printers at home ("low cost") will be a huge benefice for everyone, a true revolution. So the open source project MetalicaRap is really great, thank you !