

XZEED DLP

*A multi-material 3D printer
using DLP® technology*



Final bachelor assignment industrial design
10 July 2015, Enschede
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UNIVERSITY OF TWENTE.

Design and construction of a multi-material 3D DLP printer.

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The examination will take place on 15 July 2015

University of Twente

Industrial design

Final Bachelor Assignment

10 July 2015,

Number of pages: 91

Number of appendices: 13

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A handwritten signature in black ink, appearing to read 'R Holtrup', written in a cursive style.

Foreword

The reason for development of a multi-material DLP 3D printer is to prove the principle of multi-material printing using DLP technology. Many designers could benefit from the possibility of this technology since DLP printing is considered to be fast and more accurate than other 3D printing techniques and also has the possibility to achieve very high resolutions with smooth finished surfaces. Enabling material switching during printing might enable building new products, which can have electric conductive paths, or regionally adjustable stiffness, for example. For me this project was a bit different than the other projects in my bachelor since a full functional prototype had to be built from scratch. Since the mechanical demands in terms of accuracy, precision, and optic specifications were a lot higher than for the other projects, much investigation had to be done on how to get the materials, tools and how to calibrate the prototype. For building the prototype I required many parts, about which I didn't have knowledge in advance. The time for the project was very short and often concerned me. This resulted in long days of hard working. Designing and building the prototype really demanded a lot of me. Also the insecure feeling of dependency on other people kept me busy. For this project this resulted in unplanned slowdown. Later if I would work in the industry this would also happen, but then this would also cost money. I have applied a lot of things of what I've learned during my bachelor. From materials to construction using laser cutting, 3D printing, drilling and using a lathe, from generating concepts to modelling in Solidworks, from selecting electronics and programming and communication. It was a hard assignment. Looking at the result I'm very proud of what I've achieved in the limited time of only three months. Every part fits very neatly as I have designed and the printer looks very professional. It's a pity that I didn't have time to validate the possibility of printing objects, although I'm pretty sure that it will work as soon as it's calibrated. Now I'm looking back on the result with a very satisfied feeling.

I would really like to thank Tom for the fast response to my questions and his fast processing of material orders. I really liked his relaxed attitude. He really thought along with me where I needed it.

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Abstract

The 3D DLP printing process was studied. In DLP printing a projection coming from a DLP beamer is projected on a resin containing photo initiators, monomer and blockers. A thin layer in the shape of the projection is polymerised and a moveable build platform moves this layer one-layer thickness so that a new layer can be polymerised. Since photo initiators are sensitive to specific wavelengths of light mostly in the UV-A ($\lambda < 400\text{nm}$) and near UV band (400-420nm), the optical system has to be designed for curing within these bands. There are many aspects that influence the polymerization process: The formula of the resin, inhibition by oxygen, the wavelength band of the projected light, the intensity, the exposure time, and temperature. They result in the amount of shrink, the density, toughness, the amount of uncured resin, the thickness of the curing gradient and the optimal layer thickness. The resolution of the beamer and the projected size account for the XY accuracy of a printed object, although shrink and bleed cause inaccuracy. The minimal step resolution of the motor driving the Z-axis is called the mechanical resolution. This is the linear movement per step. The resolution in the Z-axis is also influenced by how accurate the focus is. Since the refraction index of a lens system is wavelength-dependent, the focus will differ for lower and higher wavelengths, thus the more monochromatic the light, the lower the range of focus points, thus the higher the Z-accuracy. Projecting monochromatic light at the photo initiator's peak-absorbance wavelength is also better, since less light energy will be transferred to heat because of absorbance by pigments and blockers. The higher the temperature, the higher to polymerization rate and the higher the amount of shrink.

Secondly a range of existing 3D DLP printers was analysed. One of the most important aspects of the construction is the anti-stick solution. Because of the projection of light from the bottom of the vat, the molecules closest to the bottom of the vat will be cured. This will cause adhesive forces with the bottom. Another reason why it sticks is the air pressure: Lifting the platform will cause a vacuum that 'pulls' on the printed object. The following solutions are found: Putting a layer of oxygen permeable PDMS on a solid vat floor: Since oxygen inhibits the polymerization process, a thin layer of uncured resin will be generated at the bottom of the vat. Since PDMS is a bit flexible too, it will also help to break the vacuum easier. Another method is to place a flexible film of oxygen permeable FEP at the bottom of the vat. This solution is more reliable since it is inert and not degraded by high temperatures (PDMS does this) but is less easy to make compared to PDMS. The flexibility also makes it easier to break the vacuum. Other solutions to easily break the vacuums include mechanical steps: Shoving, or tilting. These mechanical steps lower the amount pulling force significantly. Having control of the inhibition rate caused by oxygen makes these steps unnecessary. (CLIP technology)

Inspired by the existing printers and by taking care of the theory, a multi material 3D DLP printer prototype was designed (Fig.1) and build. This printer features a moving array of petri dishes covered with a layer of PDMS and a passive tilting system (1) to make the layer peeling easy. A modified DLP beamer (2) was used as the source of the projection and projects via a mirror (3) to the bottom of the petri dishes. A build platform (4) pulls the object out of the vat. The control of the stepper motors (5) was done by a motherboard (6) loaded with firmware that communicates with host software. This host software controls the beamer concurrently to the motors. The printer was mainly build using 3D printing and laser cutting, although some post processing of the parts was needed to bring up the result.

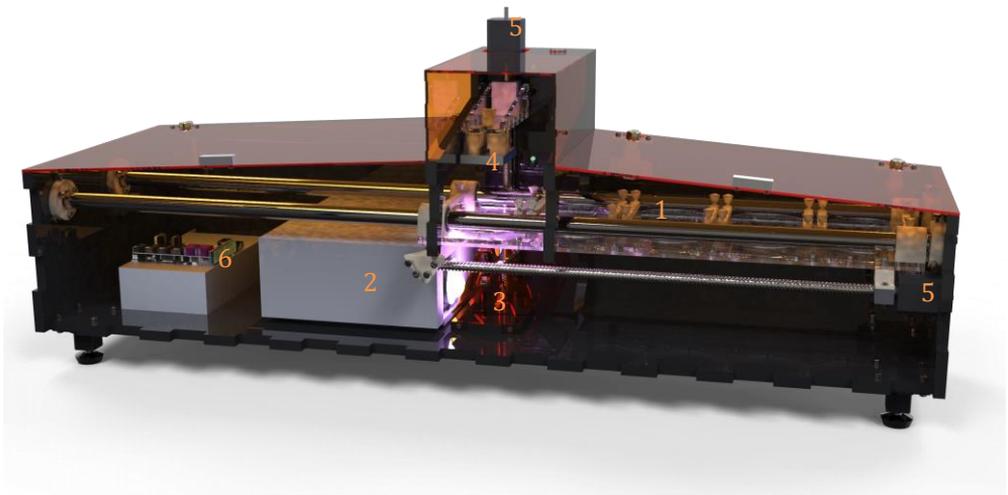


Figure 1:The result with removed front planes

Abstract (Dutch)

Het 3D DLP print proces is bestudeerd. Bij DLP printing wordt een afbeelding op een oplossing met foto initiators, monomeren en blockers geprojecteerd. Een dunne laag vloeistof wordt in de vorm van de projectie gepolymeriseerd. Vervolgens verplaatst een bouwplatform zich met 1 laagdikte zodat een volgende laag gepolymeriseerd kan worden. Omdat foto initiatoren gevoelig voor specifieke golflengtes, meestal in de UV-A ($\lambda < 400\text{nm}$) en bijna-UV (400-420nm) banden, moet het optische systeem ervoor geschikt zijn om de vloeistof te kunnen uitharden in deze banden. Er zijn veel aspecten die het polymerisatie proces beïnvloeden: De samenstelling van de oplossing, de tegenwerking van zuurstof, de bandbreedte van het geprojecteerde licht, de intensiteit en belichtingstijd en de temperatuur van de oplossing. Deze variabelen hebben uitwerking op de hoeveelheid krimp, de dichtheid, de stugheid, de hoeveelheid niet uitgeharde oplossing, de dikte van de uithard gradiënt en de optimale laagdikte. De resolutie van de beamer en het geprojecteerde oppervlakte zijn verantwoordelijk voor de XY nauwkeurigheid van een geprint object, hoewel krimp en vloeïng dit negatief beïnvloeden. De lineaire verplaatsing die één motorstap veroorzaakt is de mechanische resolutie van de Z-as. De resolutie van het te printen object wordt ook beïnvloed door de accuraatheid van de focus. Omdat breking van een lenzensysteem golflengte-afhankelijk is, zal de focus verschillen voor lage en hogere golflengtes. Hoe beter het licht monochromatisch is, hoe lager het bereik van de focuspunten is, dus hoe hoger de Z-nauwkeurigheid. Het projecteren van monochromatisch licht in de piek-golflengte van de initiator is ook beter, omdat de door het pigment geblokkeerde licht energie wordt omgezet in warmte. Hoe hoger de temperatuur, hoe groter de polymerisatie snelheid en hoe groter de krimp.

Een aantal bestaande 3D printers zijn geanalyseerd. Eén van de belangrijkste aspecten bij het bouwen van een DLP printer, is een anti-plak oplossing. Omdat de projectie van onderaf, de onderste laag moleculen in het vat doet polymeriseren, zullen deze gaan plakken aan het vat door adhesie krachten. Ook de luchtdruk zorgt voor het plakken, want het optillen van het platform veroorzaakt een vacuüm dat aan het product 'trekt'. Hiervoor zijn verschillende oplossingen bedacht: Het plaatsen van een laag zuurstof doorlatend PDMS op een solide transparante ondergrond: omdat zuurstof de reactie tegengaat, zal er een dunne laag niet-uitgeharde vloeistof ontstaan op de bodem van het vat. Omdat PDMS ook flexibel is, zal het ook helpen bij het verbreken van het vacuüm. Een andere methode is het plaatsen van een flexibele film van FEP op de bodem van het vat. Dit is een wat duurzamere oplossing, omdat FEP inert is en niet door hogere temperaturen degradeert. (PDMS doet dit wel) Het is wel moeilijker om te maken in verhouding tot PDMS. De flexibiliteit maakt het ook makkelijker om het vacuüm te breken. Andere oplossingen voor het verbreken van het vacuüm behelzen mechanische stappen. Schuiven of kantelen. De mechanische stappen

reduceren de kracht significant. Het controleren van de tegenwerkingsnelheid van zuurstof maakt deze stappen overbodig. (CLIP technologie).

Geïnspireerd op de bestaande printers en rekening houdend met de theorie, is er een prototype ontworpen en gebouwd. Deze printer heeft een bewegende houder voor petrischalen die bedekt zijn met een laagje PDMS en voorzien is van een passief kantel systeem(1) om het pellen makkelijk te maken. Een gemodificeerde beamer werd gebruikt als bron voor de projectie en projecteert via een spiegel(3) op de bodem van een vat. Het regelen van de stapmotoren(5) wordt gedaan door een moederbord voorzien van firmware die communiceert met de host software. Deze host software stuurt de beamer aan gelijktijdig met de motoren. De printer is hoofdzakelijk gebouwd door gebruik te maken van 3D printing en laser snijden. Hoewel veel handmatige nabewerking van de onderdelen nodig was om het resultaat te vervaardigen.

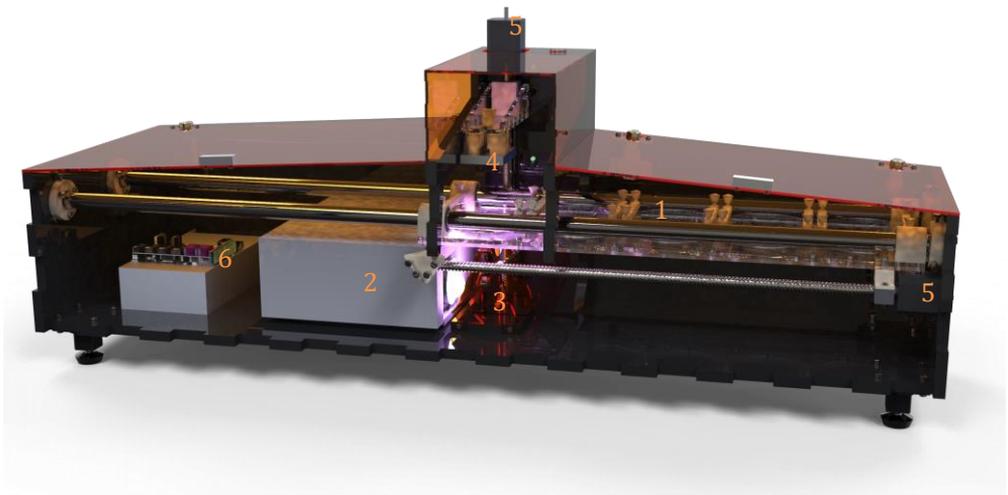


Figure 2: Het resultaat met de voorpanelen verwijderd.

Introduction

3D printing is a strong developing technology which is considered to be a very important method for making products in the future. It has certain advantages to conventional production techniques and makes it possible to make products that couldn't be built in other ways. (Hopkinson, Haque, & Dickens, 2005) 3D Printing can be done using various methods which each has their own advantages and disadvantages. A promising method is 3D DLP printing. This is one of the vat polymerisation SLA techniques. It works by projecting images to a resin in layers, partly masked. This technology uses a light source that projects light on a Digital Micro mirror Device, which reflects the light with millions of microscopic mirrors that together form an image. On the spot where the image projects, a photo polymerisation process is initialised and thus cures. By moving a build platform, a new layer can be cured and a 3D product appears. Big advantages are the possibility to cure fast and with high accuracy, with a clean appearing surface finish. One of the disadvantages is that they are limited to a single material. This is why it is not possible to print a product that has soluble support material.

Advantages

The biggest advantage related to other techniques is that a whole layer is cured at once. This reduces the positioning errors in the XY-plane due to limited mechanical movement. The mechanical system is less complex than other techniques, since it only consists of a single axis of movement. The resolution of 3D printed parts using DLP printing is considered to be very high and the surface finish is smooth. This makes DLP printing suitable for the production of masters for injection moulding. Since in DLP printing the minimal diameter of vertical oriented objects is smaller, the supports can be a lot thinner than in FDM.

Disadvantages

DLP doesn't allow soluble support material like in FDM printing, but the support has to be of the same material as the build material. The photopolymer resins that are used for DLP printing are quite expensive (around €80 per litre) and the shelf life of the material is limited. The build size is limited to the power of the light source and the area of the projection. Generally the build size is about 50x40mm to 100x80mm, which isn't very big. The cost of a DLP printer is often much higher than standard FDM printers, although not as expensive as SLS or 3D inkjet printers. However, costs will reduce as more people adopt the resin-based 3D printing systems. For good DLP printing, optics that have a high transmittance of UV light are required. These are expensive. DLP printing also uses very bright UV light, which is dangerous to the eyes.

Method

The goal of this project is to develop a prototype for a DLP printer capable of printing multiple materials. In order to do this, the printer has 5 moveable vats. Before the design of the printer could start, research to the principle had to be done in order to be able to make the right design choices. The following aspects of interest:

- (A) Photo polymerisation
- (B) The influence of light
- (C) Layer thickness
- (D) XY-Accuracy
- (E) Z-accuracy

The design of the printer was done in the following way:

- (A) Analysis of existing printer, estimating the boundary conditions for the design
- (B) Determination of available components, existing software and compatibility.
- (C) Design of the electronics and functional components (Connections, interfaces, motor control etc.)
- (D) Tuning software to own system
- (E) Building a physical prototype

A manual on how to design a normal DLP printer made from a beamer already existed. (Budel, 2013) Stepper motors, a beamer (Benq PB7230) and a 20mm lead spindle were already available. Other parts were bought from vendors. Software is available, although needs to be extended in functionality.

DLP technology

Digital Light Processing

DLP stands for Digital Light Processing. This technology is developed by Texas Instruments for multiple applications, including projectors, spectroscopy, 3D scanners, machine vision, head-up displays and medical applications, (Texas Instruments, 2015) The technology is basically a matrix of millions of microscopic mirrors which have an angle that can be controlled from a Digital Micro mirror Device (DMD) controller (1220 in Fig. 3), which has digital input from a microcontroller. (1240)

DLP Beamers

In a DLP beamer the light passes from a lamp (1210) through a spinning colour wheel (1230), on the DMD chip. From the DMD chip (1220) the light is projected through a lens system (1250) onto the screen (1270)

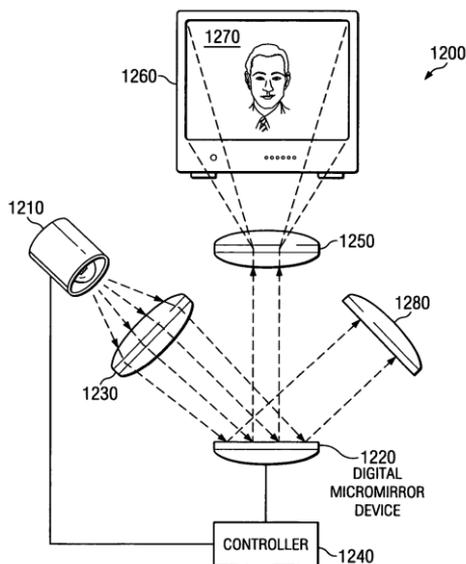


Figure 3: DLP Beamer Technology by Texas Instruments (Anthony DiCarlo, 2015)

Metal halide lamp

Typical lamps found in DLP beamers are metal halide lamps. These lamps contain mercury vapour and metal halides such as sodium iodide and scandium iodide. As soon as the running temperature is reached, the metal

ionizes and produces photons. They consist of a small fused quartz glass tube surrounded by a glass bulb with a coating to filter most of the UV, although some of it passes. (Wikipedia: Metal-halide lamp, 2015) Below is an image of the emission spectrum of a typical metal halide lamp. As you can see it outputs some UV light ($\lambda < 400$), which is the wavelength band that can trigger photo-initiators that are used in 3D DLP printing.

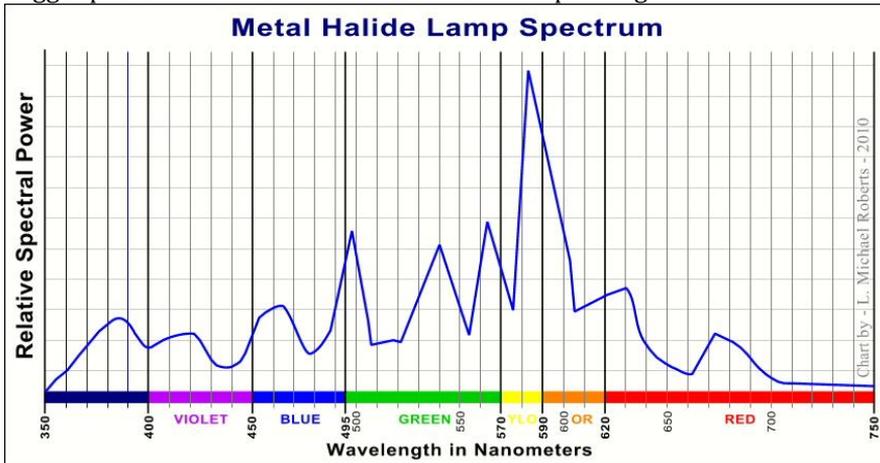


Figure 4: Spectrum of a typical metal halide lamp (Wikipedia: Metal-halide lamp, 2015)

Colour wheel

After the light has left the lamp, it passes through a colour wheel. This is a small spinning wheel, which spins at *Colour Wheel Speed* · 60Hz. In the Benq beamer it spins at 120Hz. The colour wheel filters the white light in chunks of light with specific colours by absorbing the others. The DMD chip is programmed to be timed according the position of the colour wheel. When for example a red screen has to be projected, the DMD only mirrors the light at the moments when the chunk of light that passes though the Colour Wheel is red. The colour wheel blocks certain wavelengths, however even without removing the colour wheel, there is still UV-output.

Digital Micro mirror Device

The DMD technology is owned by Texas Instruments. It is invented by dr. Larry Hornbeck in 1987. (Texas Instruments, 2015) Nowadays it consists of a thumbnail sized chip with millions of controllable mirrors. 2560x1600 is the maximum available resolution at the moment. (Texas Instruments, 2015) Typical chips used in standard beamers are the DLP5500 0.55 XGA DMD and the DLP7000 .7 XGA 2xLVDS Type-A DMD. These Chips use the XGA resolution (1024x768) Besides the resolution, another important parameter for the purpose of 3D printing is the reflection wavelength range. For the .70 this is 400-700 and for the .55 this is 420-700 (which is the DMD used in the Benq beamer that was available for this project). Texas Instruments recommends DMD chips optimized to reflect wavelengths $\lambda < 400$ to be used for 3D printing. These are the DLP7000, DLP7000UV, DLP9500, DLP9500UV,

DLP6500FYE, DLP6500FLQ, DLP9000, The DMD's with "UV" in it reflect 363-420nm (Texas Instruments, 2015) so the mirror reflect more light in the curing wavelength band and works as a filter to output just the right wavelengths at once.

DLP technology for 3D printing

DLP technology can be used for 3D printing. A thin layer of resin is cured by projecting an image on a photopolymer resin. After a thin layer is cured, a stepper motor moves the layer one layer thickness upward or downward (see the bottom-up & top-down section.) A new image is projected and this continuous until a 3D product is made. In (Fig. 5) an overview made by Texas Instruments. Is depicted.

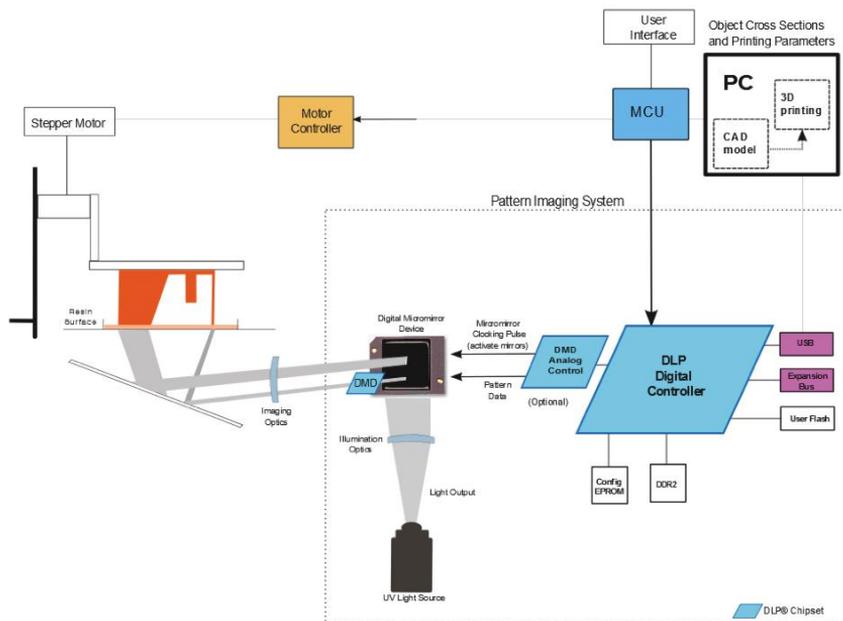


Figure 5: DLP technology for 3D printing (Texas Instruments, 2015)

Photopolymer resin

The photopolymer resin might be one of the most important parameters for accuracy and precision in DLP printing. Although the range of resins commercially available is big, they are all based on the same combination of ingredients: They consist of monomers/oligomers, a photo initiator (sometimes multiple mixed together to work at a wider band of wavelengths) and blockers. Basically there are two types of reaction mechanisms: Cationic and Free radical. The cationic is polymerization

through epoxy groups and free radical is polymerization through double bonds in for example (Meth)Acrylate.

Cationic curing (epoxides, oxetanes and vinyl ethers etc.) (Crivello & Reichmanis, 2013)

When in cationic curing a photo initiator is exposed to light with the right amount of energy it releases a Lewis acid. These acids react with epoxy groups and this results in polymerization.

Photolysis

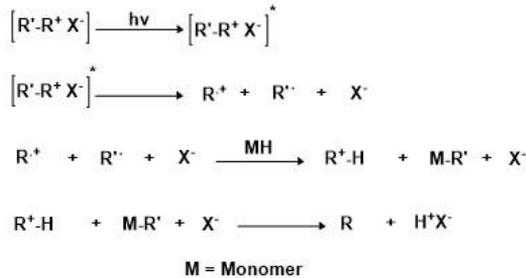


Figure 6: Cationic photo polymerization mechanism (Wikipedia: Photopolymer, 2015)

Free radical curing (acrylates, styrenes etc.)

When the initiator is exposed to a photon with the right amount of energy, it generates a free radical (initiation) and immediately seeks a double bond of a monomer/oligomer to attach to. The reaction continues by attaching to other monomers. (Propagation) The reaction stops if the end of the chain is connected to another chain. There are two possibilities: They together form one big chain (combination) or one of the chains transmits a hydrogen atom to the other resulting in two shorter polymer chains. (Disproportionation)

Initiation



Propagation



Termination



Figure 7: Free radical photo polymerization mechanism (Wikipedia: Photopolymer, 2015)

Resin formula

The resin solution determines the properties of the product. There is a strong relation between layer-thickness and resin composition. The more blocker, the thinner the layer. The more initiator, the faster the reaction, but

the lower the molecular weight and the lower the crosslink density. An example of a resin composition is the following recipe: (Bucktownpolymers, 2013)

Monomer: 1000 ml 1,6-Hexanediol diacrylate (also known as HDODA)

Photo initiator: 20 g Phenylbis(2,4,6-trimethylbenzoyl)phosphine oxide (known as Irgacure 819)

Blocker: 0,06 g 1-phenylazonaphth-2-ol (known as Sudan I)

Monomer & oligomers

For 3D printing many monomers/oligomers can be used but they all have their own specifications regarding curing speed and viscosity. Acrylates cure fast so these will be useful. There is a table in Appendix 1 that describes curing properties for various acrylic monomers. (3Dprinter.wikidot, 2011) Acrylic monomers can have different numbers (1,2 3, 4) of functional groups. Generally, but not always true: The more of higher functional group monomer number is added, the lower the reaction speed, but the higher the viscosity reduction, the higher the flexibility, the higher the higher the adhesion and the higher the uncured residual. (Idacavage, 2012) This is caused by the decreased mobility of the monomers due the formation of a cross-linked network micro gel. (Lee, Sonny Jonson, Hoyle, & Guymon, 2004)

Photo initiator

Photo initiators are sensible to specific wavelengths. The peak absorbance of the chosen photo initiator should fit with the projected light. In Appendix 2 you can find a table with common initiators and their peak absorbance wavelengths. The absorption spectra change if the concentration of photo initiator is changed. Not only the amount of absorption, but also the wavelengths can change. Sometimes multiple photo initiators are added to the resin to extend the bandwidth of sensitivity. In the (Fig. 8) various initiators are depicted. There are initiators that work in the UV-A spectrum (below 400nm) and initiators that work in the visible spectrum (400-700nm) There also exist photo initiators that work in the UV-B or UV-C, although for the purpose of 3D printing these are not very suitable since they would require expensive optic equipment and are dangerous. There are photo initiators that produce directly a free radical after light absorption (Type 1) and there are photo initiators that require a co-initiator (Type 2) The H-Nu family is of the second type and requires partners like amine and iodonium salt co-initiators. (Spectra Group Limited, 2015) The purple graph on the next page represents a suitable solution for 3D printing using a beamer, since it is quite wide, it is even a bit sensitive in the visible spectrum and doesn't require co-initiators. Like in many commercially available resins it is a mix of photo initiators.

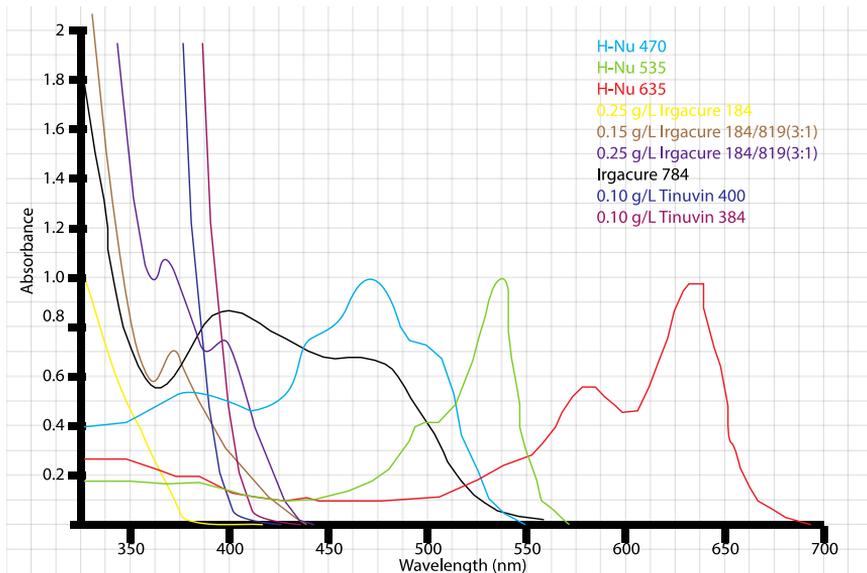


Figure 8: Absorption spectra of various photo initiators (Spectra Group Limited, 2015) (Ciba Specialty Chemicals, 2015)

Blockers

Pigments block light by absorbing or by refraction. Without inhibitors or pigments, the light would pass through all of the resin. There are two options for blocking with pigments: Refraction produces scatter which effects XY accuracy negatively. Blocking produces heat. Pigments should be chosen so that they absorb the light where the initiators are sensible to. This way the amount of pigments regulates the light penetration and thus the layer thickness. The absorption curve of some common blockers is depicted in (Fig. 9)

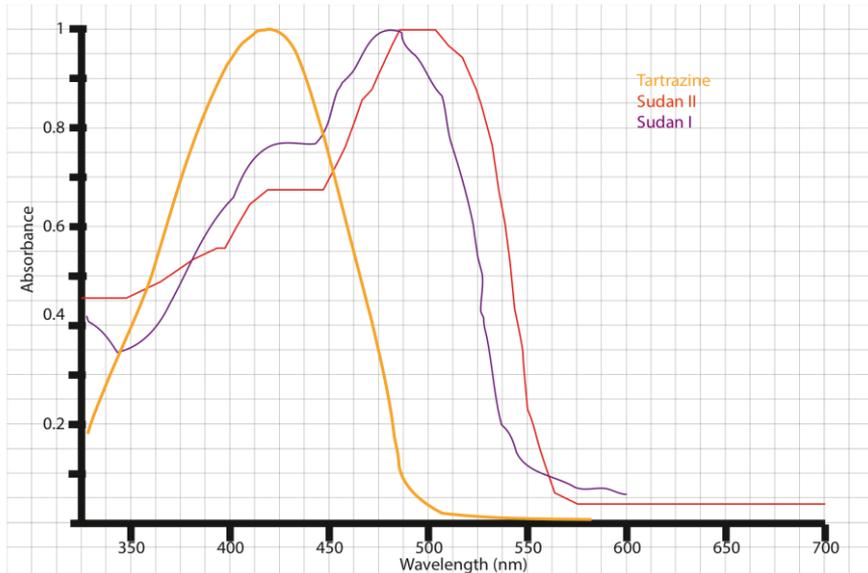


Figure 9: Absorption Spectra of various blockers. (PerkinElmer, 2015) (Li, et al., 2007)

Photosensitizers

Sometimes photosensitizers are added, to extend the photosensitivity bandwidth of the initiators. They absorb light at wavelengths where the initiators are not sensitive to and transfer the excitation to the photo initiators. This way they extend the band that causes curing.

Inhibition by oxygen (only for free radical reactions)

Oxygen can inhibit the photoreaction since it consumes free radicals. (Batch & Macosko, 1990). For (meth)acrylates, the oxygen concentration is approximately 10^{-3} mol/L (Chong, 1969), which is higher, then the concentration that allows polymerization. The influence of oxygen on the reaction depends on the chosen monomer. Trimethylol propane triacrylate is less sensitive to oxygen inhibition than 1,6-hexanediol diacrylate. Methacrylates are less sensitive to oxygen inhibition then acrylates. (Lee, Sonny Jonson, Hoyle, & Guymon, 2004)

Extra ingredients

Other ingredients can be added to the formula, like metal or ceramic powder. After printing the metal can be burned-out and produces a cast-metal product. (Venus Creator, 2015)

Shrink

Since blocked light will be directly converted to heat and the polymerization reaction is exothermal, shrink will occur. The amount of shrink will depend on the monomer that was chosen. In Appendix 1 there are different shrink percentages noted down for different materials. The amount of shrink is between 5-10% for acrylics, but can be lowered if the amount of generated heat can be lowered, by just projecting the right wavelengths. For 1,6-hexanediol diacrylate the amount of shrink decreases when the temperature decreases and also decrease when the relative amount of photo initiator is decreased. The influence of the temperature is much stronger than the influence of the photo initiator concentration. (Ji, Chang, Ming, & Nie, 2013) For 3D printing purposes shrink is undesired so the temperature of the resin and the photo initiator concentration shouldn't be too high.

Dose & layer thickness

Dose is a unit for the amount of effective light energy exposed to the resin. The curing rate increases when the rate of photons with the right wavelengths is increased. The exposure time increases the amount of photons exposed to the resin. $Dose = exposure\ time * luminence_{@ \lambda\ Photoinitiator}$ Layer thickness is dependent on the variable Dose, the amount of blocker, the monomer type and the amount of photo initiator. It is also dependent on the inhibition by oxygen. Dose can be regulated by the control of the beamer. The parameters are thus different for all resin formulas.

Wavelength

The wavelength of the light projected on the resin should be about the same as that of the wavelength where the initiator is sensible to. All other wavelengths will not initiate the reaction and since the energy of these wavelengths is absorbed will result in heat. Heat is undesired since it causes the material to shrink, which limits the accuracy of the print. Another point of why only the right wavelengths should be projected is to limit dispersion: Since the refraction index of the material of the lens is dependent to wavelengths of the light, the focal distance will be different for each wavelength. Since the UV light will be broken much more than the higher wavelengths, the focus point for UV will be further away than the focus point for visible light. This is the reason why photo camera lenses are often coated

to block UV light. The different refraction indexes will result in unsharp prints.

XY and Z resolution

While using 3D printing, one of the main parameters for choosing the right printer is the maximum resolution. For DLP printing (like for many other printing techniques) the XY-resolution is different to the Z-resolution. The XY-resolution is determined by various influencers: The resolution of the DMD, lens distortions, the distance of the beamer to the bottom of the resin, scatter generated by blockers and shrink (see “Shrink”). The theoretical resolution when using a XGA beamer on a platform size with a width of 50mm, results in a XY-resolution of $\frac{1024 \text{ pixels}}{50 \text{ mm}} \approx 20 \text{ pixels/mm}$ or $\frac{1}{20 \text{ dots} \cdot \text{mm}^{-1}} * 1000 \mu\text{m} = 50 \mu\text{m}/\text{pixel}$. The Z-resolution is determined by the mechanical resolution and is also influenced by shrink.

Mechanical resolution Z-axis

For DLP printers, manufacturers often speak about the mechanical resolution. Since a stepper motor is used to drive the spindle where the build platform is attached to, the positions of that platform are discrete. This is because the motor has a minimum stepping angle. Activating micro stepping on the stepper driver lowers the stepping angle and thus the mechanical resolution. Another parameter is the chosen lead of the spindle. A smaller lead will result in a higher mechanical resolution, but will cut the maximum speed down. $\text{Mechanical resolution} = \text{lead} / (360 / \text{Stepping angle} * \text{microstepping mode}$ for example $\frac{2 \text{ mm}}{360} * \frac{1}{0.5} = 400 \text{ steps per mm}$. Each half step will thus result in a translation of $2,5 \mu\text{m}$. However, the precision of the spindle should be 100% and the backlash should be zero in this case, which in reality will not be true. There will also be vibrations of the platform since it will not be connected with infinite stiffness.

Bottom-up or top-down printing

In DLP printing there are basically two construction types. Most often they are referenced with bottom-up or top-down. The picture below explains which is which, described in patents by Envisiontec, Carbon3D and which are the names common used by 3D SLA printer builders on the buildyourownsla.com forum. Both printing techniques have their own benefits, but also their own problems. Since a system with changeable resin vats needs to be constructed, the only suitable type will be bottom-up.

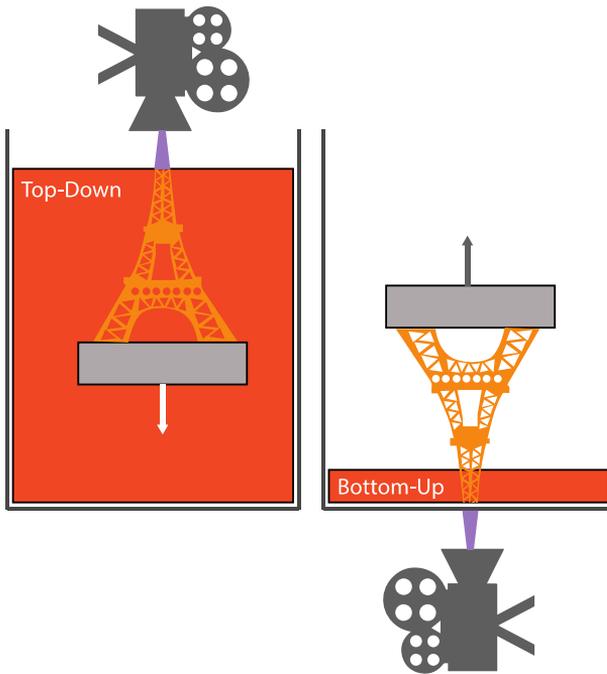


Figure 10: Bottom-up versus Top-down DLP printing

Top-down

In top-down DLP printing, the object that is printed is on top of the build platform and is moved downward during printing. The depth of the vat limits the maximum height of the printable object since the object sinks deeper and deeper. The printer cures the top layer of the fluid. While for printing an object only a small amount of resin might be needed, the vat needs to be filled completely with resin. Since the resin is not stored in perfect conditions this way, degeneration of the resin will occur. Top-down printers have one big benefit compared to bottom-up printers: They are easier to build and they don't need a mechanism to break the vacuum between the resin vat and the object. (See bottom-up) While the platform moves deeper into the fluid, it changes the fluid level of the resin. Making the support of the build-platform slim and the area of the surface relative big can solve this problem. The system can also be equipped with a fluid level sensor and an actuator to compensate for the level change as described in a patent owned by Envisiontec. (Scholnik, El-Siblani, & John, 2006)

Bottom-up

In bottom-up DLP printing, the printed object hangs upside-down on the platform. The object is pulled out of the resin. The biggest advantage is that only a small layer of resin needs to be in the vat. The biggest disadvantage is

that the cured layer is directly placed on the bottom of the resin vat. The resin vat needs to be covered with an optic-transparent anti-stick layer and the vat needs to be made of a material that is also transparent to the wavelengths where the resin is sensible to. Since the layer is cured directly to the bottom of the vat, a vacuum between the wall and the bottom of the product is formed. A force is needed to pull the product from the bottom of the vat. The vacuum can be broken by using by peeling, or by moving the object to a deeper place in the vat. This makes the design of a bottom-up printer more complex compared to a top-down printer.

Conclusions about the analysis

DLP beamers have a small output of light in the wavelength band that triggers photo initiators. There are two types of polymerization reactions that are triggered by photo initiators. Cationic and free radical reactions. Free radical photo initiation is inhibited by oxygen since oxygen consumes the free radicals faster than the monomers. Oxygen is dissolved in the resin by nature in amounts that are really significant to the curing rate. Photo initiators have peak absorbance values at specific wavelengths. Mostly they are triggered by light with a wavelength below 400nm (UV) although there also exist photo initiators that work within the visible light band. The exposed light that won't trigger reactions is converted to heat. The heat speeds up the curing rate, but also increases the shrinkage of the product. Since the quality of the 3D printed object is very dependent on this shrinkage, the temperature of the resin should be kept low and only the right wavelengths should be exposed to it. Another reason why just the right wavelengths should be projected is to limit dispersion that causes unsharp prints. There are various monomers and oligomers that can be used for 3D printing, although they all have their own curing speeds. The curing speed is very dependent on the mobility of the molecules. Very suitable for 3D printing are acrylics. The more functional groups of the acrylic molecules, the lower the mobility, thus the lower the curing rate, the higher the viscosity, the tougher the material, the more uncured resin and the lower the density of the product. Basically there are three main ingredients: the monomer, the initiator and the blocker. The ratio in which these ingredients are added influences the curing process. The more initiator, the faster the inhibition by dissolved oxygen is overcome and the faster the curing rate, but the more shrink occurs. The more blocker is added, the thinner the layer thickness is, but if the layer thickness is too thin, printing takes too long, and the product won't fully cure. The layer thickness should fit with the mechanical control of the build platform. Although in theory mixing the ingredients is not very hard, there are many variables and since the time is limited, for this project it is just easier to buy off-the-shelf resin. Some companies sell their products without pigments added to it. Since the future goal is blending dusts with the resin and the dusts influence the blocking of light, it are these kinds of resins that are the best suitable for the purpose of proofing multi-material DLP printing. The precision of DLP printing is influenced by the optical specifications, the mechanical accuracy of the printer and by the chemical composition of the resin. The higher the amount of pixels, the higher the resolution, the clearer the lens, the less distortions. The better the focus, the higher the precision. The better the filtering to wavelengths suitable for curing, the lower the shrink, thus the higher accuracy. There are two types of DLP printing: Bottom-up and top-down. Both have their own advantages and disadvantages but for the purpose of multi-material printing only bottom-up DLP printing is suitable.

Reference DLP Printers

The technology of DLP printing has been around for quite a while, however at the moment many DLP suitable for desktop usage arise. There are already many DLP printers commercially available and there are also many people that build their own printers. In this chapter some of the aspects of some printers will be evaluated since they have their own solutions to problems that arise with bottom-up 3D DLP printing.

Envisiontec Perfectory

Envisiontec sells a professional 3D DLP printer, which can print objects that have a maximum bounding box of 192 x 120 x 230 mm at a projection resolution of 100 μm . and a dynamic Z-resolution of 25-150 μm . This printer (Fig.12) has an active peeling mechanism combined with a flexible film placed over the bottom of the surface, to be able to peel the printed layer from the vat floor. (Fig. 13) The film is made of FEP, PTFE or PFA. (John & Envisiontec, 2007) The patent also describes the use of a silicon layer instead of a flexible film, which in fact has the same effect. The Envisiontec Perfectory also has an orange transparent hood. Since resin is cured at low wavelengths, only high wavelengths are allowed to pass. This is why the hood should be made of orange or red transparent material.



Figure 11: The Envisiontec Perfectory

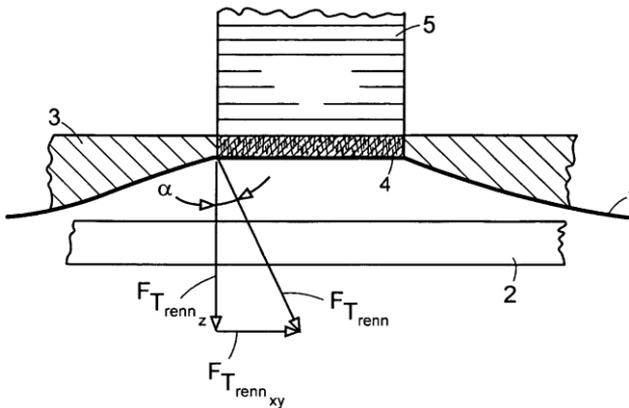


Figure 12: The thin film peeling solution from the patent with 1 is the thin layer 2 a transparent floor, 3 the photopolymer, and 5 the object (John & Envisiontec, 2007)

Tristram Budel's 3D SLA printer Instructable

Tristram Budel is a Dutch inventor and in 2013 he placed a step-by-step tutorial about how to build a DLP printer (Fig. 14) at home, using a normal DLP Beamer on the website www.instructables.com (Budel, 2013) For the structural part (Fig. 15) he used aluminium Bosch profiles. For the electronics he used an Arduino Mega with a Ramps 1.4 motherboard, Pololu stepper driver carriers, a Nema 17 stepper motor and a 12V power supply. For the mechanics he used a 360mm long, 12mm diameter spindle with a lead of 3mm and trapezium thread with a tolerance of 7e in combination with an anti-backlash nut. The resin vat was made of a borosilicate glass floor covered with a layer of PDMS (Sylgard 184 silicon elastomer kit) and he glued acrylic walls to it. As firmware he has loaded an Arduino with the Sprinter firmware and as his host software for setting up, slicing and beamer & printer control he used Creation Workshop, shareware software developed by Steve Hernandez also known as Pacmanfan. (Hernandez, 2015)

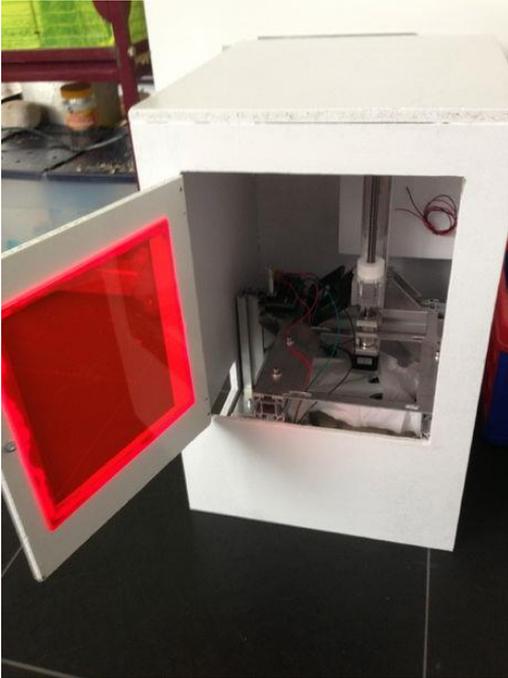


Figure 13: The DLP printer build by Tristram Budel (Budel, 2013)



Figure 14: Construction using Bosch profiles (Budel, 2013)

B9Creator

The B9 creator has another solution to the vacuum problem. The object slides horizontally into a deeper area in order to peel the object from the

surface after a layer of resin is cured. The bottom surface of the vat (Fig. 15 & 16) is covered with a layer of PDMS. This layer absorbs oxygen and creates a thin lubricating film of unpolymerized resin. (Joyce, 2013) The PDMS layer swells by absorbing resin and gets damaged during use. It is considered to be a consumable.

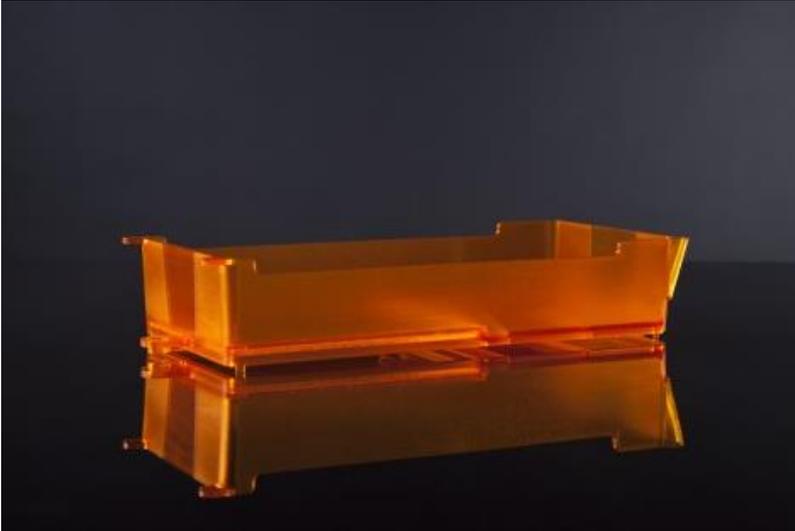


Figure 15: Resin vat of the B9Creator

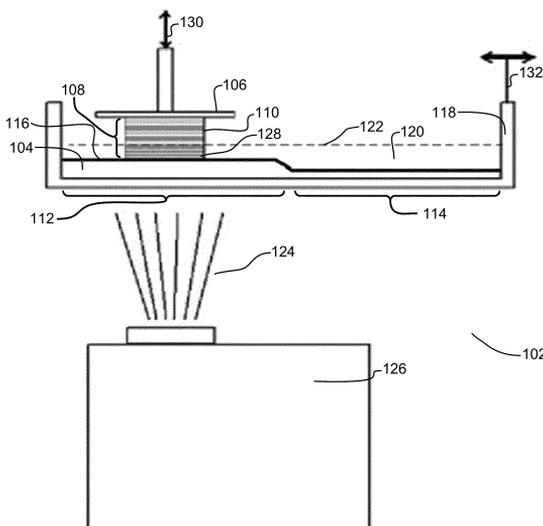


Figure 16: The slide mechanism in the B9 Creator (Joyce, 2013)

DLP printer with active tilt system made by 'watsonstudios'

There are various home-built DLP printers described, just like the one of Tristram Budel. One of the printers that are featured in this section is the printer of forum poster 'watsonstudios', (watsonstudios, 2013)(Fig.17) since it has a tilt system for peeling the layers of. The tilting causes the vacuum to break with a smaller force than when the product was pulled of in the normal direction to the floor. In order to do this, it uses a servo that tilts the vat support downward. After tilting, the platform is moved a bit up- and downward to peel the product.



Figure 17: The active tilting vat support. Left: not tilted, right: tilted (watsonstudios, 2013)

Carbon3D continuous printing using CLIP technology

'CLIP' stands for Continuous liquid interphase printing. (Desimone, Ermoshkin, Ermoshkin, & Samulski, 2014) It is a technology that cancels the need for mechanical steps as used in the Envisiontec and the B9creator. The printer uses a membrane that is permeable to oxygen. Since oxygen is an inhibitor for free radical polymerization (see Photopolymer Resin: Inhibition by oxygen), a gradient from incurable to curable resin is established. (Fig. 18) Since the bottom-most layer is not curable, it doesn't stick to the bottom of the resin vat and thus allows continuous printing. Controlling the speed of the motor referenced by the rate of inhibition by oxygen makes this possible. More information about this can be found in the patent of Desimone et. al. (Desimone, Ermoshkin, Ermoshkin, & Samulski, 2014)

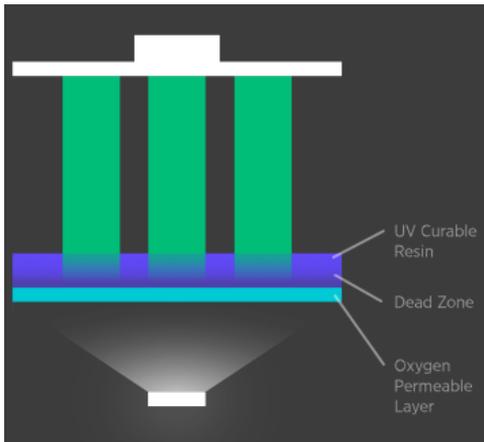


Figure 18:CLIP Technology from Carbon 3D (Carbon3D, 2015)

Opposed to normal DLP printing, there are no gradients within layers when CLIP technology is applied. This results in a very solid inner structure and smooth surface

LittleRP

While this printer doesn't have a very smart system to the resin sticking problem, it is a very simple design DLP printer kit of which some parts can be used in the printer that will be build: (Fig. 19) depicts the easy removable anodized aluminium build-platform (1) and a petri dish that is used as the resin vat. (2) (Little RP, 2015)



Figure 19: LittleRP Kickstarter project (Horsey, 2014)

Conclusion about the existing printers

Vat floor

The resin sticking is a serious problem with bottom-up DLP printing. There are basically three solutions: The first solution is to make the vat floor of a semi permeable flexible, optic transparent (<400nm) membrane. This results in a reliable vat-floor. A little less reliable but easier to build is a solid vat floor covered with a (oxygen donating) PDMS layer. (Sylgard 184) The sustainability of the PDMS layer can be prolonged if the object is peeled-of, or shoved instead or pulled in the normal direction. The third solution is to use a semi-permeable membrane together with control of the oxygen inhibition rate.

See through-parts

See-through parts can be added to the printer, although they need to filter the wavelengths around 400nm that trigger curing. The parts could be made of sunglass material, but they can also be made of orange or red PMMA.

Construction

The printer will be an accuracy tool. This means that the structural part has to be really accurate. Tristram Budel from the intractable suggests to make it from Bosch extruded profiles.

Build platform

The build platform should be made of a material that the resin sticks to, but the cured object should be able to be peeled of easily after printing is done. Anodized aluminium is a very suitable material for this since it has a high corrosion resistance. It is very hard at the surface and is rough at microscopic scale to be able to let the resin stick to it.

Design Brief

Now the theory of DLP printing is clarified, a design brief for a multi material 3D DLP printer can be made. Note that the time to build this printer is limited to a very short period, so there will be a lot of features that may improve the printer, although they can't all be applied in the first prototype. However, it would be wise to build the system in a fashion that other features can be applied easily.

A#	Functional
1	XY Precision in the 50-200 micron range
2	Layer thickness in the 50-200 micron range
3	3 resin-containers
4	Easy detachable resin-containers
5	Detachable building platform
6	Operation speed in the range of 1:30-6 hours for single material printing based on a object with a height of 8 cm --> with a layer thickness of 0.1mm this means that the running time for one layer lies in the range of 7-27s
7	Hardware needs to be 'ready' to be able to print multi-material products
8	Small object size: bounding box of 5-10cm ³

B#	Technical
1	Should be able to break the vacuum between the bottom of the resin container and the build platform/product
2	Should project the right wavelengths needed for curing

C#	Aesthetic
1	Reliable, solid
2	Attractive (clean, smooth finished)
3	Moveable

D#	Wishes
1	Ability to implement multi-material printing without many struggles.
2	Speed optimization where easily implementable
3	5 resin containers
4	A webcam to view the printing process
6	The printer with other features or another beamer.
7	Cooling for the resin
8	Cut-off filter to just allow the right wavelengths to reach the bottom of the resin

E#	Already available parts
----	-------------------------

1	DLP Beamer: Benq PB7230
2	Stepper motors: Nanotec ST4209S1006-B
3	Motor drivers: Big Easy Driver ROB-10735
4	Precision spindle with nut. L=500mm, lead=20mm, 5 threads, Diam.=12mm

F#	Boundaries
1	Project deadline July 2015

Idea Phase

The goal is to design a multi-material bottom-up 3D DLP printer with five changeable resin vats. To achieve the vat changing there are two options: rotary, or linear. The linear way is chosen since it is simple, and the motor and spindle are already available. Compromises have to be made between easiness to build, precision and operation speed. Since this prototype is a proof-of-principle setup, easiness to build and precision are the main focus. Future development could focus on speed optimization.

Linear printer

The 3D printer will be a contraption equipped with a linear resin container array, with a bottom-up printing direction. It will use spindles for the movement along both axes. The beamer will project images from the bottom through the resin container and the building platform will move upward during printing.

Since dedicated DLP-printing firmware for microcontrollers doesn't exist yet, FDM printer firmware is customized to fit for DLP printing. The DLP printing will use the firmware's accelerated motor control. Acceleration control is needed in order to prevent the resin to splash out of the vat.

Simplicity

The production of the parts will be done using mainly rapid prototyping techniques since they are available at the university and it allows parts to be complex and accurate, without having to worry too much about how to make them using conventional techniques. (Milling, turning sawing, drilling etc.)

Compatibility

A first investigation was done to estimate compatibility of the many functional components. There might be a lot of suggestions in order to make the product cheaper, although cheaper may be incompatible. Although this was done in the idea phase, the results are described in the next chapter since it has a big overlap.

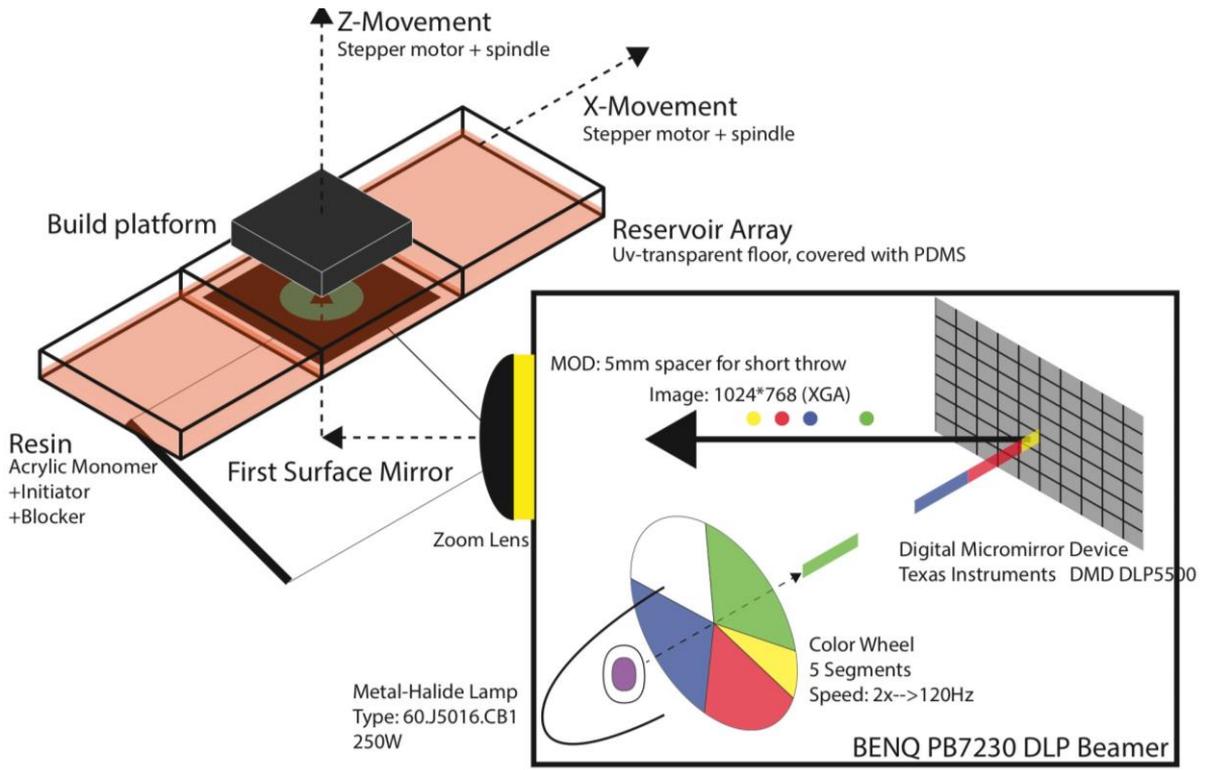


Figure 20: The idea of the linear contraction

Ideas worth mentioning

There were some ideas that weren't applied in concept in the next chapter. The speed of the Z-platform can be optimised by using a second (mini) spindle and mini guide. These parts are found in CD drives. The idea was to move between two certain positions with a high speed, when needed and to use a bigger spindle to do the absolute positioning. Another idea was to use an air-conditioning pump system to cool down the resin and the electronics at once. A pocket air-conditioning system is very cheap and works better than the small fans on the beamer. This idea didn't manage to get into the concept, since it was uncertain if heat would be a problem.

Conclusions about the idea phase

Simplicity is important since the time for this project is really limited and a lot of work has to be done. When complexity is needed, the parts have to be made using 3D printing and laser cutting since they require minimal human effort to make. The printer (Fig. 20) will consist of a beamer, a mirror, a vertical movable build platform and a linear moving vat array.

The EXZEED printer

Budel's manual on instructables.com will be the common thread in developing the parts of this multi-material DLP printer. However there are many things that were decided to be changed, since there were different components and tools available and there were certain issues with the design of Budel's printer that could be improved easily.

Moving vat carrier

Budel's printer didn't feature a moving vat carrier, since it was a DLP printer for only a single material. Part of the assignment was to design a system to change the vat during printing. Two shafts (1) with bearings (2) support a movable array (3) with round vats (4). Light is projected with a beamer (5) via a mirror (6) on the bottom of the vat. The build platform (7) is moved vertically by the z-spindle (8). The x-spindle (9) moves the array to change the vat.

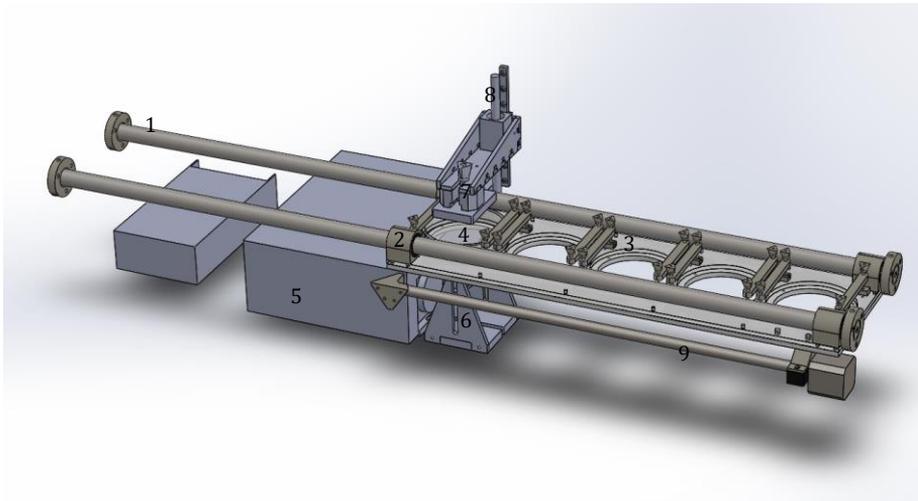


Figure 21: Overview of the inside

Vats

Modularity of the resin vats is one of the demands. They need to be easy to be replaced, have standard dimensions and they need to be easy to build. The floor of the vat needs to be optic transparent to low wavelengths. In the section: Reference DLP printers was described that there are two types of floors. Chosen is to use a solid floor, since this is easier to build. The size of

the vats depends on the length of the spindle. If the diameter of the vats is 100mm and the vats will be placed at 15mm from each other, the minimal translatable length of the spindle needs to be 460mm, which is shorter than 500mm and would thus work. 100mm is thus the right diameter for the vats. The vats are made of borosilicate glass since it has the required high optical specifications and is covered with a PDMS layer, which has high optical and anti-stick specifications.

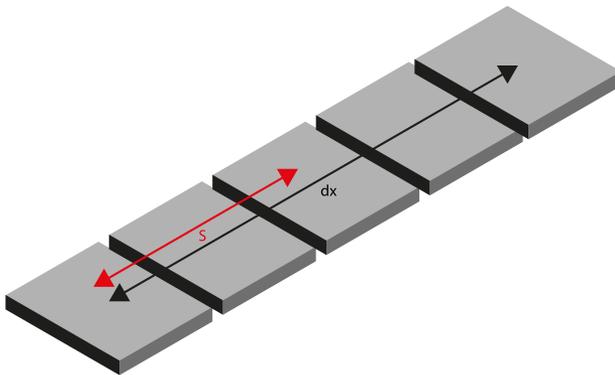


Figure 22: Schematic view of the resin vats

Stepper motor control

The motors that are used in the EXZEED are the Nanotec stepper ST4209-1006B stepper motors. These are Nema 17 sized motors just like the motors used by Budel, although they have different specifications. (See the datasheet in Appendix 3). If the motors are working at the maximum current, there's a maximum torque output for given rotation speeds. Applying a too high frequency of input steps, might cause the motor to skip them, or doesn't allow the motor to reach full torque. This is because of self-inductance in the coils. The graph with the green line in the figure below displays the settings that are used within this project.

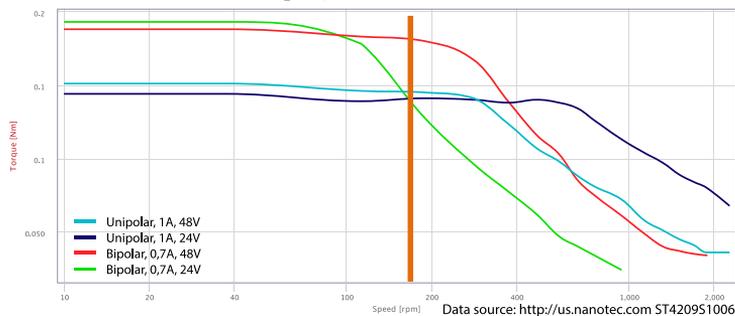


Figure 23: Speed/torque plot of the ST4209 stepper motors

Motor setup used for the printer

The motors are connected in bipolar mode. This means that the white and black COM cables shouldn't be connected. The jumpers on motherboard should be set so that the motor will run in ½ step mode. Using a 24V bus voltage results in a maximum rotation speed of about 150RPM with a torque output of about 0.18Nm (See the orange and green line). More information about the choice for these settings is in Appendix 4.

Spindles

For the translations spindles will be used. They are available in different types: buttress, acme, ball screw, or square thread. The difference between the types is efficiency, price, force direction and bulkiness. Square thread spindles were chosen since they have high efficiency and precision, but not the bulkiness like ball screws have.

The lead of the spindles is chosen that the system with a motor with a maximum turning speed of 150 RPM can drive the system fast and precisely. In appendix 5 are calculations for different leads. Since a precision of 20 (half) steps per layer is acceptable for the Z-movement, a width a lead of 4mm will be the best choice for the Z-spindle. There wasn't a nut-screw combination with this specification available, so a 2mm nut-spindle combination was bought. The other spindle was already available (20mm). For the x-spindle the acceleration setting is more important than the speed, since the acceleration will determine if the resin will be spilled out or not. The acceleration will be set by experimenting.

Arduino & motherboard

The printer's motherboard works as a terminal for all incoming and out coming connections so all external components are provided with the right power and are controlled from the right pins of the microprocessor. They are equipped with fuses to prevent burning the circuits. Budel used a Ramps 1.4 motherboard that is placed on top of an Arduino Mega 2560. Since all printer firmware available are written for use on Arduinos equipped with these kinds of motherboards, using such a motherboard really eases building and setting up the firmware. The Ramps 1.4 has standard solderless terminals for Pololu stepper driver carriers, however other carrier boards can be connected using wires. The Ramps boards are claimed to be deprecated technology. The new motherboard that is cheaper and has more features and is Ramps 1.4 compatible is the Megatronics V3 (Reprapworld, 2015) The Megatronics v3 is a motherboard that is equipped with an on-board AVR ATmega2560 microchip, which is the same as that of one on an Arduino Mega2560. Compared to the Ramps 1.4 it is designed to use a power supply of 12 or 24V instead of only a 12V power supply, allowing the motor drivers to be driven at a bus voltage of 24V. The Megatronics v3 was chosen to be used as the printer's motherboard. (Fig. 21)

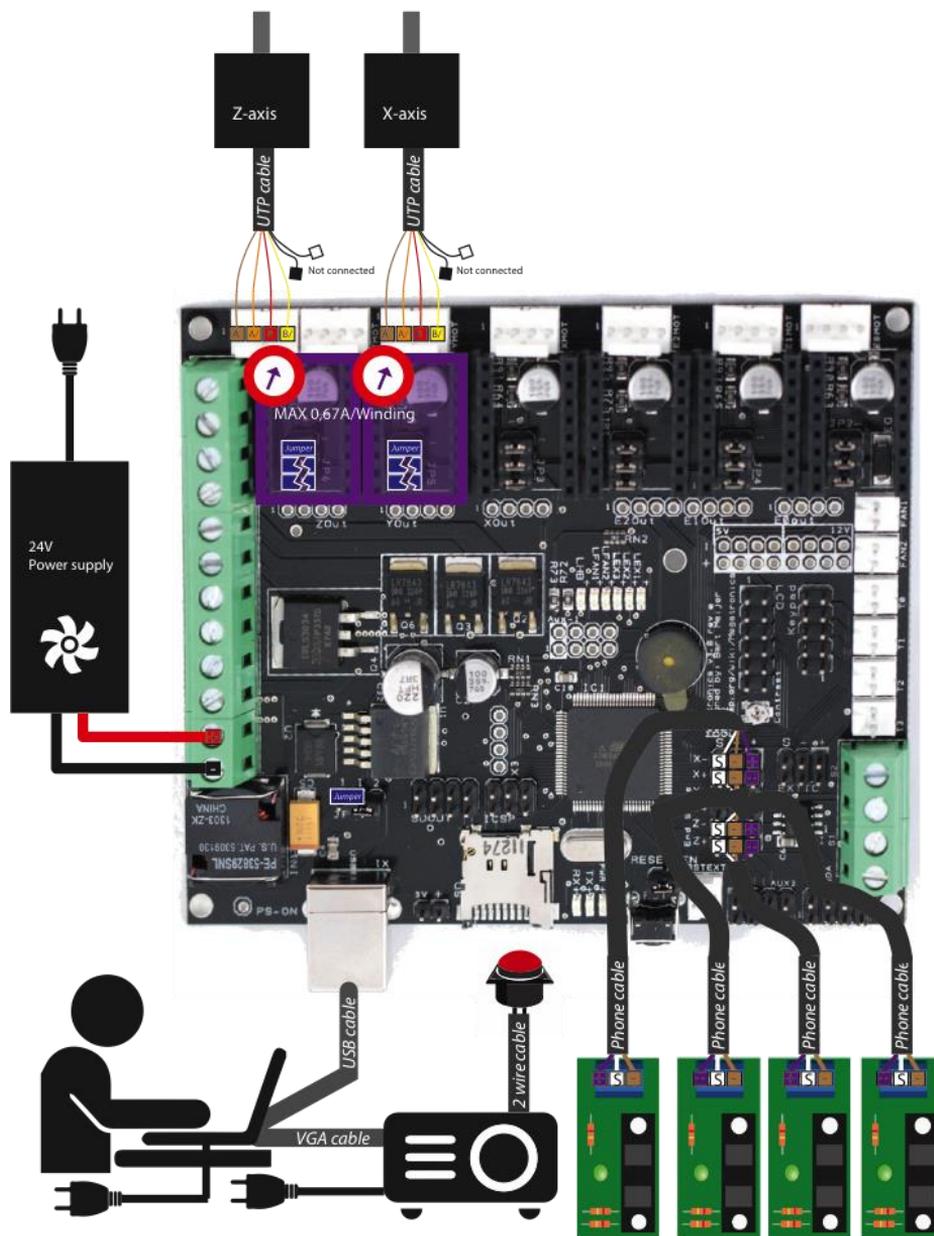


Figure 24: Overview of the electronics. In the middle the Megatronics v3 board.

Opto-endstops

The printer will be equipped with four opto-endstop sensors. They prevent the system to be blown apart when the stepper-motors skip steps and they determine the references for homing the printer.

Power supply

As written in the motor section, a 24V 15A power source will be used instead of the 12V power source that was used by Budel. It is connected to the power input on the Megatronics v3 board and is adjusted using a voltmeter to output exactly 24V using the small screw on it.

Firmware

There exist many firmwares that are developed to be used for 3D printing, although they all have their own properties. For DLP printing with Creation Workshop as the host software a firmware that works by communicating with G-code and M-code that is send over the serial port needs to be chosen. There are firmwares that do support acceleration control of the motors and there are firmwares that don't. For this purpose a firmware with acceleration control needs to be chosen: too stiff movement will cause the material to spill out of the vats. Many information about firmwares can be found on the wiki on reprap.org (Reprap, 2015) The Marlin firmware (Fig. 25) is chosen, since it has full end stop support, is accelerated and can be PID tuned for achieving better speed & accuracy properties. On the forum of Buildyourownsla.com there are many people that use the Marlin firmware. (Buildyourownsla.com, 2015)



Figure 25: Logo of the Marlin firmware

Host software

Tristram Budel used Creation Workshop (Fig. 26) as the host software. For building the multi material printer this host software will be used as well, since it is the only software that can control the motors and the beamer at the same time. It communicates with the printer using RS232 serial communication.

As you can see in (Fig. 26), it has options for setting up the printed object, has manual control and can be configured to be used for DLP printing.

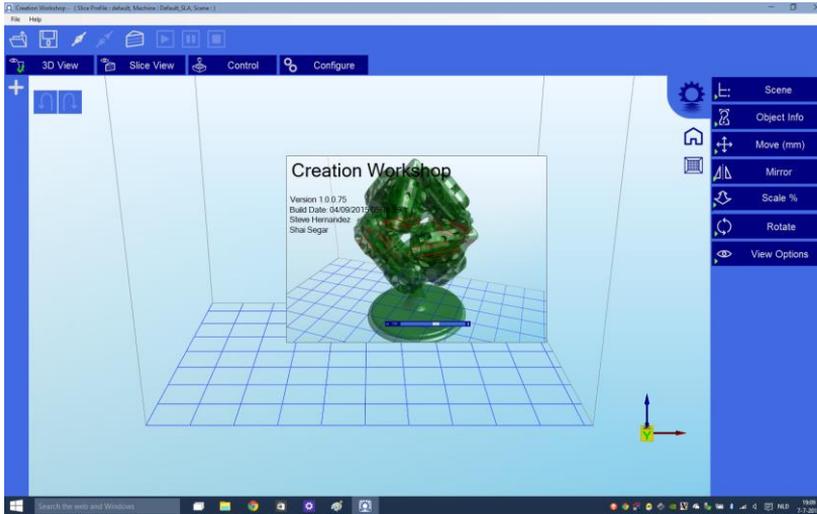


Figure 26: The Creation Workshop host software

Beamer

The beamer that is used in this project is a Benq PB7230 DLP beamer. It works at the XGA resolution (1024 *768) the beamer is modified to be able to have a shorter throw: Normal beamers can project only big images at a minimal distance of about 1,5m. For the purpose of 3D printing, the beamer needs to project a very small image at a very short distance. Installing a 5mm spacer between the lens assembly and the DMD chip did this. In Appendix 9 there is an image of the spacer. The spacer increases the object distance. How this works is described in Appendix 6. A side effect is that the edges of the projected image become a little bit blurry. The beamer will be turned upside-down: Normally a beamer projects a bit upward, and this would project light into the resin vat directly, which is not desired. A little cable is soldered to the beamer's PCB to be able to operate it from outside the printer. Directly behind the light source there was a 3mm thick filter installed. This filter is removed since it is very likely that it blocks UV light. On the buildyourownsla.com forum there are many people suggesting to move the colour-wheel away so that it's no longer in the light-path. It is likely that it blocks some UV light, although no one measured the influence of moving it away. For this project it isn't removed yet since it doesn't seem to be easy to do. The colour wheel shouldn't be removed completely, since it will cause the beamer to fail because it measures the colour of the wheel to sync with the DMD.

Mirror

The mirror is needed to position the beamer horizontally instead of vertically, since vertical mounting would require more space and is not very easy. The size of the mirror is limit, since it should fit under the platform. It should be a first-surface mirror, since normal mirrors will block UV and will cause dispersion. The size of the mirror is determined by testing with the

beamer. For the EXZEED an 85*101 400-600nm first surface mirror was used. The position and angle of the mirror are designed to be easy adjustable.

Vat array assembly

The vat array assembly, see the figure below, houses the resin vats and allows them to be moved horizontally. Each petri dish (1) is supported with three M3 screws. This way the position of the petri dishes can be adjusted to make the PDMS layer equal level, which is needed for multi-material printing. These M3 screw are placed in self-taped holes in a Delrin sheet (2). Delrin is chosen since it's well suitable for tapped holes. The horizontal movement of the dishes is limited by a 5mm thick Plexiglas sheet (3) with 105mm holes. Four linear-bearing housings (4) were screwed on top of this sheet. The 10 spring assemblies (5) were also screwed on top of this sheet. Through the bearings two 1000mm shafts were placed. These shafts were fixed to the body with four shaft supports (7) These supports have a very loose fit with the shafts, but through the supports bolts are mounted in order to adjust the position of the shaft. This is needed since high accuracy of the height is needed.

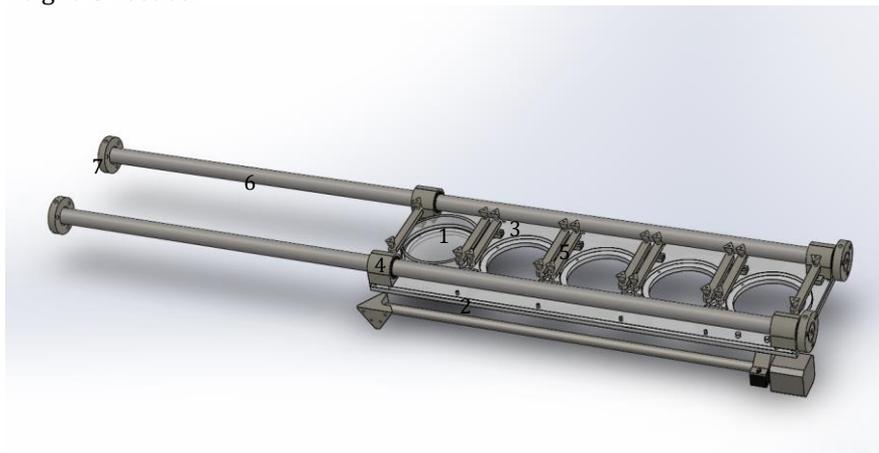


Figure 27: The vat array assembly

Vats

Petri dishes will be used as the resin vats. (Fig. 28) They have standard dimensions and don't require a lot of effort to make and assemble. Petri dishes are sold in different materials. The best suitable material is borosilicate glass since it has a higher transmittance at low wavelengths. (Fig.29) High dishes were purchased and were filled with a +-2mm layer of Sylgard 184. After pouring the solution in the petri dishes the vats have to dry for at least two days on a flat surface at room temperature, or 45 minutes at 100°C. (Dow Corning, 2015) The downside of using this PDMS layer is that it is considered to be a consumable so it needs to be replaced after a number

of prints. The thicker the layer, the longer it lasts. PDMS is sensible to temperature and isn't completely chemically inert.



Figure 28: 100mm Borosilicate Petri dishes (Duroplan) (Cloup, 2015)

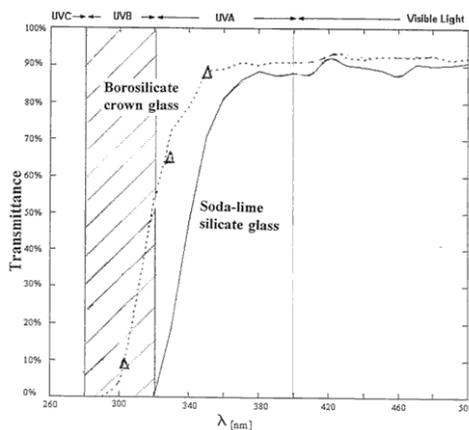


Figure 29: Transmittance of borosilicate glass compared to normal glass (Publiclab, 2013)

Passive tilting system with spring assemblies

In the section 'Reference 3D printer' was described that besides the adhesive force that causes the material to stick to the vat floor, also the air pressure causes the material to stick. Since the bottommost molecules in the resin are cured, a vacuum is created when the cured parts are pulled from the surface. Some sort of 'peeling' action needs to be created and in this case it was done by using a 'passive tilt' system. In the reference 3D printer section an active tilt system was described and the concept of that active tilt system was simplified to the passive tilt system. The petri dishes are clamped with the spring assemblies (Fig. 30). Tilting will be facilitated by tightening the nuts on one side tight, and on the other side loose. (Fig. 31) When the platform moves upward, the force that pulls on the resin containers will be different for both sides and cause the tilt.

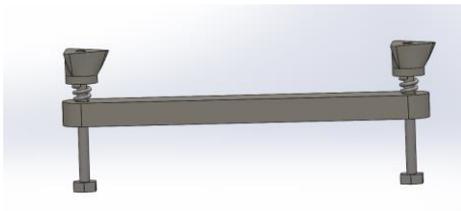
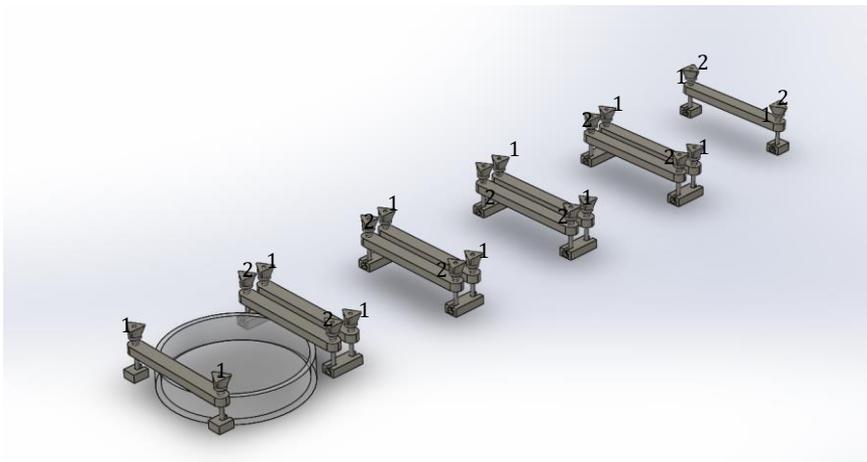


Figure 30: The spring assembly



**Figure 31: The grasping of the petri dishes by the spring assemblies.
Nuts with '1' will be tight, nuts with '2' will be loose to allow passive tilt**

Platform assembly (Fig. 32)

The platform (1) needs to fit in the resin container, but should be big enough for the projection. The resin should stick to the platform, but should be able to be peeled-off after the print is completed. Experiences of other DLP printers say that anodized aluminium is a well suitable material since it has a rough but hard surface and doesn't react with the resin. The platform hangs on a spacer (2) with 3 bolts. Without this spacer the Plexiglas support (4) would hit the shaft. The spacer is connected with one thick bolt (3) to the support. To limit the rotational freedom a small stick is placed on top of the spacer. On top of the spacer 3 M3 screws are placed. These are there for adjusting the angle of the platform with the platform support.

A linear carrier was screwed to the backside of the support and placed on the linear guide (5). The nut housing of the z-spindle assembly was screwed to the floor of the support.

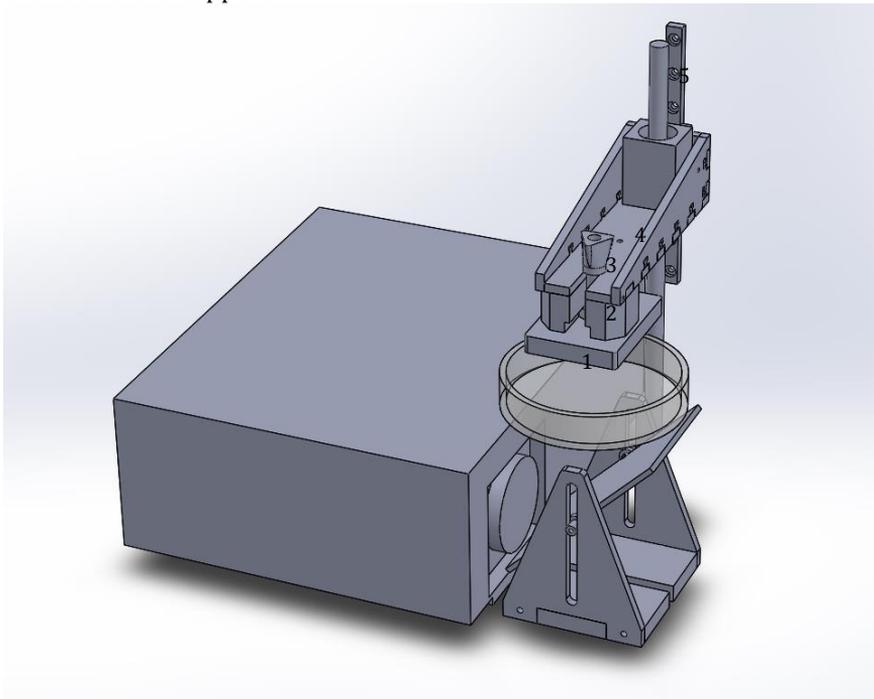


Figure 32: The platform assembly

Hood

The hood is made of 3mm thick orange PMMA since it blocks the strong light emitted by the beamer. The hood is also designed with 'fingers' since it eases the assembling. It has holes for the motor and for the switch.

Making the parts

The building of the printer was eased by the availability of laser cutters (Appendix 8) and 3D printers. (Appendix 9) These tools made it easy to make complex parts with a high accuracy. The aluminium hand knobs and the aluminium build platform were the only parts that were built manually. In the Appendix 10 there are descriptions about how all parts are made. The Solidworks files are available at the disk provided with this document.

Assembling

All the parts were assembled. Some of the parts required a little bit of sanding and some of the holes need to be drilled a bit wider. All the bolts were collected and were sawed-off at the right lengths. In Appendix 11 there are detailed descriptions about how all parts were assembled.

Conclusion

A 3D DLP printer with five moveable vats was designed and built, after the analysis of the 3D DLP principle. DLP printing uses a photo polymerisation process. There are two types of photo polymerization. Cationic and free radical. The one that's of importance in this project is 'free radical polymerisation'. When a photo initiator is exposed to photon with the right energy, a free radical is released. Monomers will combine with this radical until another chain or radical closes the chain. The mobility of the monomers plays an important role and is influenced by the temperature and the number of functional groups of the monomer. Generally, the more functional groups, the more entangled the network of polymer will be, the slower the reaction, the tougher the material, the lower the density and the more uncured resin. The more functional groups, the less it is sensitive to oxygen inhibition. The higher the amount of light energy, the more photo-initiators are activated and the thicker the gradient will be. This gradient determines the layer thickness that should be used. A too thick mechanical configured layer thickness will result in semi cured-waxy objects and a too thin configured layer thickness will cause layer inaccuracies due the focus range, instead of focus point. The optical XY resolution of the printer is about 50 micron, although bleed and shrink are neglected in this number. Analysis of existing printers was done. One of the main issues in bottom-up printing is the problem that cured layers stick to the bottom of the vat. The EXZEED has a passive tilt system and a layer of PDMS as solutions to this problem. For DLP printing there exists an easy modifiable software tool called Creation Workshop written by Steve Hernandez. This software can be used to control both axes and the beamer. The electronics and the functional components were chosen, configured and assembled. A Megatronics v3 motherboard loaded with the Marlin firmware was used to control the motors and is controlled by exchanging motor commands with the host software. The firmware and the host software were setup for the own system. A physical prototype was designed. On the next pages there are some renders of the result.

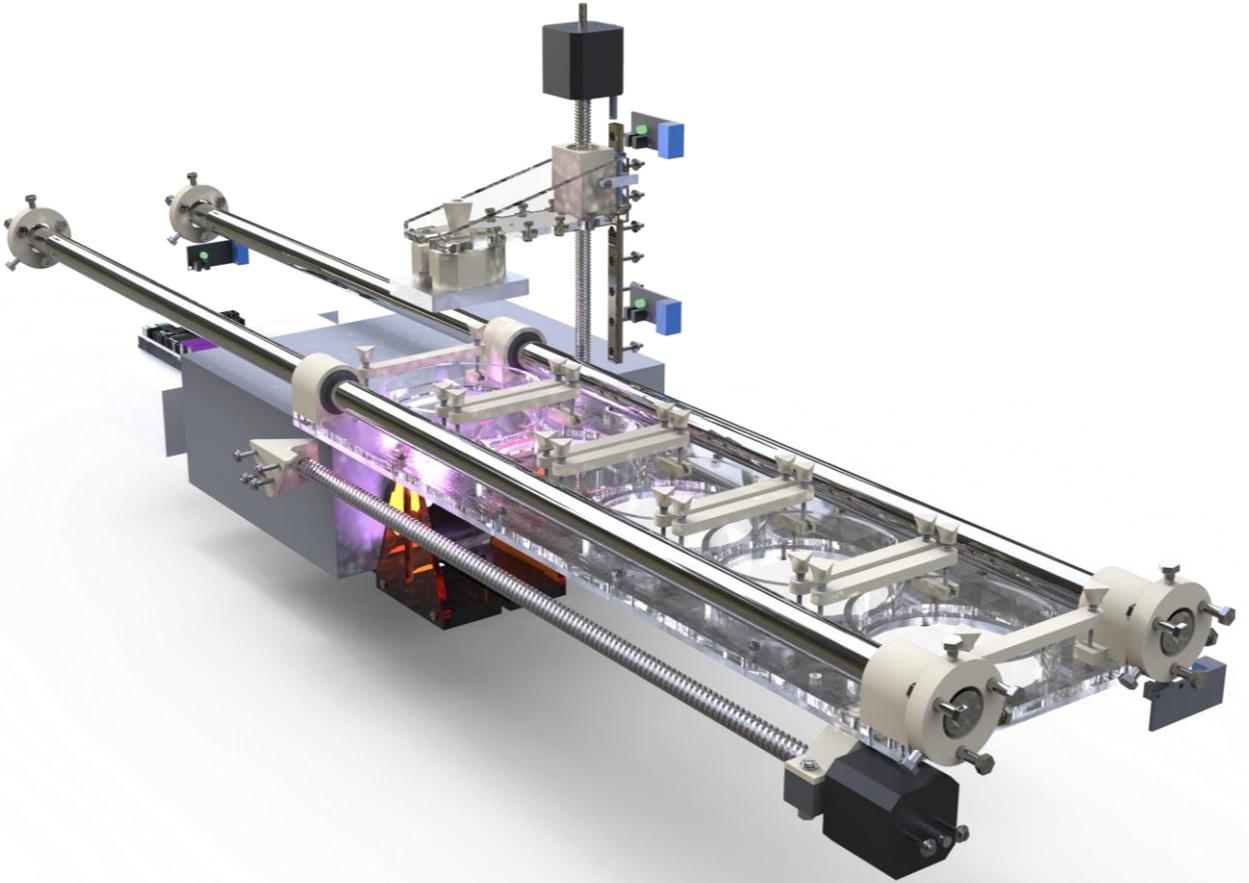
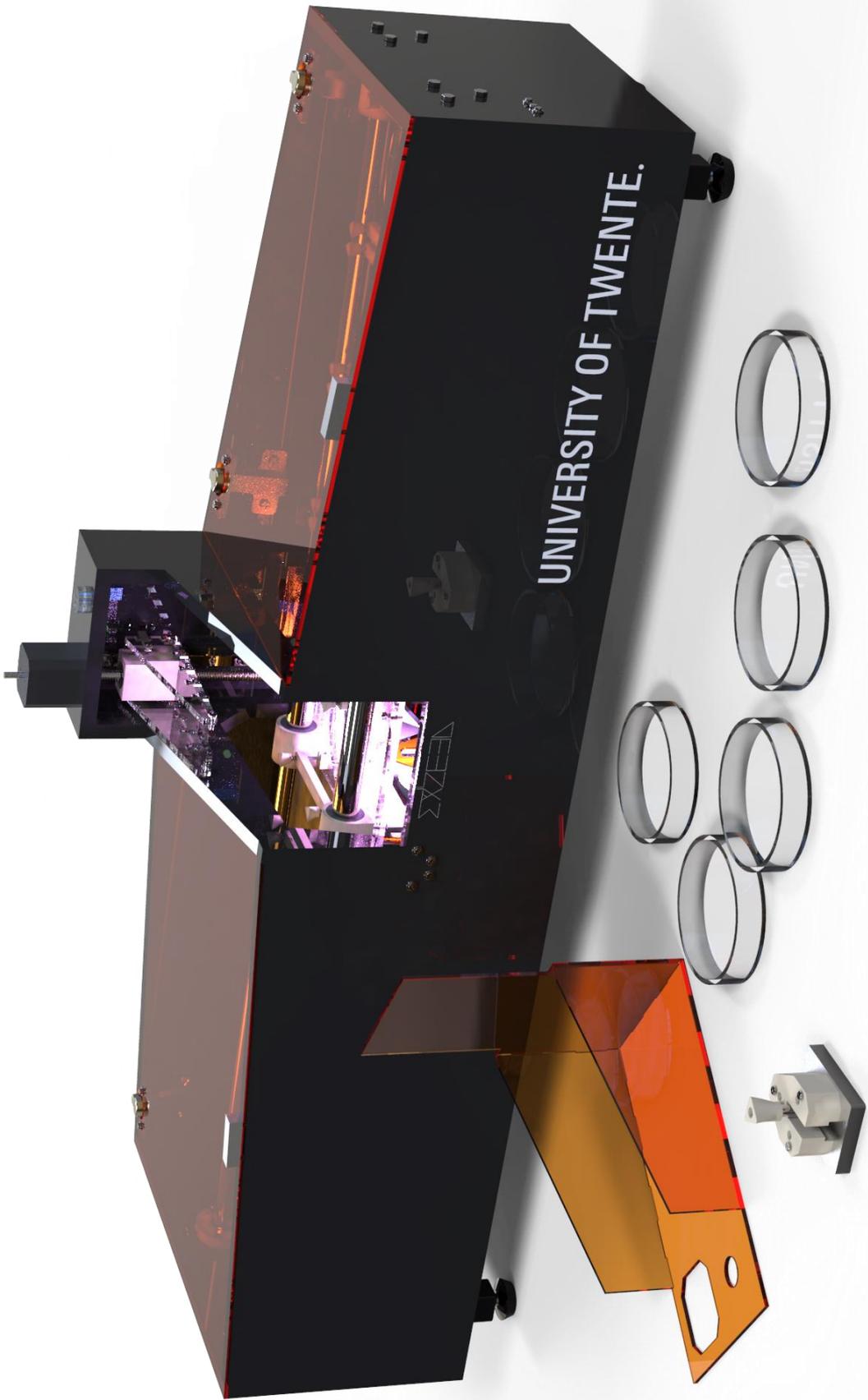
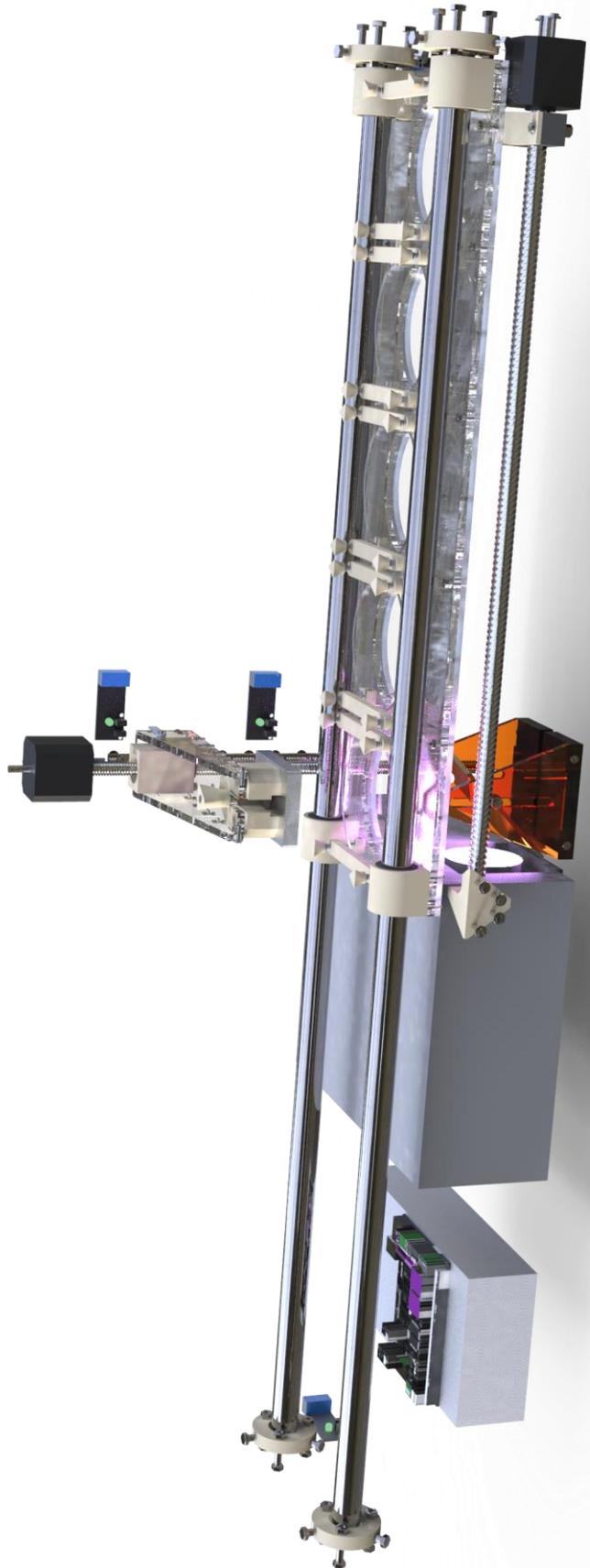


Figure 35: The inside of the printer





Recommendations

The prototype that was realised in this project is not perfect yet. This is why the printer was designed to be easily upgradeable.

Problems

- a) The printer that was build has a problem with a dangling spindle. This spindle is only fixed on the motor side, but should also be fixed to the bottom of the body. The dangling causes a XY-movement of the platform that causes inaccuracy of the printed products.
- b) The printer becomes hot on the inside because of the heat generated by the beamer. A pocket air-condition combined with some computer fans could be the remedy.
- c) The vats are a bit lower than expected. They were designed with petri dishes with a height of 20mm, although the 15mm petri dishes were in stock and could be sent earlier. Higher vats would allow higher acceleration speeds for the horizontal movement.

Opportunities

- a) The printer could be equipped with aquarium pumps to refill the resin vats. The Megatronics v3 board could also control these.
- b) A display showing the current layer that is printed could be added easily. This is a standard feature of Marlin and the Megatronics board.

Future research

- a) Experiments with the resin thickness and the building of test-geometries are still left to do.
- b) Also research has to be done to the amount of bleed in the XY plane.
- c) Using a beamer is not really the best option for the light source in DLP printing. It consumes a lot of power, generates a lot of heat, and outputs just a little amount of useful light for curing. The rest of the light will be transferred to heat which result in shrinkage. The beamer's light output is not measured; this should be done to get more insight about the performance. Beamers using DLP chips with better specifications for 3D printing might be available. A Wood's filter +IR filter could be installed in front of the beamer to filter out the unused wavelengths that cause heat.
- d) The PDMS layer degrades by heat. This might become very unhandy when multi-material printing is done, since it could cause the height to vary. When more time is available, flexible vats should be build.

Hlocke on the website 'projects, interests and etcetera' described how to build them. (hlocke, 2015)

- e) There are already people experimenting with LCD technology for 3D printing. LCD displays with removed filters and removed backlights are used and replaced by UV LEDs and a Fresnel lens. LCD screens can be made very big and don't need a lens system that blocks UV and causes unsharpness at the edges.
- f) There are more things that need to be setup in the host software to be able to print. This includes layer thickness and the movement of the motors to change the vats. Estimating the layer thickness requires many experiments and there's just not enough time for that within the extend of this assignment. Motor controls for controlling the X-axis automatically can be setup in the custom G-code section. This can be used to setup the movement for multi-material printing. An overview of the G-code commands can be found on reprap.com/wiki/G-code

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Appendix 1: Properties of monomer & oligomers

Table 1: Curing properties for various acrylates (3Dprinter.wikidot, 2011)

	P.Ester Acryl Olig. (16)	P.Ester Acryl Olig. (16)	Ethox.(3) BP-A Diacryl.	Ethox.(4) BP-A Diacryl.	Ethox.(10) BP-A Diacryl.	Ethox.(6) BP-A Triacryl.	Di-PEG Diacryl.	Epoxy(2) Soybean Oil Acryl.
Fast Cure	Excellent	High	Good	Good		Good	Good	Very Low
Photocuring Specific	Yes	Yes	Yes	Yes	Yes			Yes
Abrasion Resistance	Excellent	Excellent	Good	High	Good	High	High	
Hardness	Good	Good	Good	Good	Good	Good	Good	Low
Impact Strength			Good	High	Good	High	High	
Heat Resistance			Good	Good		Good		
Weatherability	Excellent	Excellent				Good	Good	
Shrinkage	Low 9.0%	Low 7%	Low (5% ?)	Low (5% ?)	Low (5% ?)	Low (5% ?)	Low	Low (5% ?)
Adhesion	High	Good	Good	Good	Good	Good	Good	Good
Flexibility		High			Good		High	Good
Pigment Wetting								Good
Chemical Resistance	Good		Good	Good	Good	Good	Good	Low
Cost Effectiveness		Yes						
Viscosity	Low 300 mPa.s	Good 0.4-1 Pa.s	Intermediate 1-2 Pa.s	Good 0.65-1.2 Pa.s	Good 0.61 Pa.s	Low 75-150 mPa.s	Very Low 8-14 mPa.s	High 16-26 Pa.s
Health RiXs	Skin, Eyes Low Irritant	Skin, Eyes Irritant	Eyes Irritant	Skin, Eyes Irritant	Skin, Eyes Irritant	Low	Skin, Eyes Irritant	Skin, Eyes Low Irritant

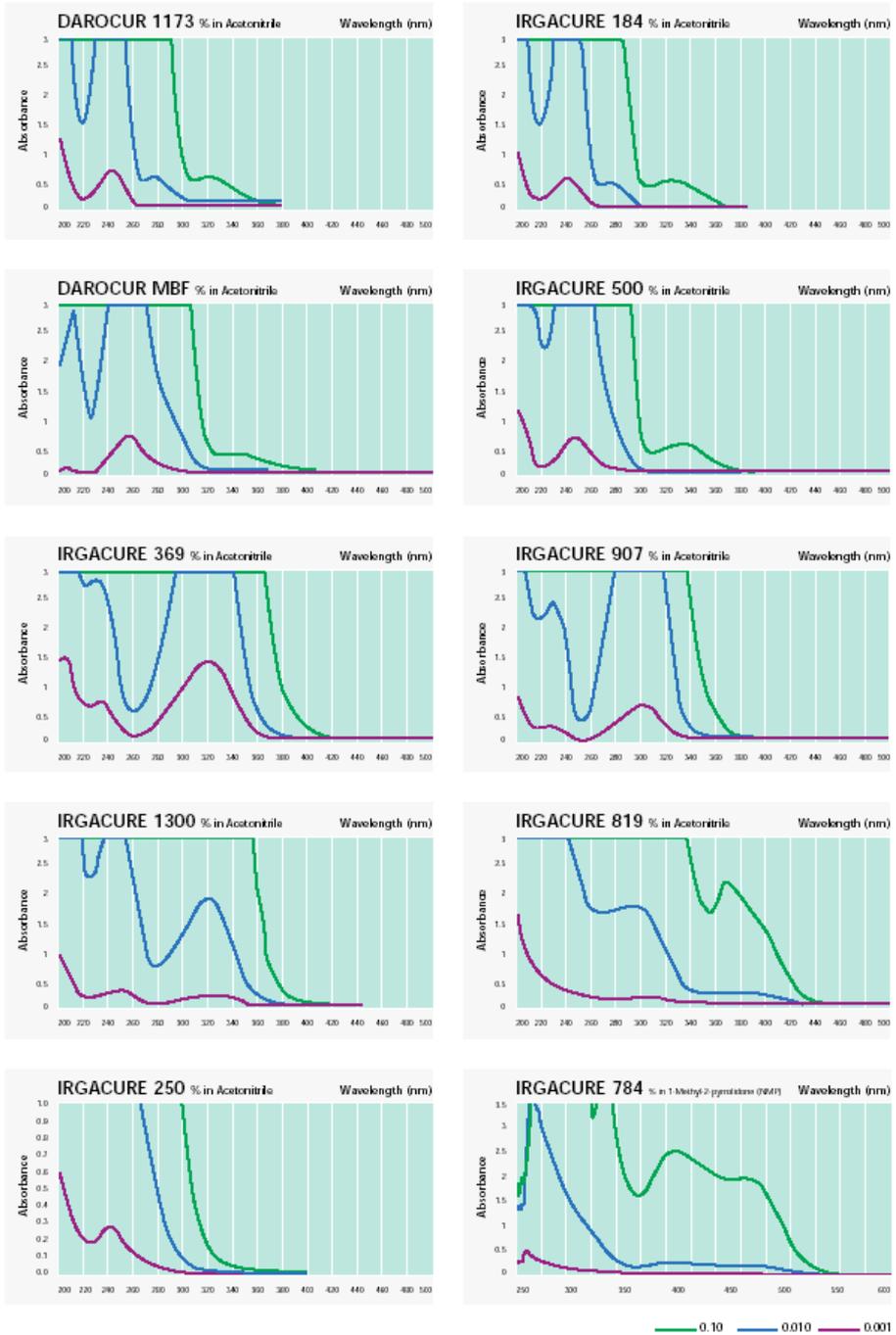
Table 2: Properties of oligomer types (Idacavage, 2012)

<u>(Meth)Acrylated</u>	<u>Characteristics</u>
Epoxies	fast curing, hard, solvent resistant, lower cost
Aliphatic Urethanes	flexible, tough, non-yellowing, best weathering properties
Aromatic Urethane	flexible, tough, lower cost than aliphatic urethanes
Polyesters	low viscosity, good wetting properties
Acrylics	good weathering properties, low Tg
Specialty Resins	adhesion, special applications

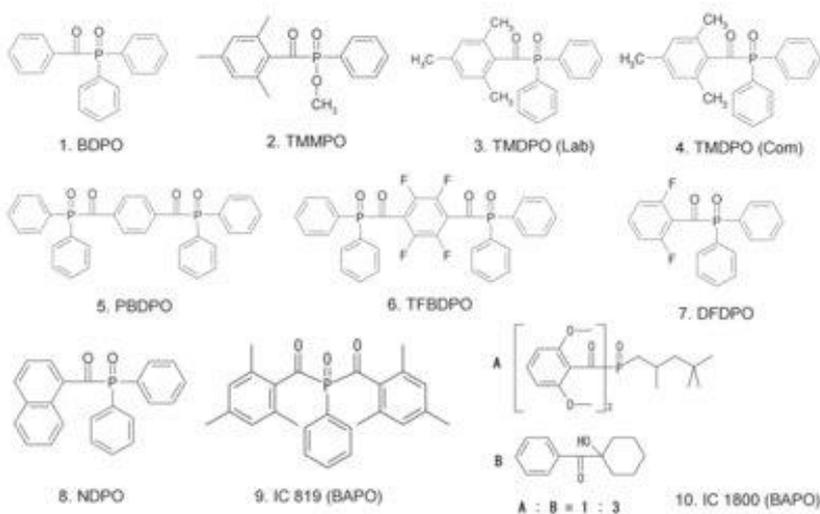
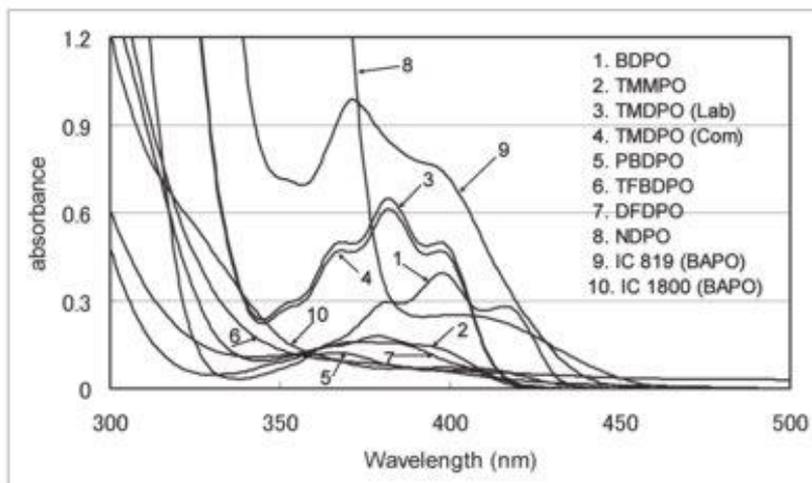
Appendix 2: Properties of Photo initiators

Table 3: Photo initiators (Bucktownpolymers, 2013)

CHEMICAL IDENTITY	LIGHT ABSORB- TION SPECTRUM [NM]	BRANDNAME (WHERE AVAIL- ABLE)
2-Methyl-1-[4-(methylthio)phenyl]-2-(4-morpholinyl)-1-propanone	230, 304	IRGACURE 907
2-Benzyl-2-(dimethylamino)-1-[4-(4-morpholinyl) phenyl]-1-butanone	233, 324	IRGACURE 369
Mix of 1 weight part of Diphenyl (2,4,6-trimethylbenzoyl)-phosphine oxide and 1 weight part of 2-Hydroxy-2-methyl-1-phenyl-1-propanone	240, 272, 380	DAROCUR 4265
Iodonium, (4-methylphenyl)[4-(2-methylpropyl) phenyl]-,hexafluorophosphate(1-)	242	IRGACURE 250
2-Hydroxy-2-methyl-1-phenyl-1-propanone	245, 280, 331	DAROCUR 1173
1-Hydroxy-cyclohexyl-phenyl-ketone	246, 280, 333	IRGACURE 184
Mix of 1 weight part Phosphine oxide, phenyl bis (2,4,6-trimethyl benzoyl) to 4 weight parts of 2-Hydroxy-2-methyl-1-phenyl-1-propanone	246, 282, 370	IRGACURE 2022
Mix of 1 weight part 1-Hydroxy-cyclohexyl-phenyl-ketone to one weight part Benzophenone	250, 332	IRGACURE 500
Alpha, alpha-dimethoxy-alpha-phenylacetophenone	250, 340	IRGACURE 651
Mix of 3 weight parts 2-Benzyl-2-(dimethylamino)-1-[4-(4-morpholinyl) phenyl]-1-butanone to 7 weight parts of Alpha, alpha-dimethoxy-alpha-phenyl-lacetophenone	251, 323	IRGACURE 1300
oxy-phenyl-acetic acid 2-[2 oxo-2phenyl-acetoxy-ethoxy]-ethyl ester and oxy-phenyl-acetic 2-[2-hydroxy-ethoxy]-ethyl ester	255, 325	IRGACURE 754
Methylbenzoylformate	255, 325	DAROCUR MBF
Not available	275, 370	IRGACURE 2100
2-Hydroxy-1-[4-(2-hydroxyethoxy)phenyl]-2-methyl-1-propanone	276	IRGACURE 2959
Diphenyl (2,4,6-trimethylbenzoyl)-phosphine oxide	295, 368, 380, 393	DAROCUR TPO
Phosphine oxide, phenyl bis (2,4,6-trimethyl benzoyl)	295, 370	IRGACURE 819
Phosphine oxide, phenyl bis (2,4,6-trimethyl benzoyl) (45% active) dispersed in water	295, 370	IRGACURE 819DW
Bis (eta 5-2,4-cyclopentadien-1-yl)Bis [2,6-difluoro-3-(1H-pyrrol-1-yl)phenyl]titanium	398, 470	IRGACURE 784



Graph 1: Absorption spectra for various photo initiators and concentrations (Ciba Specialty Chemicals, 2015)



Appendix 3: Stepper motor and driver datasheet

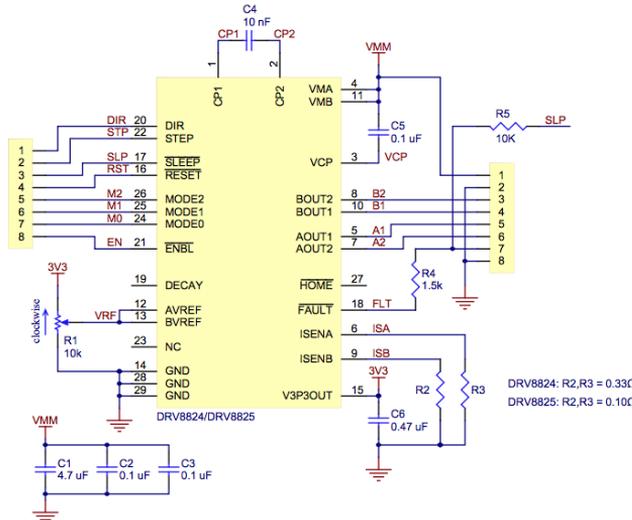


Figure 36: The Pololu driver carrier for the TI DRV8825 (Pololu Robotics and Electronics, 2013)

CONNECTION	UNIPOLAR OR BIPOLAR-1 WINDING	BIPOLAR SERIAL	PERMISSIBLE RADIAL+AXIAL FORCE
VOLTAGE (VDC)	4.0	5.63	
AMPS/PHASE	0.95	0.67	
RESISTANCE/PHASE (Ohms)@25°C	4.2±15%	8.44±15%	
INDUCTANCE/PHASE (mH) @1kHz	4.0±20%	16±20%	
HOLDING TORQUE (Nm) [lb-in]	0.15 [1.328]	0.212 [1.876]	
DETENT TORQUE (Nm) [lb-in]	4.5x10 ⁻³ [0.0398]		
STEP ANGLE (°)	0.9		
STEP ACCURACY (NON-ACCUM)	±5%		
ROTOR INERTIA (NON-ACCUM) (kg-m²) [lb-in²]	3.5x10 ⁻⁶ [0.012]		
WEIGHT (Kg) (lb)	0.22 [0.485]		
TEMPERATURE RISE: MAX.80°C (MOTOR STANDSTILL; FOR 2 PHASE ENERGIZED)			AXIAL-FORCE Fa (N)
AMBIENT TEMPERATURE -10° ~ 50°C (14° ~ 122°)			5 10 15 20
INSULATION RESISTANCE 100 MOhm (UNDER NORMAL TEMPERATURE AND HUMIDITY)			RADIAL-FORCE Fr (N)
INSULATION CLASS B 130° [266°F]			58 36 26 20
DIELECTRIC STRENGTH 500VAC FOR 1 MIN. (BETWEEN THE MOTOR COILS AND THE MOTOR CASE)			AXIAL RADIAL
AMBIENT HUMIDITY MAX. 85% (NO CONDENSATION)			0.075 0.025
			SHAFT PLAY (mm)
			AT LOAD MAX: (N)
			10 5.0

TYPE OF CONNECTION (EXTERNAL)	BIPOLAR 1WINDING	SERIAL	CONNECTOR PIN NO.	LEADS	MOTOR WINDING
UNIPOLAR	A	A	1	BRN	A
COM	COM	COM	5	BLK	COM
A	A	A	3	ORG	A
B	B	B	2	RED	B
COM	COM	COM	6	WHT	COM
B	B	B	4	TEL	B

STEP	A	B	A'	B'	CCW
1	+	+	-	-	
2	-	-	+	+	
3	-	+	-	+	
4	+	-	+	-	

REV	DESCRIPTION	DATE	APVD	ST4209S1006	SCALE FREE	APVD	S.Ha.	26.02.07	STEPPING MOTOR
					x	±0.5	CHKD		
					VPL	±0.2	DRN	J.W.	29.06.06
					ANGLE	±0.1	SIGNATURE		DATE
						±30°			

Figure 37: Nanotec Stepper ST4209-1006B Datasheet (Nanotec, 2007)

Appendix 4: Stepper motor properties

Unipolar/bipolar mode

The motor is a 6-wire stepper motor. This means that it is a hybrid motor and can be connected in two modes. It was chosen to use the bipolar setting since the torque output is much higher. Having a much higher torque output will prevent the motors to skip steps.

Micro stepping settings

The higher the micro stepping setting, the more the torque output drops down, but the lower the resonance. (Solarbotics, 2015) It was chosen to use half step driving, since it will result in a higher resolution and doesn't decrease the torque output too much.

Phase	Wave Drive				Normal full step				Half-step drive								
	1	2	3	4	1	2	3	4	1	2	3	4	5	6	7	8	
A
B	
\bar{A}						
\bar{B}			

Figure 38: Excitation sequences of different drive modes (Solarbotics, 2015)

Bus voltage, rated current and step rate

Although the motor's rated voltage is only 5.63V, a much higher bus voltage is applied to the motor. This will allow the motor to ramp up faster and thus allow higher step rates. Since the motor controller controls the current (open loop) and not the voltage, the motors don't get damaged if the maximum current rate is set properly on the motor controllers. Negative side effects are that the motor runs stiffer (more vibrations) and can become hot due increased winding power loss. Collin Stoner on selene.com explains how this works including graphs of step responses etc. (Stoner, 2011)

Mixed/slow or high decay mode

Mixed Decay, especially when using micro stepping is a must. Some boards have a programmable mixed decay rate, while others have a fixed mixed decay rate. For most applications a fixed mixed decay rate is enough. The chosen stepper driver carriers have a fixed mixed decay mode.

Appendix 5: Spindle choice

It is assumed that the number of steps/mm translation is the precision. It is also assumed that the acceleration of the platform is infinite. Since the spindle needs to move the platform up-and downward for every material change, the height of the reservoir determines the time needed to rise the platform. The height of the fluid containers will be about 10mm.

$$Lead_{\text{minimal}} = \frac{\text{Linear speed}_{\text{desired}}}{\text{motor rotation speed}_{\text{max}}} = \frac{10\text{mm/s}}{2.5R/s} = 4\text{mm}$$

Using this lead the chosen motor specifications, the precision can be determined:

$$\begin{aligned} \text{precision} &= \frac{360^\circ}{\text{angle}_{\text{steppermotor}}} * \frac{1}{\text{mode}_{\text{stepping}}} * \frac{1}{\text{lead}} \\ &= \frac{360^\circ}{0,9^\circ} * \frac{1}{\frac{1}{2}} * \frac{1}{\text{lead}} = 200 \text{ (half steps) per mm} \end{aligned}$$

Using an estimated layer thickness of 0.1mm will result in a precision of 20 steps/layer. The results (A,B,C,D) of the calculation for different speeds are in the next table:

	A	B	C	D
Lead	2mm	3mm	4mm	9mm
Precision	400 half steps/mm	242 half steps/mm	200 half steps /mm	81 half steps/mm
Steps/layer of 0.1mm	40 half steps/layer	24 half steps/layer	20 half steps/layer	8 half steps /layer
Max linear speed @ 150RPM (mm/s)	5mm/s	7.5mm/s	11.25mm/s	22.5 mm/s
Time to move 10mm	2s	1.33s	0.88s	0.44s

Appendix 6: Explanation of the throw modification of the beamer.

Although the system is in reality a multi-lens various focus system, the relation for thin lenses explains the working of the spacer: When S_1 is increased by the spacer, S_2 decreases. When the object is placed further from the lens, the image size also decreases.

$$\frac{1}{F} = \frac{1}{S_1} + \frac{1}{S_2}$$

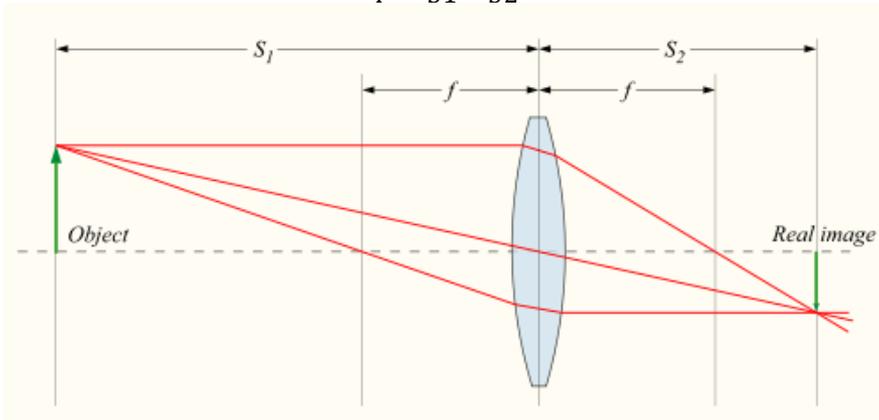


Figure 39: Lens formula.

Alternatively it could have been done using a macro close up lens (which would increase f), however installing a spacer was easier.

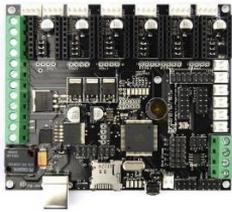
Appendix 7: Bill of materials

Many parts and materials had to be bought from vendors. Here's a short overview in one table. The one's with vendor 'UT' were already available at the university. Many screws and bolts weren't available in the desired size, so they were sawed-off from longer screws and bolts.

1	PART	VENDOR	QTY.
2	Black spraypaint	Action	2
3	White wall paint	Action	1
4	Petri dishes 100*15 Borosilicate	boomlab.nl	5
5	PMMA sheet orange 750*750*3	bouwplastics.nl	1
6	First Surface mirror	edmundoptics.com	1
7	Heat shrink	Elonka	3
8	Phone cable 4m	Elonka	1
9	UTP Cable, black 2m	Elonka	1
10	Concealed hinge	Gamma	4
11	Hex Bolt, various sizes	Gamma/UT	many
12	Hex nut various sizes	Gamma/UT	many
13	Inspirations furniture legs	Gamma	4
14	Levellers for furniture legs	Gamma	4
15	MDF filler, Alabastine	Gamma	1
16	MDF Screw	Gamma	8
17	MDF sheet 1600*1200*12	Gamma	1
18	Panhead screws various sizes	Gamma	many
19	Megatronics v3 Board	reprapworld.com	1
20	Opto-Endstop	reprapworld.com	4
21	Power supply 24V 15A	reprapworld.com	1
22	Anti-Backlash nut	rs-online.com	1
23	Linear ball Bearing	rs-online.com	4
24	Linear guide	rs-online.com	1
25	Linear guide shaft 1000mm	rs-online.com	2
26	Spindle 300mm	rs-online.com	1
27	Colorant	Spot-A materials	2
28	Resin:Spot-GP	Spot-A materials	1
29	Benq PB 7230 beamer	UT	1
30	Filament for 3D priter	UT	1
31	Location bolt M5*27	UT	12
32	Spindle 500mm	UT	1
33	Spindle nut Delrin	UT	1
34	Springs for m3, 10mm long	UT	20
35	Stepper Motor	UT	2
36	Delrin 600*200*4	UT, TCO	1
37	Perspex 800*200*5	UT, TCO	1
38	Aluminium block 69*52*10	UT, TCO	1
39	Aluminium rod square 12*12*40	UT, TCO	2

Figure 40:Bill of materials

Megatronics V3



79,99 (1)

[Link](#)

24V, 15A power supply



19,99 (1)

[Link](#)

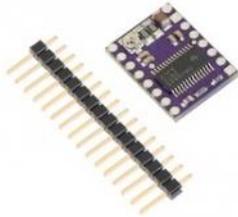
Opto endstops



5,87 (4)

[Link](#)

Pololu 8825 Driver carrier



11,99 (2)

[Link](#)

Thomson Linear Lead Screw, 10mm Shaft Diam. , 300mm Shaft Length



56,69 (1)

[Link](#)

Thomson Linear Anti-Backlash Nut Anti-Backlash 2mm 10mm 0.82in
1.875in



51,53 (1)

[Link](#)

NSK Linear Guide Carriage PAU09TRS, PU



42,03

[Link](#)

NSK Linear Guide Rail, P1U090155SKN-PCT PU



34,84

[Link](#)

SKF 1000mm Long Steel Closed Bush Shaft, 20mm Shaft Diam. , Hardness 60
→ 64HRC, h6 Tolerance



41,57 (2)

[Link](#)

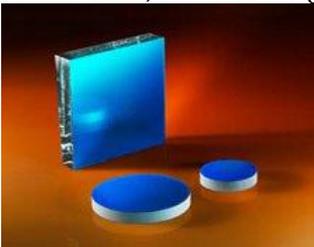
SKF Linear Ball Bearing LBBR 20-2LS



24.47 (4)

[Link](#)

85 x 101mm, 4-6 λ Mirror (Front surface mirror)



24,70

[Link](#)

Sylgard 184

PETRI DISH borosilicate GLASS 100MMX10MM DIA X DEPTH Duroplan



[Link](#)

Body

Gamma

Plexiglas 3mm oranje getint 750*750



[Link](#)

Spot-A GP



65,00

[Link](#)

Pigment



6,50 (2)

[Link](#)

Other parts, bought at local shops:

Gamma MDF sheet 1600*1200 (1)

Gamma Metal pan head screws (many)

Gamma Hex bolts (many)

Gamma hinges (2 sets of 2)

Gamma Alabastine MDF filler (1)

Gamma furniture legs (4)

Gamma transparent silicon kit (1)

Gamma levellers (1 set of 4)

Action black glossy paint (4)

Action clear glossy paint (3)

Action white acrylic ground paint. (1)

Appendix 8: The laser cut parts

There were four sheets of material used and these four sheets were laser cut by exporting unannotated Solidworks 1:1 drawings to DXF files. All changes that are made to the 3D model automatically apply to the drawing sheets. This way the materials could be ordered early, since an estimation of the needed materials could be made before all the details were applied. (Ribs, holes etc.) Another important thing is that all sheets are imported from the highest-level assembly, since 'assembly features' were used that don't apply to the drawings of the lower level parts. The DXF files can be imported in Adobe Illustrator to convert them to EPS files that are loadable into the laser cutter's host software. The size and the material type are of big importance to manufacturing the parts. Laser cutting MDF emits toxic smoke. Some type of filters that are used by for example Trotec laser cutters need to be replaced frequently if MDF is cut. This is why owners might not like to cut MDF. The size of the laser cutter determines the maximum size that can be cut. Since the longest parts of the body are longer than 1000mm, a big laser cutter was needed. The settings for the velocity, power and frequency of the laser cutter are very specific to the material and the thickness of the material that is used. Varying the parameters and observing the penetration of the cut determined the right settings. Generally the higher the power, the more material is burned away so the deeper and thicker the cut, but also the higher the chance is that the material catches fire. The velocity also determines the depth of the cut and the chance on fire. Cutting with lower speed, and lower power reduces the risk of fire and reduces the cutting width, but increases the cutting time. The frequency is the number of pulses per inch. The higher the number of pulses, the hotter the material gets. Cutting flammable materials should thus be done with a lower power, lower velocity and lower frequency setting than less flammable objects. The tougher the material, the higher the amount of energy is needed. The flammability and toughness of materials like Delrin and PMMA really depend on the manufacturer of the material, so for each material of each manufacturer different settings are needed.

Laser cutting the body and mirror base made of 12mm thick MDF

The body and mirror base are cut from a MDF sheet of 1600*1200. This was done by Jan-Gert Kamping, JKCreations in Enschede with a 100W CO2 BRM 100160 laser cutter. The time needed for cutting was 1,5 hours.

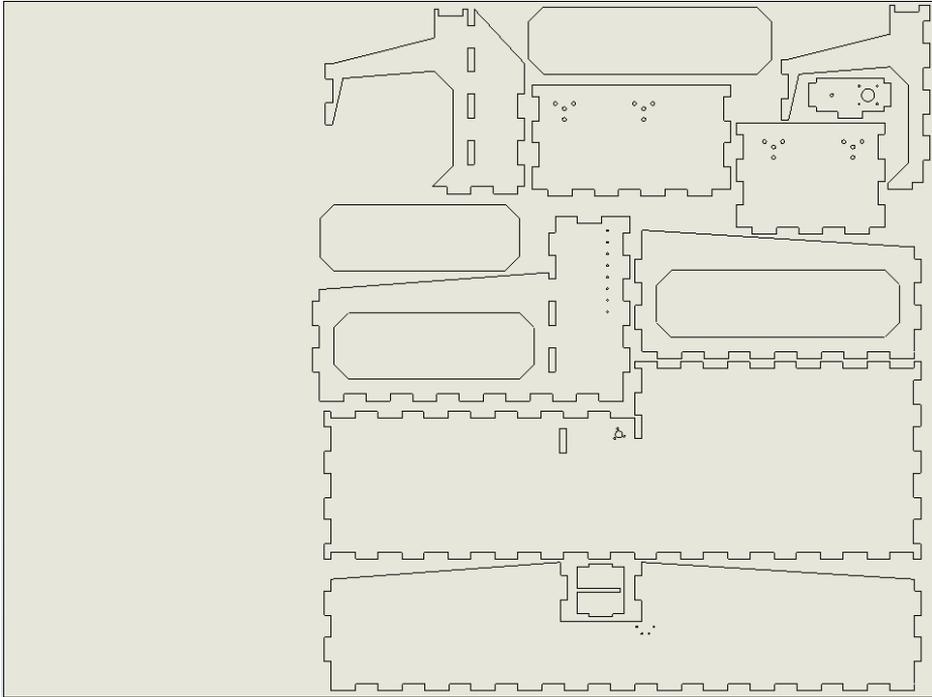


Figure 41: The body and mirror base on the 1600*1200 MDF sheet

The covers, hood and mirror side walls made of 3mm thick orange PMMA

The transparent orange parts were made using a 100W CO2 Trotec 500 laser cutter operated by Andrea Minuto in the Design lab of the University of Twente. The cutting time was about 20 minutes.

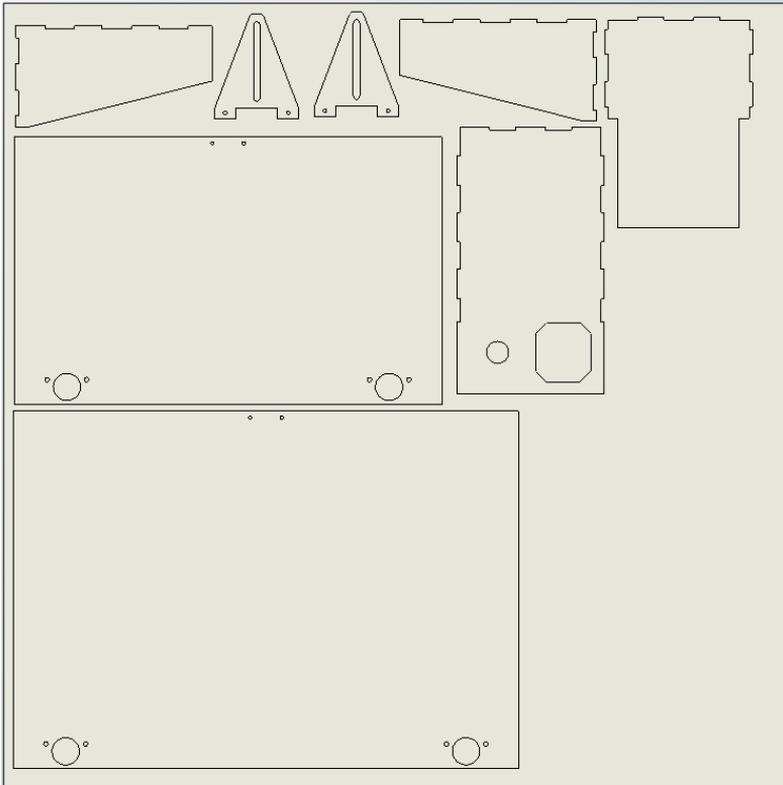


Figure 42: The orange parts on a 750*750mm sheet

The top sheet of the container array, the UT-switch button and the platform support made of 5mm clear PMMA

Andrea Minuto also cut these parts in the Design Lab. The cutting time was about 20 minutes.

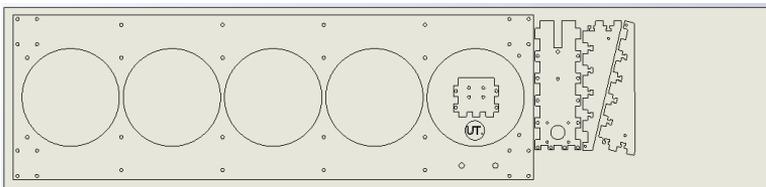


Figure 43: The clear parts on a 800*200mm sheet

The bottom sheet of the container array

The bottom sheet of the container array was cut in the SmartXP lab at the University of Twente using a 40W Trotec 300 laser cutter operated by Alfred de Vries. Compared to the others, the settings were set to cut very slowly, since Delrin emits an explosive gas that can cause the object to move, or catch fire. The cutting time was about 20 minutes.

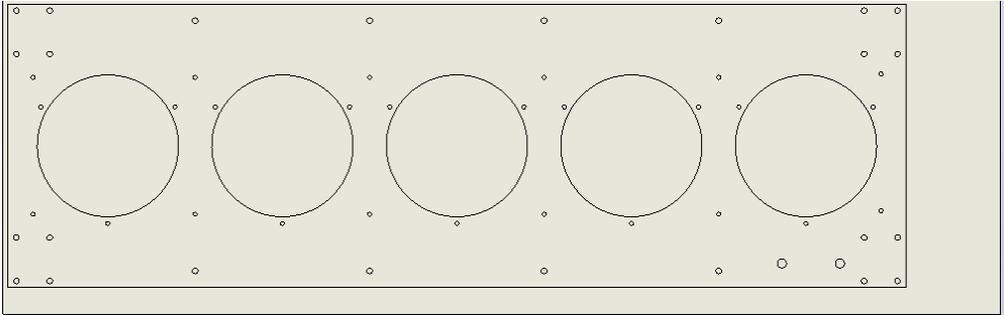
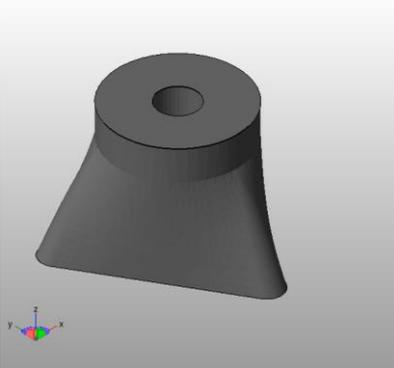
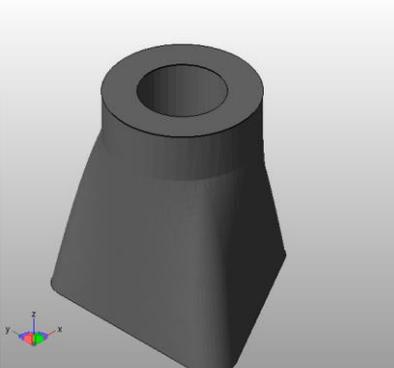
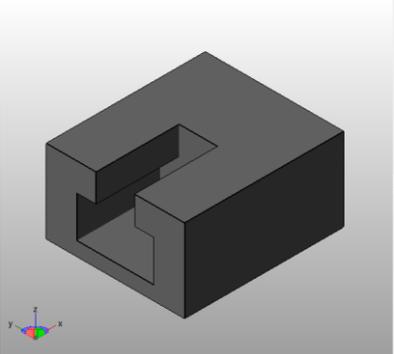
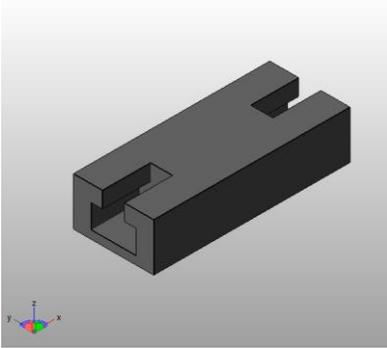


Figure 44: The Delrin sheet of 200*600mm

Appendix 9: 3D printed parts

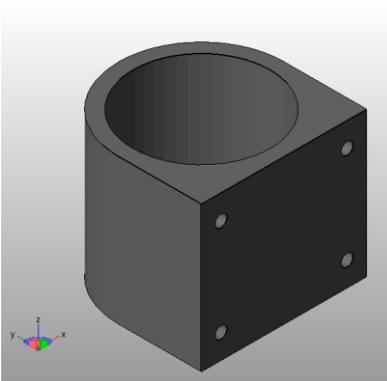
The small parts were made using a FDM printer with support material, using thin filament. This printer was operated by Tom Vaneker at the OPM workshop in the University of Twente. The files were delivered as STL files and were loaded in host software of Objet. Two printer beds were needed to build all the parts.

	Name	QTY.
	M3 Triangular nut	20
	M8 triangular nut	1
	Place keeper for the spring assemblies, single	4



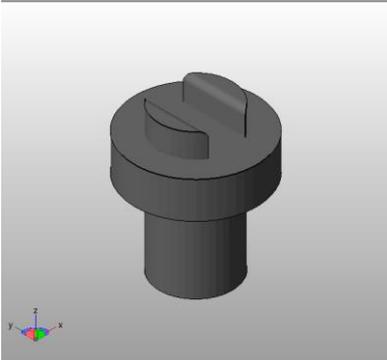
Place keeper for the spring assemblies, double

8



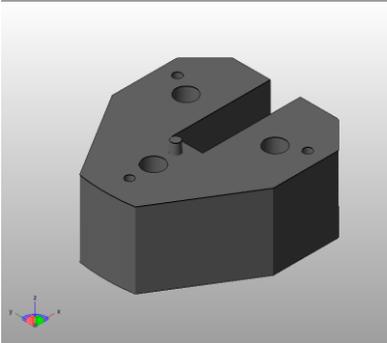
Linear bearing housing

4



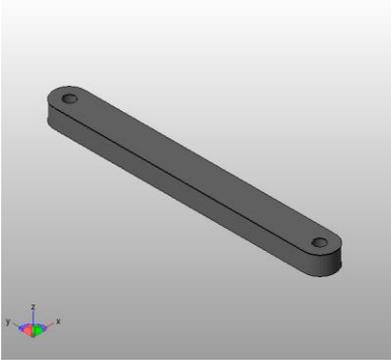
Mirror clip

2



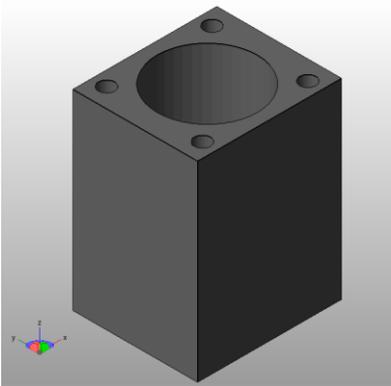
Spacer for the platform

1



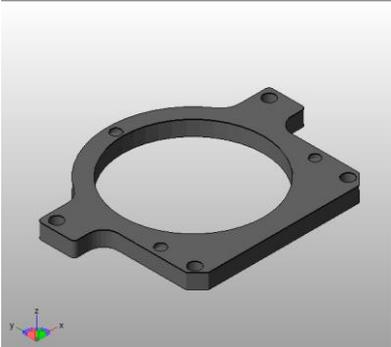
Vat holding rods

10



Anti-backlash nut housing

4



Spacer for the beamer

1

Appendix 10: The aluminium parts

The aluminium parts were made in the metal workshop of TCO from the University of Twente. The platform was cut using a circular saw. The holes were made using a column drill and were threaded using a tap.

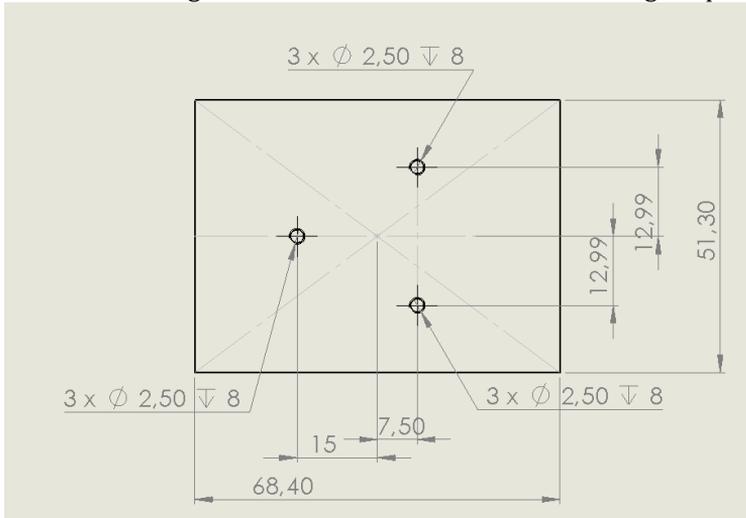


Figure 45: The build platform made of 10mm thick aluminium

The aluminium grasps were cut of a rod using a band saw. The holes were made with a column drill and were treaded using a tap.

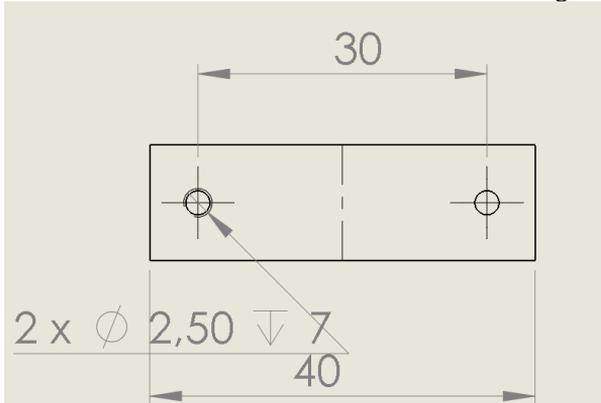


Figure 46: The grasps made of 12X12 mm square aluminium rod

Appendix 11: Assembling the parts

The parts were assembled using bolts, nuts, O-rings and screws. The holes were already made by the laser cutter and 3D printer. Narrow holes had to be enlarged a little bit using a hand drill. A few holes in the platform assembly had to be drilled manually, since they couldn't be laser cut. The metal screws are self-tapping in the plastic material. The holes that were used to tighten the body together were made after the laser cutting. They needed to be drilled and countersunk. Since the supply of m3 screws was very limited, a lot of screws had to be sawn-off at the right length.

Assembling the z-spindle

The Z-spindle (1) and anti-backlash nut (2) were purchased from rsonline.com. Since the shop didn't sell a spindle-nut combination of the preferred lead size of 4.5 with a length of 300 and a little mistake was made, a spindle-nut combination with a 2mm lead was purchased. The result is that the maximum speed is a bit lower than desired but the accuracy is bit higher. At the end of the spindle a hole with a close-fit to the 5mm motor shaft was drilled using a lathe with a 4.8mm drill and a 5mm reamer, since this is the easiest way to connect it to a motor (3). A nut housing (4) was 3D printed to be able to connect the nut to the platform support.

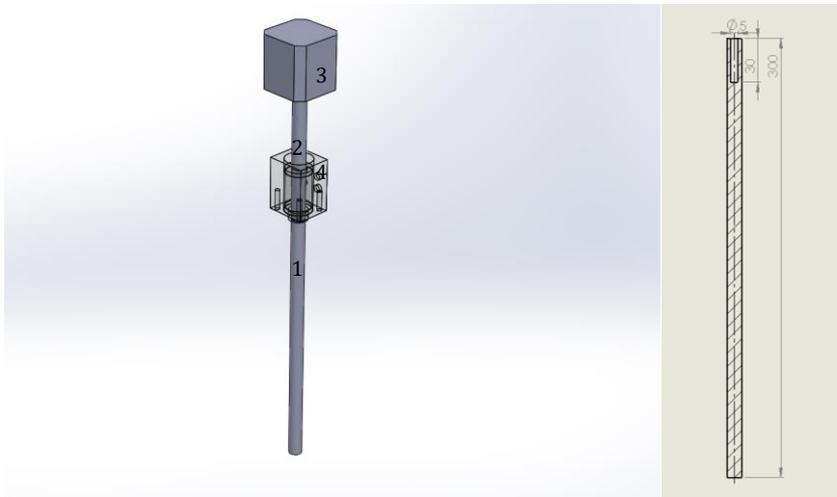


Figure 47: The Z-spindle assembly

Assembling the x-spindle

The X-spindle, see the figure below (1) was already available. It is a 12mm diameter 5-tracks high precision screw with a length of 500mm and a lead of 20mm. The nut (2) was also already available and is made of Delrin. The end of the spindle needs support and this was done by printing a little support (3) that is connected to the body. A small spacer (4) is printed to be able to let the vat array assembly pass over the motor (5). This spindle was connected to the motor in the same way as the other spindle.

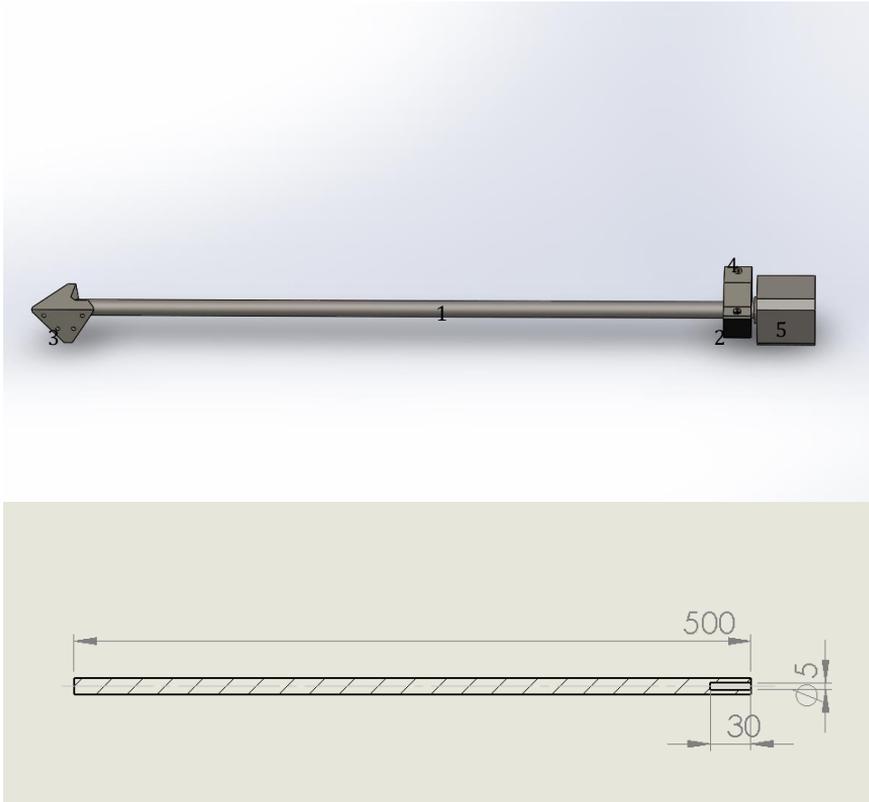


Figure 48: The X-spindle assembly

Gluing the hood

The hood was glued together using transparent silicon kit since it is easily removable if it would be spilled. Another reason to use silicon is that it won't eat the plastic, so it doesn't mess with tolerances.

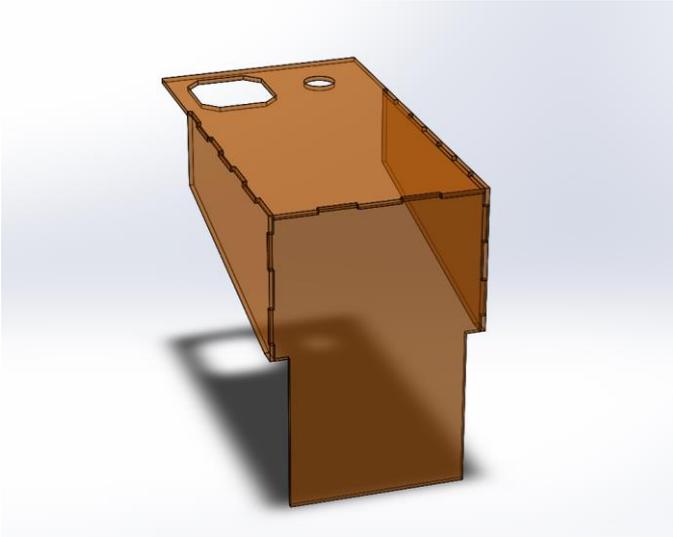


Figure 49: The hood

Assembling the covers

The covers are designed to be easily installable, and have four concealed hinges (1) to be able to fix the sheets at a 90° angle to get easy access to the internal parts. A small rectangular knob (2) is placed at the edges. The hinges stab a little bit out since the material is only 3mm thin. The 3D printer could print small parts to cover these hinges when the printer is finished.

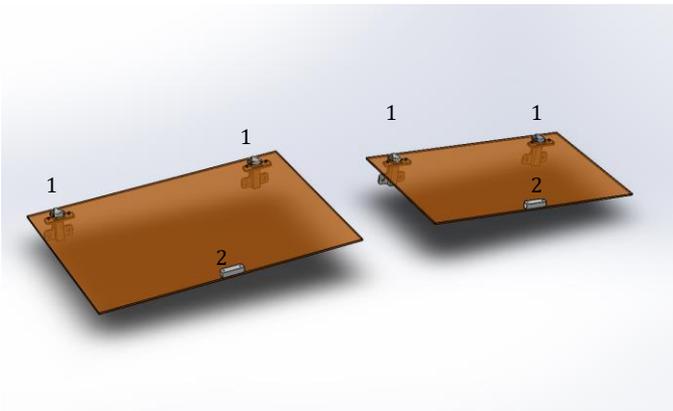


Figure 50: The covers

Assembling the mirror

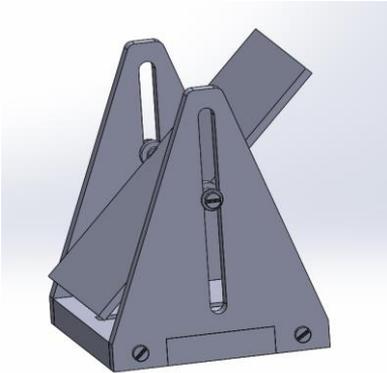


Figure 51:The mirror assembly

Leg levellers

Four leg levellers were bought and installed under the body using bolts. They were bought at the local D.I.Y. shop.

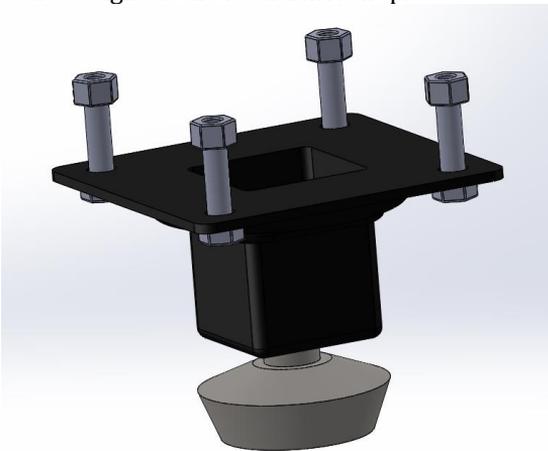


Figure 52: Leg leveller

Connecting the wires

All the wires were connected to the motherboard. The jumpers under the purple Pololu driver carriers were set to half stepping mode. The board can either be powered from USB or from the power supply; the jumper setting for the board power should be set to either 2 or 1. Since a computer is needed it needs to stay connected with the USB cable, so the board power setting doesn't matter. A small pushbutton was installed at the top of the printer. With this button the beamer can be switched on and of. The UT logo

was placed on top of it by cutting of a bit of the head of the pushbutton. How the wires are connected is drawn in the picture on the next page. The motor cables were soldered to black UTP cables and on other end prototyping cables were soldered. The connections are sealed using heat shrink. For the optical end stops the same was done, but instead of an 8-wire UTP cable, phone line was used. The cables were routed through the body and connected to the Megatronics v3 Board.

Limiting the drive current to the stepper motors.

A small potentiometer is installed on the Pololu driver carriers. (see the arrow in the picture with the wire connections) This potentiometer is there for limiting the output current to the motor's maximum drive current. A small firmware was uploaded to power just one of the motor's windings, but without stepping. The current through the wire was measured using a multi meter and the potentiometer was adjusted to output 0,67A. Now the motor will be able to run at its maximum speed without getting damaged.

Appendix 12: Firmware configuration

For uploading firmware to the Megatronics v3 board a modified version of Arduino IDE that lists the board can be downloaded from reprapworld.com (Reprapworld, 2015) It also hosts the Marlin firmware on that page. In the firmware there is a file called configuration.h. In this file the variables about the printer needs to be set. Since the firmware is made for FDM printing some changes need to be made. The sections that need to be adjusted are depicted in the following image sequence.

```
51 // SERIAL_PORT selects which serial port should be used for communication with the host.
52 // This allows the connection of wireless adapters (for instance) to non-default port pins.
53 // Serial port 0 is still used by the Arduino bootloader regardless of this setting.
54 // :{0,1,2,3,4,5,6,7}
55 #define SERIAL_PORT 4
56
57 // This determines the communication speed of the printer
58 // :[2400,9600,19200,38400,57600,115200,250000]
59 #define BAUDRATE 115200
60
```

Figure 53: Setting up the serial communication speed and port

```
64 // The following define selects which electronics board you have.
65 // Please choose the name from boards.h that matches your setup
66 #ifndef MOTHERBOARD
67 #define MOTHERBOARD BOARD_MEGATRONICS_3
68 #endif
```

Figure 54: Setting up the board type to MEGATRONICS_3

```
157 // The minimal temperature defines the temperature below which the heater will not be enabled It is used
158 // to check that the wiring to the thermistor is not broken.
159 // Otherwise this would lead to the heater being powered on all the time.
160 #define HEATER_0_MINTEMP 0 // These are all set to 0 for DLP printing, since none of the sensors are used.
161 #define HEATER_1_MINTEMP 0
162 #define HEATER_2_MINTEMP 0
163 #define HEATER_3_MINTEMP 0
164 #define BED_MINTEMP 0
```

Figure 55: Setting the minimal temperatures to 0

```

577 * MOVEMENT SETTINGS
578 */
579
580 #define HOMING_FEEDRATE {600, 50*60, 300, 0} // set the homing speeds (mm/min)
581 //this was set to be the maximum safe travel speed: 150 RPM, 2mm movement each rotation
582 . -->300mm/min for the Z-axis and for the X-axis it is set to 600 as a guess that the fluid
583 . won't spill with this speed.It might be increased to a maximum of 150*20=6000mm/minute
584 . according the motor's specifications.
585
586 // default settings
587
588 #define DEFAULT_AXIS_STEPS_PER_UNIT {40,78.7402*2,400,760*1*1.5} // default steps per unit
589 . are changed: 800 steps per rotation (0,9° resolution--> half stepping with a lead of 2mm
590 . this results in 400 steps per milimeter for the Z-axis, and 40 steps/mm for the Z-axis.
591
592 #define DEFAULT_MAX_FEEDRATE {100, 300, 5, 25} // (mm/sec)
593 . //The maximum feedrates were set for the x-axis to be the same as the homing speed/60 since
594 . this is in seconds! and for the Z_axis it is left to default at 5mm/sec as this is already
595 . the maximum Z-speed.
596
597 #define DEFAULT_MAX_ACCELERATION {300,300,10,1000} // X, Y, Z, E maximum start speed
598 . for accelerated moves. E default values are good for Skeinforge 40+, for older versions
599 . raise them a lot.
600 . //The acceleration settings are raised alot from the default values (3000,3000,100,10000)
601 . since else alot of steps will be missed and resin will spill out of the containers. They
602 . were set to 1/10 of the default.
603
604 #define DEFAULT_ACCELERATION 300 // X, Y, Z and E acceleration in mm/s^2 for
605 . printing moves //also set to 1/10 of the default
606 #define DEFAULT_RETRACT_ACCELERATION 3000 // E acceleration in mm/s^2 for retracts
607 #define DEFAULT_TRAVEL_ACCELERATION 300 // X, Y, Z acceleration in mm/s^2 for travel
608 . (non printing) moves
609
610 // The speed change that does not require acceleration (i.e. the software might assume it can
611 . be done instantaneously)
612
613 #define DEFAULT_XYJERK 20.0 // (mm/sec)
614 #define DEFAULT_ZJERK 0.4 // (mm/sec)
615 #define DEFAULT_EJERK 5.0 // (mm/sec)
616

```

Figure 56:Setting up the speed and acceleration

Level adjustment of the vats

First the linear guides need to be setup to be exactly parallel. This can be done using the 3 screws at each edge while measuring with a dial gauge. Secondly the resin vat floors need to be exactly of equal level, since else multi-material printing won't work. This can be done using a dial gauge that's hung up in a stand. The floor level of the petri dishes needs to be measured at three location and the 3 screws need to be adjusted. The build platform can be tilted with 3 screws in order to make it perfect parallel to the resin floors.

Positioning the beamer, focussing and placing the mirror.

The beamer has to be placed at the right distance in front of the mirror. The height of the mirror, and beamer needs to be adjusted to project the right area. The focus distance needs to be projected to produce a sharp image, at first glance. (In the visible light) However this looks like good focus, in the UV spectrum the image might be out of focus due dispersion. (See wavelength in the analysis section) The right focus has to be estimated by trying.

Appendix 13: Setting up the host software

As in the concept phase was described the software written by Steve Hernandez called Creation Workshop will be used to setup the properties of the printer and the slicing and printing behaviour. The first things that need to be set are the beamer and printer connection settings. The baud rate should match the baud rate that is set in the firmware. In this case it is set to 115200. The render options will be set to the beamer's resolution: 1024 * 768. The platform size also need to be set to correspond with the physical maximum bounding box, by measuring the projected size and the length of the moveable z-length of the printer.

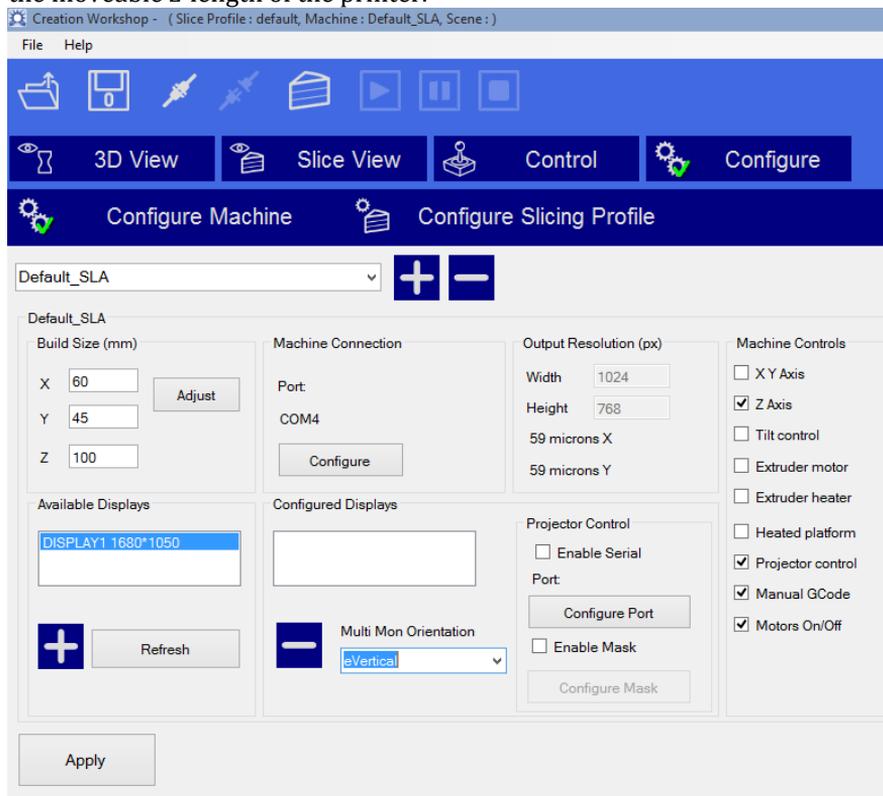


Figure 57: Setup the communication and build-size settings

Further settings

There are more things that need to be setup to be able to print. This includes layer thickness and the movement of the motors to change the vats. Estimating the layer thickness requires many experiments and there's just not enough time for that within the extend of this assignment. Motor controls

for controlling the X-axis automatically can be setup in the custom G-code section. This can be used to setup the movement for multi-material printing. An overview of the G-code commands can be found on reprap.com/wiki/G-code (Reprap, 2015)

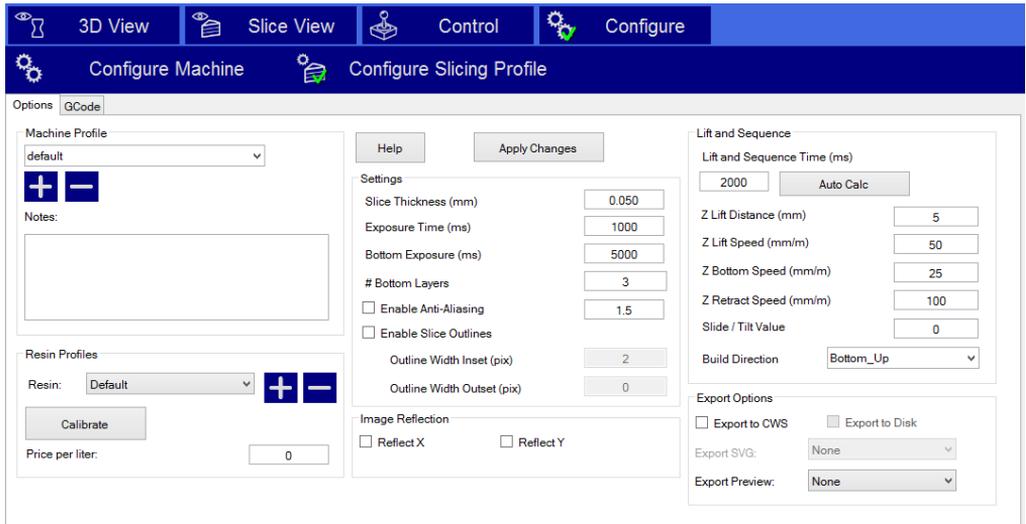


Figure 58: Setup the slicing options

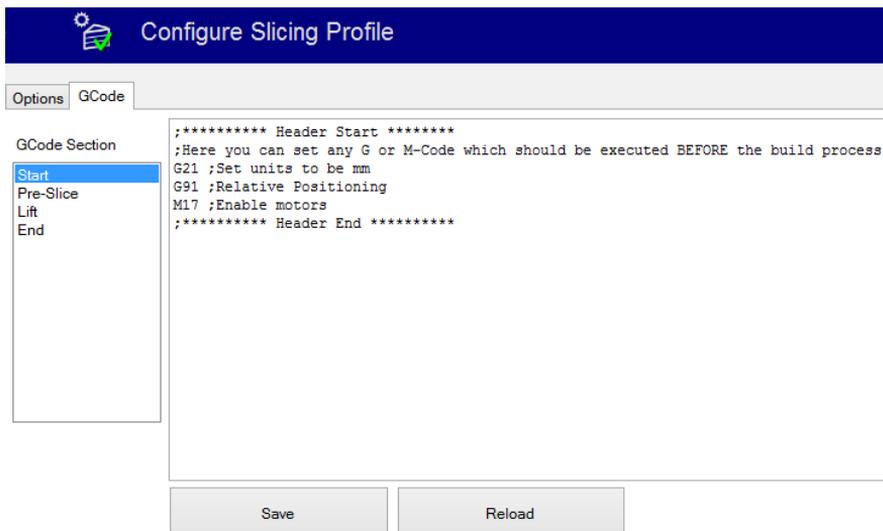


Figure 59: Setup the manual G-code