Design of 3D printer with delta kinematics

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1. Vypracujte literární rešerši v oblasti 3D tisku a kinematiky pohybu tiskové hlavy.
2. Navrhněte model 3D tiskárny s delta kinematikou ve 3D návrhářském programu (CADu).
3. Ověřte funkčnost delta kinematiky.
4. Sestavte funkční vzorek 3D tiskárny s delta kinematikou.
5. Ověřte funkčnost prototypu 3D tiskárny s delta kinematikou.

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ABSTRAKT

Tato práce se zaobírá návrhem 3D tiskárny s delta kinematikou v 3D CAD programu, následným sestavením a otestováním prototypu. Zároveň čtenáře seznámí s historií 3D tisku, používanými technologiemi, typy tiskáren a materiály. Práce by měla dále sloužit k vysvětlení vlastností a výhod delta kinematiky. Vysvětlena budou taktéž konstrukční řešení a důvod jejich použití oproti standardnímu designu tiskáren s trojúhelníkovou základnou.

Klíčová slova: Návrh 3D tiskárny, Delta kinematika, 3D tisk, Aditivní výroba, FDM, Delta 3D tiskárna, LP Delta

ABSTRACT

Presented thesis dels with Delta 3D printer design in 3D CAD program, assembling and prototype testing. It will familiarize readers with 3D printing history, commercially used technologies, different designs and materials. The bachelor thesis will further serve to explain characteristics and advantages of delta kinematics. Construction design solutions will be expounded as well as the reason for their implementation in comparison with a standard delta design using a triangular base.

Keywords: 3D printer design, Delta kinematics, 3D printing, Additive manufacturing, Fused deposition modeling, Delta 3D printer, LP Delta

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INTRODUCTION

Technological advance in the 21st century along with increasing demands on development and prototyping has led to a new term - Industry 4.0. Rapid prototyping and 3D printing is a indivisible part of this new term and manufacturing processes. These technologies made it possible to shorten the time delay between development and production from weeks to days. Great example of advantages is a plastic injection molding. Standard procedure of product testing and manufacturing was to mill an expensive injection mold, make a small batch and test these parts. Now we are able to 3D print the product and test it's dimensions in a matter of days. It is also possible to use 3D printing technology for small production which decreases costs of the manufacturing by thousands of dollars.

One of the most important part of the RP is decreasing manufacturing cycle time, which leads to smaller expenses and profit growth. We are able to achieve this with 3D printing integration into the manufacturing cycle. Technologies such as fused deposition modeling, stereolithography, selective laser sintering are so advanced that the dimensional deviation of printed parts can be about 0.01 mm which is suitable for most of the industry applications.

3D printers can be divided into different groups according to used technologies, expenses, accuracy, speed and other criteria. For the purpose of this bachelor's thesis I will divide them into two groups based on the printing speed. SLA, DLP, SLS technologies belong to slow 3D printers and FDM technology into the second group. Main focus will be on FDM and delta kinematics.

I. THEORETICAL PART

1 3D PRINTING AND RAPID PROTOTYPING

1.1 History

The first article [1] about a functional 3D printing method called stereolithography was published by Hideo Kodama in 1981. It uses intense light illumination with defined wavelength and photosensitive liquid to create solid 3D objects. This scientific discovery impressed many other scientists in the world and accelerated development in this field. Just a few years later in 1986, Charles W. Hull published his work on stereolithography [2] and patented his solution to this problem which led to foundation of 3D Systems Corporation and the first commercial 3D printer SLA-1 in 1987.

Figure 1.1 SLA-1 printer [3]

Another method called FDM was invented in 1988 by S. Scott Crump [4]. This technology has become the most popular in the following years thanks to the much simpler design, lower price and higher speed. FDM was patented in 1989 by Starasys inc. and there where only a few other companies using the license due to it's price. A turnabout happened in 2004 when a group of enthusiasts from a British university started working on a commercially accessible 3D printer under a project called RepRap. This effort has inspired other communities to create other projects such as Marlin or Klipper firmware. In 2009 the Statasys's patent expired and a new era of cheap 3D printers available for everyone has started.

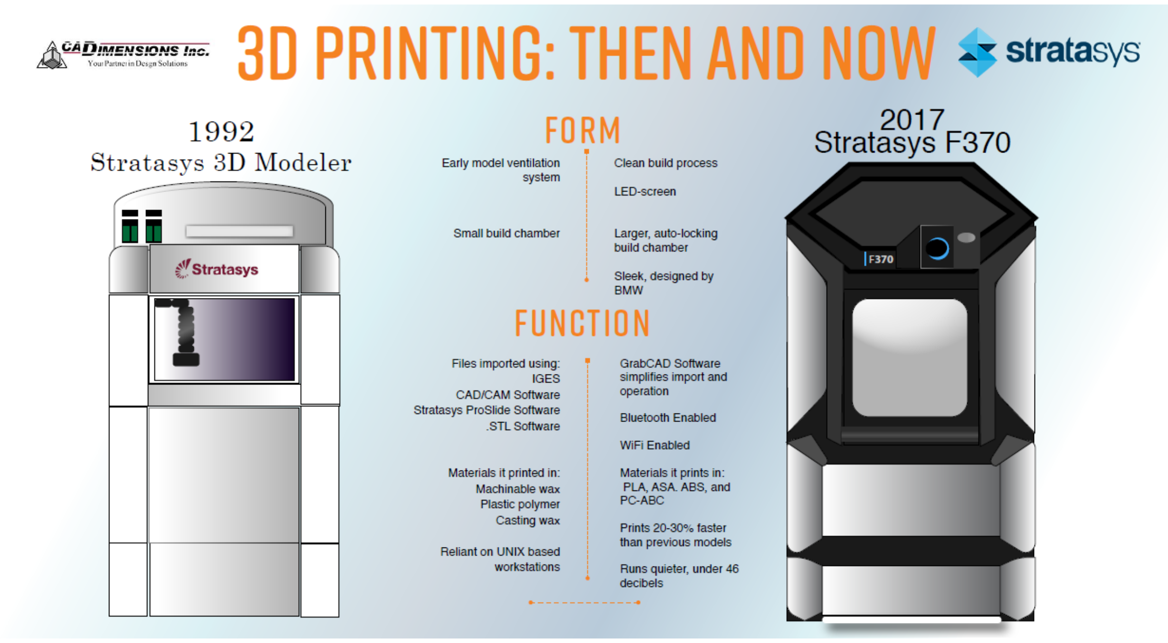

Figure 1.2 Stratasys' first FDM 3D printer [5]

SLS Technology was introduced in 1987 and patended two years later by Carl R. Deckard [6]. However this technology was very expensive and not so common thanks to that fact. The first company that made SLS commercially available and affordable is EOS STEREOS 600 first sold in 1993 [?]. Another successful company is Hewlett-Packard with their HP JET Fusion 3D printer [7] introduced in 2016.

Figure 1.3 SLS HP JET Fusion [7]

1.2 Rapid prototyping definition

Rapid prototyping is a new method of fabrication that has revolutionized the whole manufacturing process by implementing modern 3D CAD technologies. Integration of CNC machinery such as milling machines, 3D printers or 3D scanners has considerably reduced manufacturing cycle time and improved the ability to create a prototype [8].

1.3 3D printing definition

3D printing is a process of creating a three-dimensional physical object from a digital model using additive manufacturing by printing it layer by layer. Each of these layers is a cross section of the object with defined height. This process is the opposite of a standard subtracting method such as milling or turning and enables to create much more complex parts unable to make with older procedures and techniques [9].

Great example of a complex object that cannot be made by milling, drilling or turning is a 3D printed titanium SpaceX's SuperDraco engine core. Using this technology has improved fuel efficiency, weight and manufacturing cost [10].

Figure 1.4 3D printed SuperDraco rocket engine core [11]

2 FDM TECHNOLOGY

2.1 FDM principle

FDM or FFF technology consists of pushing a plastic string called filament to the printing head and creating a positive pressure in the melting zone in the nozzle [12]. Melted plastic is pushed out due to the pressure creating a line on the bed surface where it solidifies. Using only heat and pressure to print a 3D object made this technology the most used in the whole world.

A standard E3D V6 hot-end consists of a aluminum heat sink with a bowden coupler. Fan with a shroud is attached to aluminum body and provides sufficient air flow to keep the temperature about 20°C above outside environment. This whole assembly is called a "cold side". The "hot side" consists of a heater block, nozzle, thermistor and a heating element. Connection between these tho assemblies is provided by a heat-break made of a low thermal conductivity material such as titanium alloy.

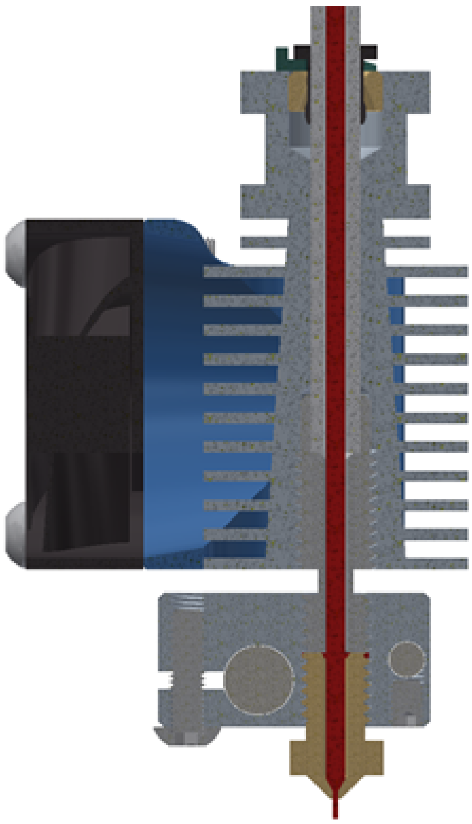

Figure 2.1 Cross-section of a standard E3D V6 hotend

2.2 FDM materials

2.2.1 PLA

Is the most widely used material in 3D printing. Majority of the production is made from a corn starch, which makes it the only bio-plastic used in this field. Each spool contains about 85% of PLA, the rest is additives and colorants [13]. Pure PLA should be able to decompose in natural environment in about 6 - 12 months and it has become one of the most generally used bio-plastics. This plastic is also used in food industry as an alternative to commonly used materials for products such as coffee cups, plates, cutlery, etc.

2.2.2 PETG

Another widely used material is PETG. It's glass transition temperature is about 70°C, which is about 10°C higher than PLA's. It has also higher elastic modulus allowing use in other applications. PETG consists of about 90% Polyethylene terephthalate glycol and additives plus colourants. Another advantage over PETG is a smaller shrinkage and better bed adhesion, so it is more suitable for bigger projects.

2.2.3 CPE

Made of Chlorinated Polyethylene is becoming more popular these days. It's properties are similar to PETG offering excellent mechanical and chemical resistance. A typical application is for structural parts. Glass transition temperature is similar to PETG with 80°C.

2.2.4 ABS

ABS has been one of the first materials used in 3D printing. It offers great mechanical properties and a glass transition temperature about 105°C which makes it a good choice for most applications. Thinner or IPA can be used to etch the outer surface of the printed object to make it glass-like smooth. However, this filament is not recommended to use in household without a full enclosure and filters, because it's vapors are toxic.

2.2.5 ASA

This material was created in 1970s as an alternative to ABS which can be used in outdoor applications such as mirror cases in automotive. It has very similar mechanical and thermal properties, but is much more UV resistant. Derivatives such as ASA275 are also easier to print than a standard ABS and ASA.

2.2.6 Nylon

Is the most widely used engineering filament in RP offering much higher impact strength and ability to be used in environments with up to 120°C. Nylon must be printed in a fully enclosed 3D printer with a sufficient temperature, because it tends to shrink and bend, therefore a majority of hobby printers cannot use it.

2.2.7 Other materials

There is a lot of other filament materials available on the market and most them are not so common due to the price or technical requirements. I have divided them into two groups: exotic materials and filaments with additives. Group 1: Polycarbonate, Polypropylene, Polyether ether ketone, Polyvinyl alcohol, High Impact Polystyrene. Filaments with additives: Carbon fibre filaments such as CF-PETG, CF-PLA, CF-ABS, Wood PLA filament, Silk PLA [14]

2.3 FDM process

Digital model must be exported to suitable 3D format, such as a most common STL file and imported into a pre-processing software called slicer where it can rotated, moved and prepared for the next step. Object is divided into different sections such inner and outer wall, bottom and top layers, infill and support. Each of these sections has different settings and properties. The object is sliced into layers with defined height and each layer is processed and a nozzle path is created. Each section, layer and path is converted to movement command such as Move to X Y Z coordinates and the whole model is exported to a standard GCODE file.

After importing GCODE file and hitting a start button on the 3D printer, the first part of the GCODE commands initiates. The 3D printer homes all of it's axes and

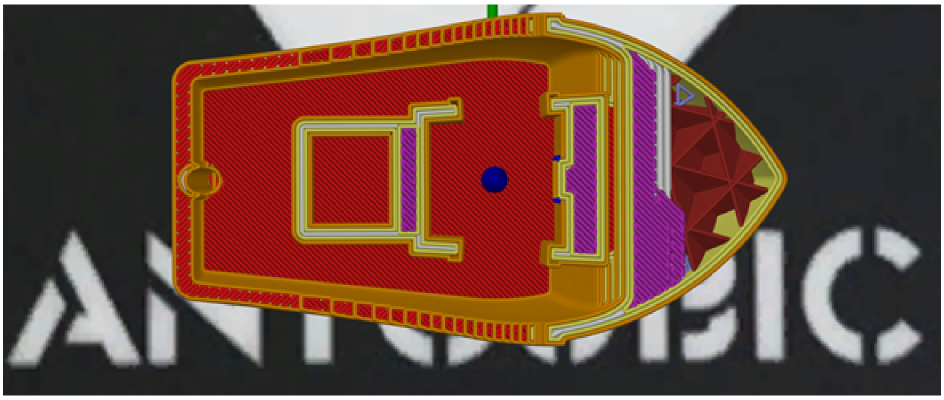

Figure 2.2 Cross-section of a sliced object

starts heating up the nozzle and bed. Object printing initiates when this sequence is finished and the 3D model will be printed layer by layer. Initial layers are printed solid and their count depends on slicer settings. Raft or brim supports are usually added for low adhesive materials to keep the object in it's place. Next layers use this sequence: outer walls, inner walls, infill, supports. Walls are printed first to ensure smooth surface, because infill is printed with a overlap connecting it to the walls. Top layers are printed last and can be combined with ironing which is a procedure when a hot nozzle smoothens the top layer.

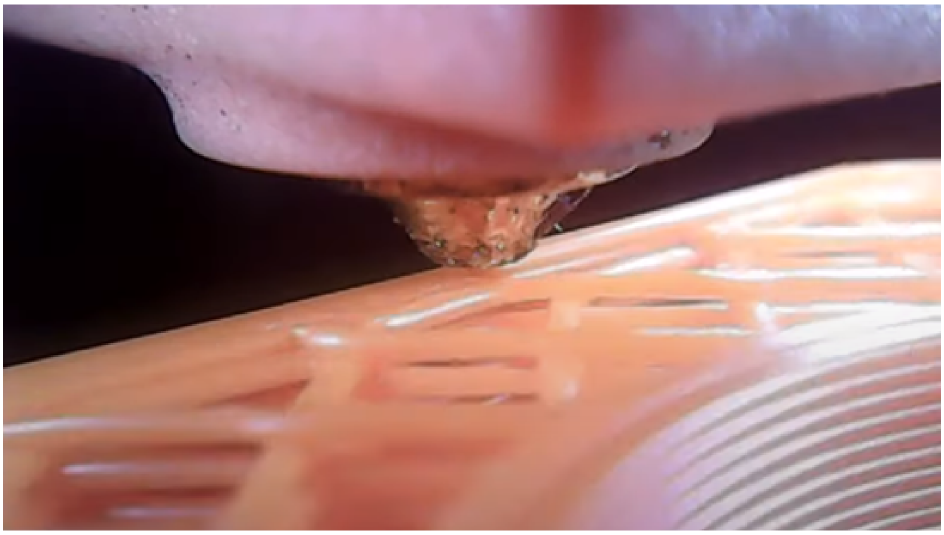

Figure 2.3 FDM technology - Nozzle view [15]

3 MSLA TECHNOLOGY

3.1 MSLA principle

This technology uses a photosensitive liquid - resin to create a solid object. Resin reacts with luminous flux in a UV spectrum and solidifies. Layer height is usually between 0.01 and 0.2 mm. Higher layers such as a 0.3 mm are not recommended to print, because the desired object and it's dimensions would be degraded by light leakage.

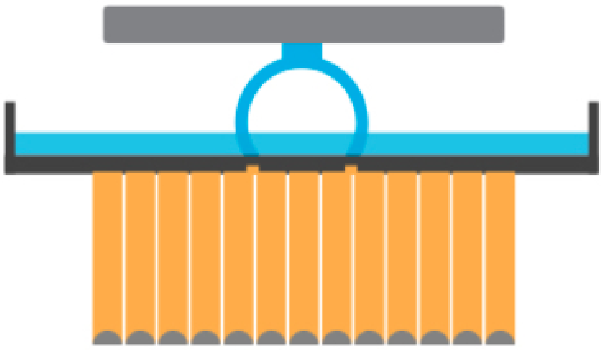

Figure 3.1 MSLA principle [16]

Mask stereolithography 3D printer uses a UV LED matrix and a LCD screen. LED matrix creates sufficient luminous flux for the resin to solidify. LCD screen is used for hiding areas where the model will not be printed. XY dimensional precision is defined by the pixel size. Stepper motor and micro-stepping determines Z axis precision. If we multiply XY size of the pixel and Z height, we create a Voxel which is a 3D pixel and the smallest printable object [16].

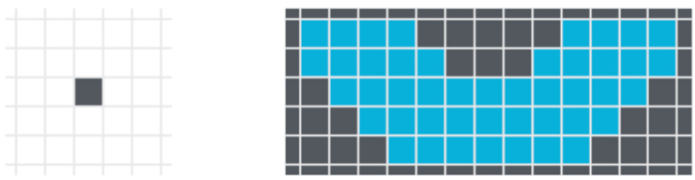

Figure 3.2 MSLA LCD screen [16]

3.2 MSLA process

Export digital model into STL format and import it into the slicer. Orientate object into desired angle, space and generate supports. Add stronger manual supports if needed and push Slice. However there is a significant difference between FDM and MSLA technology - the layer will be printed whole at one time.

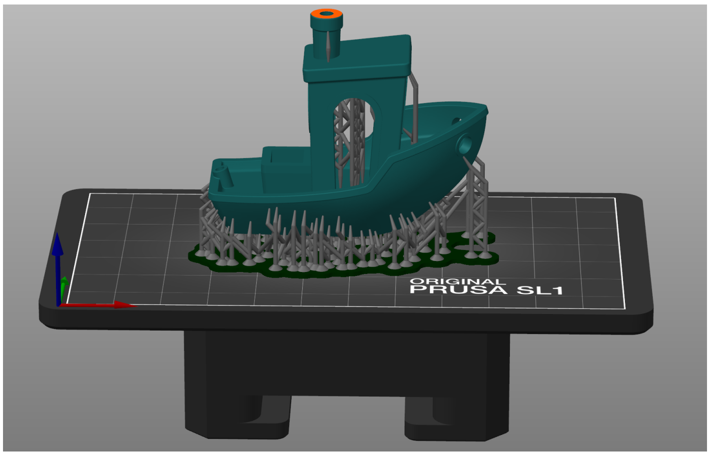

Figure 3.3 MSLA sliced model

Creation of the object begins with the first layer that use much longer exposition time to sufficiently adhere to the build surface and continues with standard layers and times. Resit vat is fixed and the build plate moves between each layer allowing the resin to flow under the build plate. This movement also helps with UV LED matrix cooling, because the light-source is turned off at this moment. Afterward the base is moved to the LCD's protective foil with offset equal to number of printer layers * layer height.

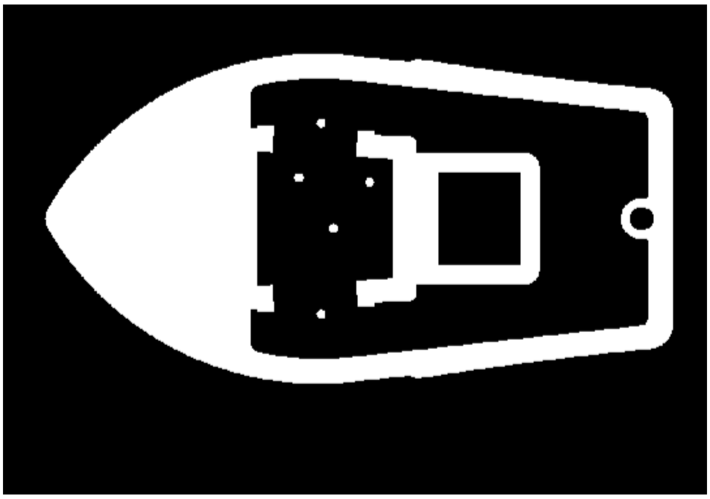

Figure 3.4 MSLA printing layer from PrusaSlicer

4 SLA TECHNOLOGY

4.1 SLA principle

Stereolithography uses a UV laser to solidify photosensitive liquid in the resin vat to create a solid object on the build plate. Laser is fixed in the printer and the beam is being deflected by a mirror to the build plate. Object is printed layer by layer, path by path. Major difference between MSLA and SLA is the shape of the printable spot. MSLA using LCD technology creates a rectangle shape with size of the LCD pixel, on the other hand SLA creates a rounded shape whose dimensions are defined by the laser beam.

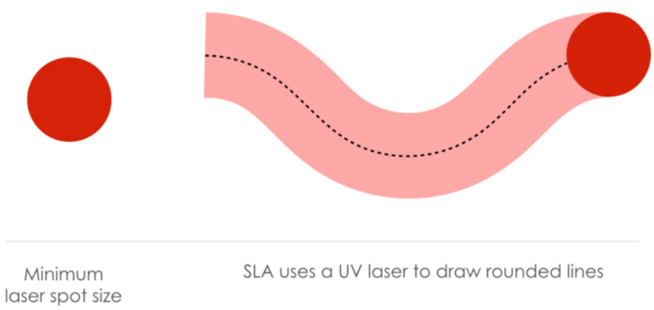

Figure 4.1 SLA principle [16]

4.2 SLA process

The process of SLA 3D printing is basically the same as SLA, the only major difference is that each layer is divided into paths and not printed whole at one time.

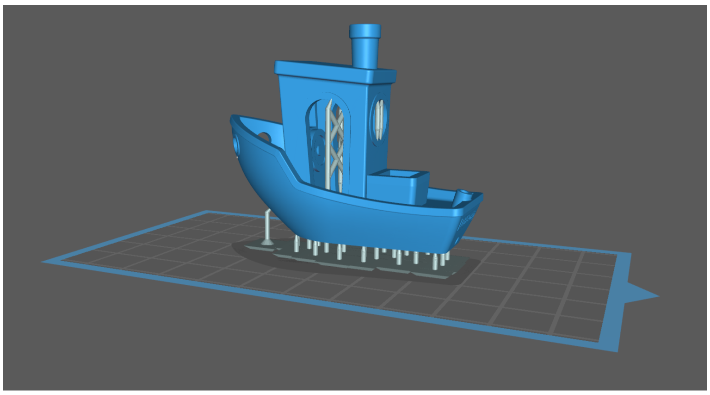

Figure 4.2 SLA sliced model

5 FDM PRINTER KINEMATICS

5.1 Cartesian kinematics

Most of the commercial FDM 3D printers use Cartesian kinematics. The build plate is usually not fixed and moves in one axis which limits the maximal speed and acceleration in this direction, because build plate is usually the heaviest moving object in the 3D printer. Effector is located on gantry that moves in a Z axis and is connected to one or two motors depending on a construction. This gantry includes a linear motion set - rails or rods. Effector is mounted on a carriage moving in the last axis using one actuator connected with a timing belt.

Figure 5.1 Anycubic Mega-S Cartesian 3D printer
[17]

5.1.1 Advantages of Cartesian kinematics

Each axis uses only linear motion, so there is no need for complex calculations. The number of steps needed to move 1 mm can be easily calculated from gear ratio and stepper motor driver settings 5.1.

$$\text{Steps Per mm} = \text{Motor steps per one rotation} * \text{Microstepping} * \text{Gear ratio} \quad (5.1)$$

5.2 CoreXY kinematics

CoreXY was designed to improve standard Cartesian kinematics and overcome it's disadvantages such as a low printing speed and backlash. Both X and Y motors are located in the same gantry and their movement is connected. There are 5 possible states: stop and moving in both directions in both axis. For example if X and Y actuator rotates in the same direction, effector moves in X axis. If they rotate in opposite direction, the effector moves in Y axis [18]. X and Y belts are longer than on a standard Cartesian printer, but distance of each straight path of the belt is usually shorter and the belt can be tighten easier due to the multiple supporting points. Using two motors and higher amount of belt tension elements has drastically improved stability and firmness of the whole gantry. These improvements a long with a much lower backlash made it possible to use much higher speed and acceleration settings. I will further divide CoreXY kinematics into two groups for a simplification: with fixed or a moving build plate..

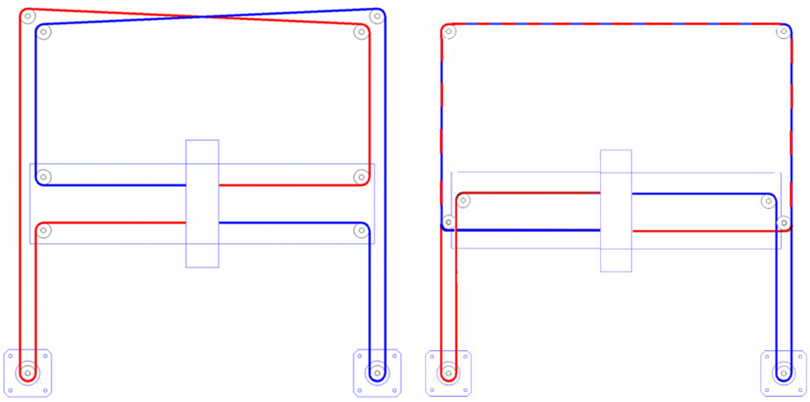

Figure 5.2 CoreXY kinematics [19]

5.2.1 Movable build plate

This group uses a build plate for movement in Z axis, usually connected to stepper motor via lead screw. It can be used with smaller and lighter build plates and there are many configurations depending on the number of actuators connected to the build plate from 1 to 4 independent stepper motors. A typical CoreXY 3D printer using a movable build plate is a BLV MGN Cube [20]. This configuration makes the Z axis kinematics simpler and cheaper. It is also possible to use less powerful control-board and firmware, because bed mesh calibration does not use a quad gantry level option in most of the cases.

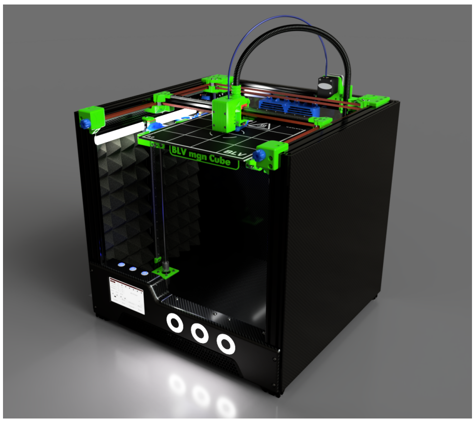

Figure 5.3 BLV MGN Cube [20]

5.2.2 Fixed build plate

The most modern and my favorite CoreXY configuration is with a fixed build plate. These printers can be equipped with heavier and flatter bed made of a CNC milled aluminium plate. It is also safer to use a high voltage heating element in this configuration, because cables of the heater do not move, so there is a smaller chance of disconnecting or wearing a hole in the cable's insulation. Z movement is usually managed by 4 stepper motors moving a U or a square shaped gantry. Both X and Y motors are located on this gantry, including all motion parts needed for X and Y axis.

One of the best CoreXY designs is a community project Voron [21] using a 8 mm thick thermal treated aluminum build plate.

Figure 5.4 Voron 2.4 [21]

5.3 Delta kinematics

This design came up from a three point plane definition. The basis of a delta 3D printer is a triangle configuration with 3 towers. Each tower is equipped with a linear motion carriage, a pair of arms with spherical bearings and an actuator, usually a stepper motor. Rotation movement generated by the motor is transferred into linear motion of the carriage connected to the motor with a timing belt. Moving the carriage in a parallel axis with the tower causes rotation movement of connected arm pair resulting in an effector motion. These three identical kinematic sets ensure printing head movement in all x, y, z axis on a plane parallel to the build plate [22].

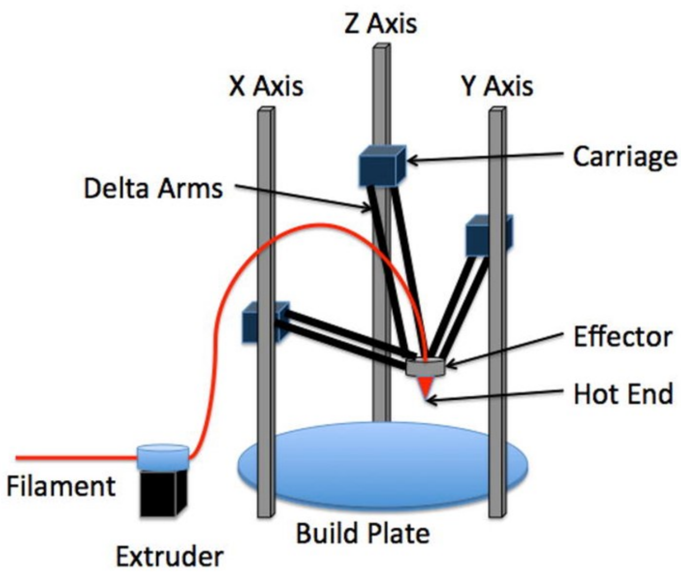

Figure 5.5 Delta kinematics [12]

5.3.1 Delta geometry

Is based on a triangle configuration with only two parameters requisite for most of the applications, Z height and delta radius. Z height is defined as a distance between tip of the nozzle and a build plate when the effector is in default, home position. Tower height and rod length affect it the most. The other parameter - delta radius is defined mainly by the size of the build plate, rods and also by carriage and effector offset [23].

For example Marlin firmware uses these parameters: Delta printable radius, Delta diagonal rod, Delta smooth offset, Delta effector offset, Delta carriage offset and calculates a delta radius the following formula.

$$\text{DeltaRadius} = \text{DeltaSmoothRodOffset} - \text{DeltaEffectorOffset} - \text{DeltaCarriageOffset} \tag{5.2}$$

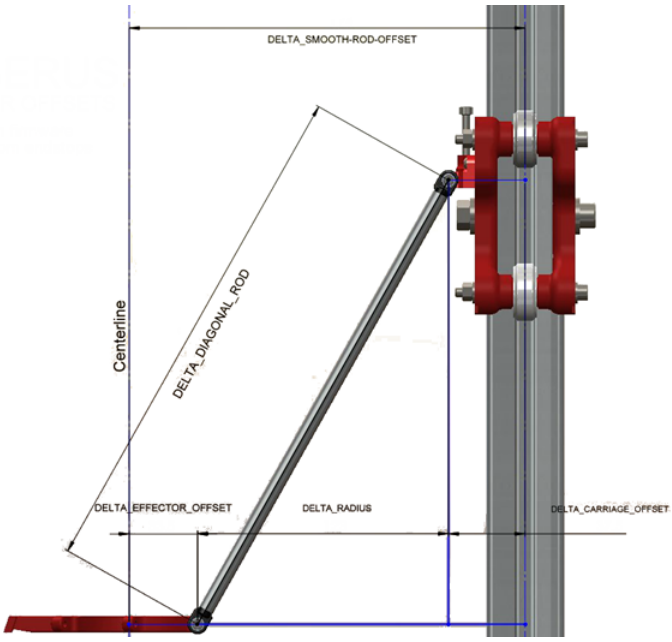

Figure 5.6 Delta geometry [23]

5.3.2 Advantages of delta kinematics

One of the biggest advantages over other kinematics is scalability. Printable height can be very easily modified by length of all towers. The next step is to lengthen linear rails, if they are used and use longer belts. Build plate size can be altered by changing the side of a equilateral triangle of the base and length of the rods. After that new bed with different dimension can be used. Simplicity of the construction is also an advantage. Standard delta printers consists only of two triangle bases and 3 towers, however different designs can be used, such as a hexagon base, which is a preferable for bigger printer sizes due to the better area utilization and a stiffer frame [24].

Printers with delta kinematics are also usually able to achieve better printing speed using higher acceleration and jerk settings. This is allowed on high speed delta printers using as light effector as possible. For example: a standard effector of a commercial Cartesian 3D printer weights about 250g and a lightweight delta effector about 100g. If we simplify the problematic with a thought that the stiffness and backlash of both printers is the same and apply 5.3, we can say, that we can use 2.5 higher acceleration values with delta kinematics and have the same acceleration forces on the kinematic

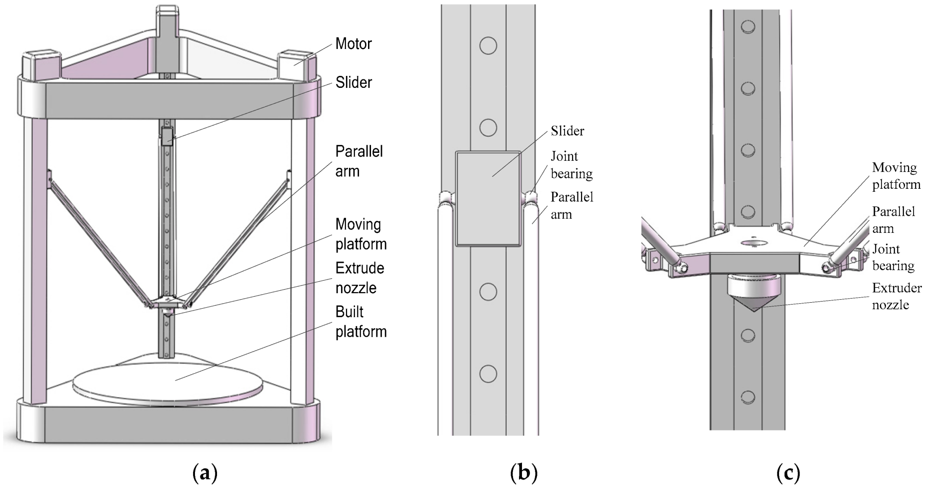

Figure 5.7 Delta construction [24]

system.

$$F = m * a[N] \tag{5.3}$$

Fixed build plate eliminates the need of a slow motion in one axis typical for most of the Cartesian printers. This leads to the option of using a much thicker bed made of aluminium with a special treatment which ensures minimal surface deformation from thermal stress, such as an ALQAL alloy.

II. PRACTICAL PART

6 3D PRINTER DESIGN GOALS

6.1 Printable volume

3D printer design is based on a desired printable volume - diameter at least 500 mm and minimal Z height 1000 mm.

Figure 6.1 LP delta version 1.0

6.2 High acceleration and speed

Delta kinematics was created for achieving high speed. A stiff frame, minimal backlash and lowest possible moving mass are requirements to be able to apply high acceleration values to achieve fast 3D printing. HIWIN MGN12H rails and carriages were picked to eliminate any backlash in Z axis. Gates GT2 10 mm wide belts provide reliable movement transfer between each stepper motor and carriage. MP-JET V2 spherical bearings and 6 mm carbon rods are tough enough to move effector without any free play. Due to the long distance between bearing axis of each rod, NEMA23 motors with a 0.8° rotation per step - 400 steps per revolution were implemented instead of more widely used standard stepper motors with only 200 steps per revolution.

6.3 High flow

It wouldn't be possible to print high volume parts with insufficient hot-end flow. The goal is to choose, test and implement a low-weight high-flow hot end. I have decided to create two different effector setups, both of them with powerful hot-ends. High speed variant uses a NF Zone heat-sink and heat-break with a V6 or Volcano heater-block depending on the use case. V6 version can achieve flow rate of 15 mm^3/s [25] and volcano about 45 mm^3/s [26]. The high tech version uses a NF-Crazy hot-end allowing easy standard V6 nozzle changing with sufficient maximal flow rate about 25-30 mm^3/s.

6.4 Automatic calibration

The most significant 3D object layer is the first one. Printing too low leads to over-extruding in the next layers and can be a cause of poor bed adhesion. The opposite leads to insufficient bed adhesion and deformed first layers. This problem combined with the fact that most of build plates are not flat calls for bed calibration techniques. The most basic technique that does not solve uneven bed surface is called "paper calibration". We move with the nozzle to at least 3 points on the bed leaving a space between the nozzle and bed, tighten/loosen screws attached to bed until we fell friction on the paper.

Manual bed mesh is the next step allowing to compensate any Z height issues. It must me done after the standard "paper calibration" ensuring that he bed surface plain and effector plane are parallel. After that the nozzle is moved via firmware instructions into defined X, Y points and Z offset is calibrated via FW and paper method. After measuring all points, the values are saved and firmware compensates Z offset. However each of these methods require a lot of effort, so automatic calibration with a probe is recommended.

Probes such as a detachable micro-switch, inductive probe or a piezo sensor are used on the effector for automatic calibration. The only manual part is setting up the probe Z offset. Firmware offers different techniques and point approximations to create a bed mesh. FW settings allow XY center probe offset and defying different point counts and patterns. Calibration routine can be called via FW or can be implemented in a complex macro including saving calibration values etc. However performing a full bed mesh and build plate calibration before each print takes a lot of time, so the standard procedure is creating a bed mesh - complete calibration every few months and using a 3 - 4 point calibration before every print to ensure that the effector plain and build plate surface are parallel.

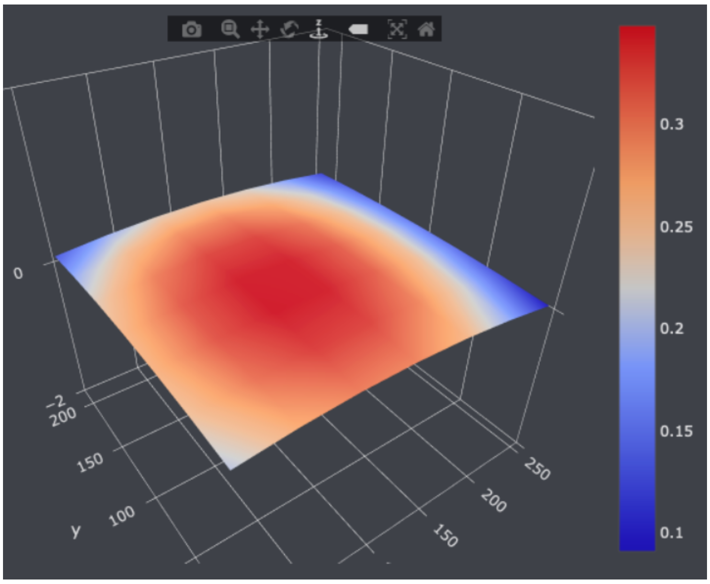

Figure 6.2 Bed mesh visualization

7 DELTA 3D PRINTER DESIGN

7.1 Base geometry

Standard frame configuration uses a triangular base based on a three tower delta kinematics. This works for smaller printers, but it creates many problems with increasing build plate size. Triangular frame with a inscribed circle requires longer distance between the bed and towers resulting in a lot of unused space. This also negatively affects enclosure and thermal insulation application, when the frame must be enlarged proportionally. Due to those facts that a triangular base is not a good choice for large Delta printers, I have chosen a hexagonal base allowing better area utilization. This decision also makes the frame much stiffer and provides sufficient space for thermal insulation and enclosure with minimal frame dimension changes.

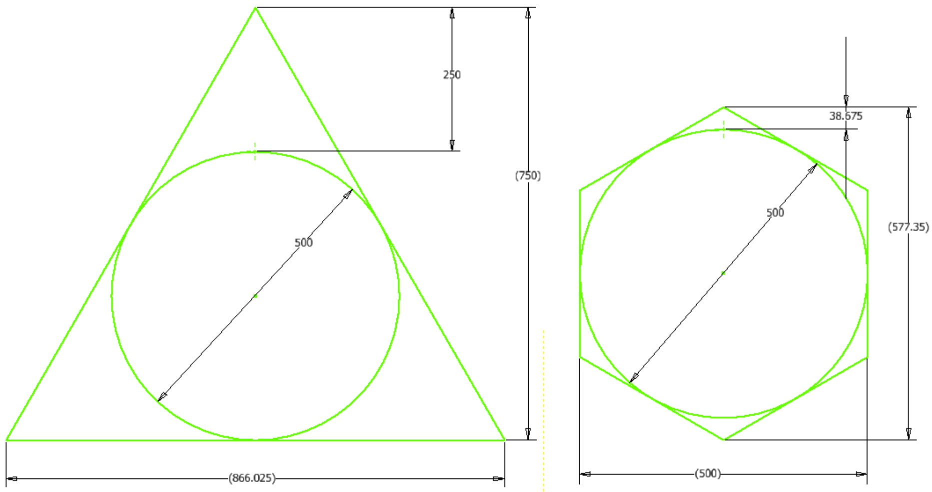

Figure 7.1 Triangular and hexagonal base comparison

7.2 Frame

Lower base is assembled from HFSB5-2040 aluminium profiles. Poly-carbonate plate mounted at top of the base ensures that all profiles are at the same plane. HFSB5-2020 are used for a build plate attachment. Central part adds reinforcement to the frame and ensures enough stiffness even without complete enclosure. Upper base uses a poly-carbonate plate for electronics mounting and HFSB5-2020 profiles with 35 mm gap between then to create enough space for NEMA23 motors and electronic parts. HFSB5 aluminium profiles were chosen for enough strength, availability and their 5 mm groove for M3/M5 T-nuts.

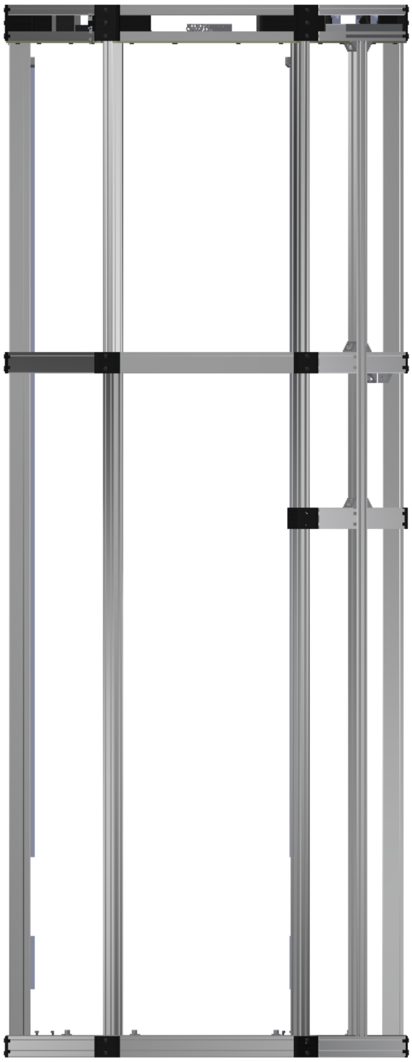

Figure 7.2 Hexagonal frame

7.3 Belt tensioner

Belt tensioner was one of the hardest parts to design. It must allow at least 10 mm movement in Z axis, easily accessible adjustment and cannot be to large, because it would limit the effector movement and printable radius. After about 20 different designs and iterations, I have selected two of them. The first version is located in the lower corner with 10 mm adjustable distance. This will be my default setup and the second version is designed as a backup. It is mounted on a MGN12H carriage and a 150 mm long linear rail. One iteration uses a pulley with internal ball bearing and second a standard GT2 20T 10 mm pulley with external 625 ball bearings.

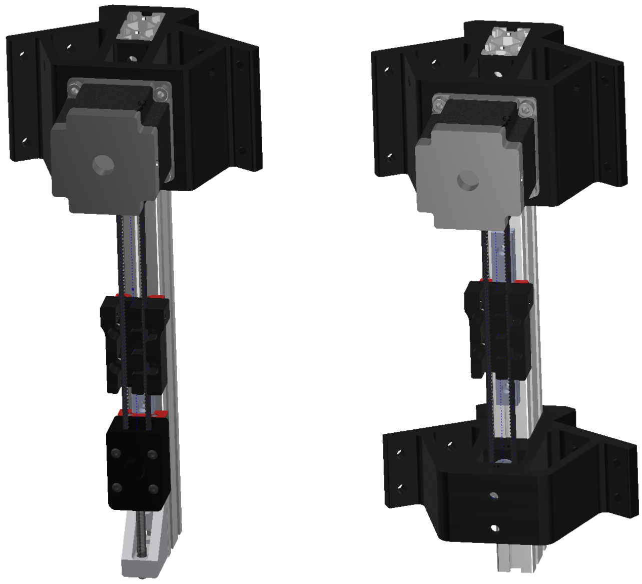

Figure 7.3 Belt tensioner, version 1 (right) and version two (left)

7.4 Linear motion

Thanks to the HIWIN business partners, I was able to use original HIWIN MGN12-C 1500 mm long rails with MGN12H carriages. These linear motion sets provide smooth Z movement and minimal backlash in X,Y axis. They are also easier to install and maintain than cheaper roller sets. 1500 mm length was selected due to the printer design and rod dimensions allowing effector movement over the whole build plate.

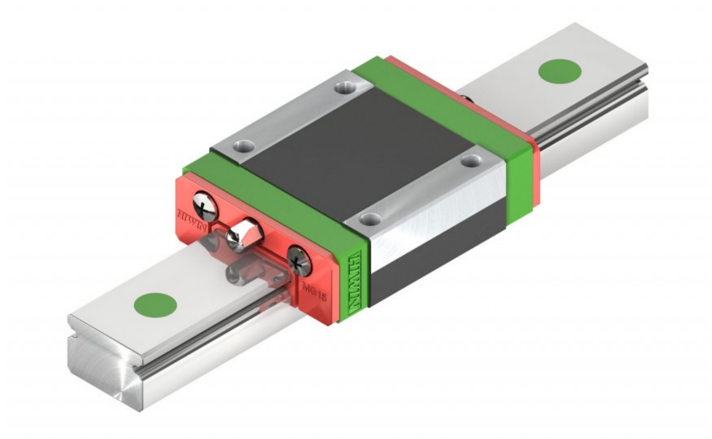

Figure 7.4 HIWIN MGN12H carriage on a MGN12-C rail

7.5 Carriage

Rod carriages provide a stable base for effector rods. Their design has to be compact and sturdy. Threads for rods are located as high as possible to eliminate any Z height reduction. Four inner blocks are used for belt installation and keeping it in place without any backlash. Thread located at the top is for a M3 set screw used for tower calibration. This screws will block signal in an IR gate that is galvanically isolated in each optical sensor for each tower.

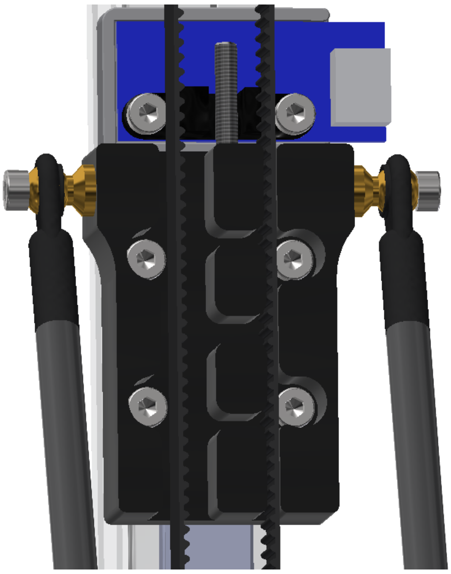

Figure 7.5 Delta carriage

Carriage calibration is totally necessary to be able to print with delta kinematics. Every 1 mm of Z tower offset causes up to 0.2 mm bed Z offset on a 100 mm radius bed with 150 mm long rods. The goal is to trigger end-stops at the same distance from build plate on each tower. This is the first step before any enhanced delta calibration.

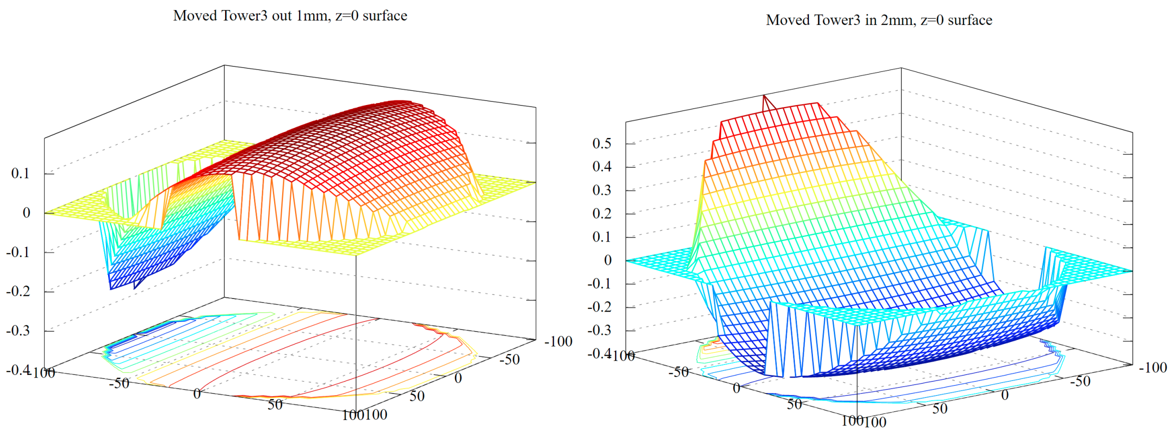

Figure 7.6 Carriage deviation [27]

7.6 MGN12 centring tool

I have designed this tool to make sure that MGN12 linear rails will be installed in the center of each tower. This is a must and it is not possible to calibrate the 3D printer without ensuring that axis of the rail and tower are parallel. 3 centering tools are recommended for each tower assembly.

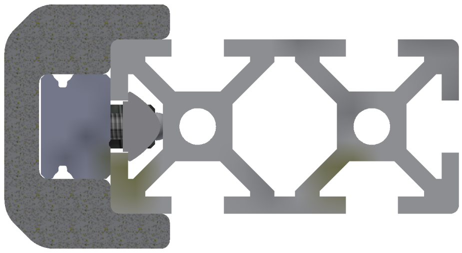

Figure 7.7 MGN12 centring tool cross-section

7.7 Build plate

Build plate has 550 mm in diameter and is made of an ALQAL aluminium alloy. This material is specially treated to remove any thermal tension inside the plate. It is CNC milled with a 0.1 mm maximal deviation. Each custom made piece is water cut into specified dimensions. Keenovo made-to-order 1100W 230V heater with a 3M sticker will be attached to back of the build plate. This high quality heater uses a NTC 100K thermistor and will be controlled via motherboard and a SSR relay. Magnetic layer is attached to top of the aluminium plate as a base for a PEI/Powder coated flex-plate.

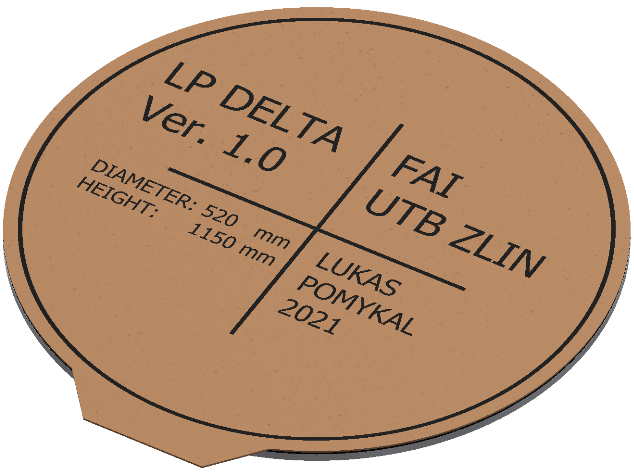

Figure 7.8 LP Delta build plate

7.8 Stepper motors

Majority of commercial 3D printers use Nema17 motors with 200 steps per rotation. However in this case, 1.8° turn for step would not be enough due to the rod length, that is about 2x longer than on standard delta printers. I have selected NEMA23 0.9° motors after a long research with a 1.26Nm moment suitable for every future effector change. Micro-stepping will be applied for better accuracy with up to 256 micro-steps per step. Motherboard will use TMC5160 drivers with SPI interface and current control to achieve desired speed and acceleration.

Table 7.1 Nema23 23HM22-2804S specification

Stepper type	Step angle	Holding torque	Rated current	Shaft Diameter	Phase voltage	Phase Resistance	Phase inductance
bipolar	0.9°	1.2 Nm	1.8A	6.35mm	2.5V	0.9 ohm	4.5mH

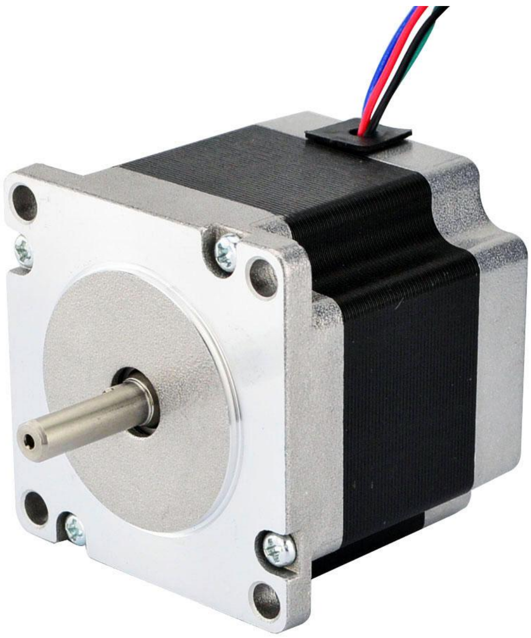

Figure 7.9 Nema 23 stepper motor

7.9 Light-weight effector

This effector was designed to be as light as possible to achieve high acceleration and speed to suppress any resonance [28]. Standard bowden setup was applied with external extruder on a frame. It uses a NF-Zone hot-end setup with aluminium heat-sink, ceramics-copper heat-break, aluminium heater block, standard V6 brass nozzle, 40W heating element and high precision thermistor. Nozzle is also used as a tip of a calibration probe - the whole hot-end assembly is used as a probe. Piezo sensor is installed between the hot end and effector and triggers when nozzle touches the build plate with defined force. External high-power air pump is used as a part cooling system. This printing head can be easily modified into a high flow unit with a Volcano heater block and nozzle.

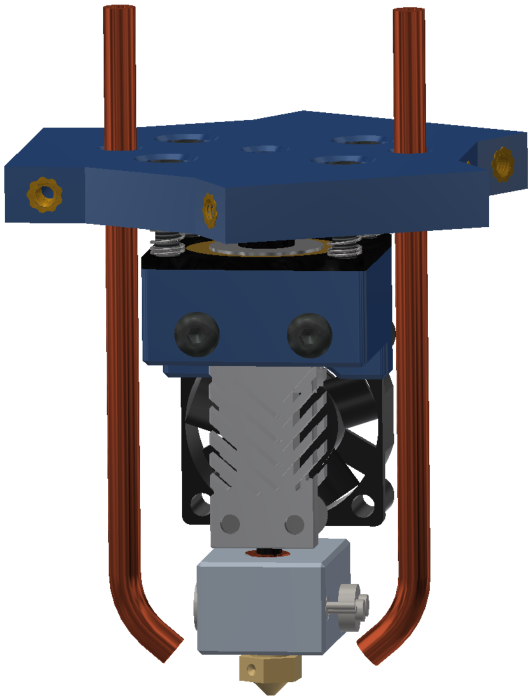

Figure 7.10 Lighweight effector

7.10 High flow effector

Standard bowden setups have a problem with insufficient retraction causing oozing and stringing. It is simply not possible to retract filament fast enough to prevent this [29]. Even bigger problem is with materials such as TPU, TPE, PETG that require minimal distance between the heat-break and extruder gears for sufficient retraction and pressure. Delta printer effector must be as light as possible, so mounting an extruder motor is on an option. However two companies provide alternative - bowden driven extruder. Motor is mounted on a frame with it's shaft connected to effector by a bowden shaft. This rotation is translated by a worm gear set to extruder gears on the printing head. This setup requires only about 5 cm long PTFE tube for filament and adds about 30g mass. Calibration probe is the same - piezo sensor. Another difference is a NF-Crazy Magnum hot-end. Magnum stands for a longer melting zone that increases maximal filament flow rate even with a standard V6 nozzle [30]. Another great feature is a better heat-break performance and larger distance between the heater block and top of the heat-sink allowing better hot-end cooling. 5 point heat-break ensures that the heater-block cannot rotate resulting in much easier nozzle changes.

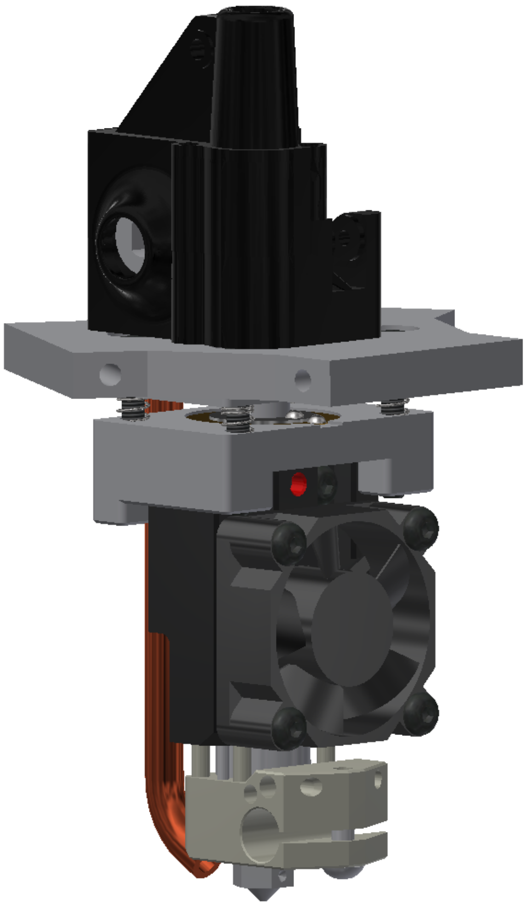

Figure 7.11 High flow effector

7.11 Cooling - air pump

Efficient printer-part cooling is on of the requirements for fast 3D printing. The most common setup is a 4020 blower that is capable of cooling up to 40mm/s with low acceleration values. Dual 4020 blower or a single 5015 cooling fan configuration can handle about 140mm/s printing speed with a 0.4 mm nozzle on larger and about 80 mm/s on smaller models with 6000 mm/ss acceleration. I have decided to use external cooling solution - 24V air pump with 15L/min air flow and a higher output pressure [31]. Two pumps can be used if needed.

Figure 7.12 24V air pump [31]

7.12 Cooling - air compressor

High flow effector design uses only one cooling tube, thus a more powerful air source must be used. I have chosen a 24V 48W air compressor with 500KPa output pressure and 45L/min flow as a backup. It will be connected via 2m long silicone hose to copper cooling duct on a effector. The only advantage over the air pump is the noise at a 60db level with full power [32].

Figure 7.13 24V air compressor [32]

7.13 Delta rods

Stiffness and low weight is the key. Three different materials are usually used to make high quality rods: carbon fiber, aliminium, carbon. I already used carbon rods on my Kossel delta 3D printer, so I have decided to use more advanced material - carbon fiber. Rod design starts with a joint selection and testing. For example, I have tried MP-JET V2 with a 7mm ball, IGUS EBRM-4 and KBRM-3 joints. The best option was to use MP-JET V2, because the shape of the brass bearing allows them to be used without any additional spacers. They are also stiff and light-weight. Bearing has a 3 mm mounting hole for effector and carriage assembly. Body of the joint has a M4 thread, so a M4 set screws will be used. Next step is looking for a suitable rod with 4 mm inner diameter and at least 1 mm thick wall. Standard carbon fiber tubes with this inner diameter are made with 0.5-1 mm wall thickness. And because we are looking for the best possible firmness, 6x4 mm variant is our choice [33].

Figure 7.14 Carbon rods with MP-Jet V2 joints

Rod length is a critical parameter for Delta kinematics, so each rod assembly must have the exact joint axis-axis distance. Enhanced delta calibration can improve the outcome by changing the tower heights, but it will never be ideal. Each 1 % of length difference causes up to 1.5 Z offset in middle of the build plate.

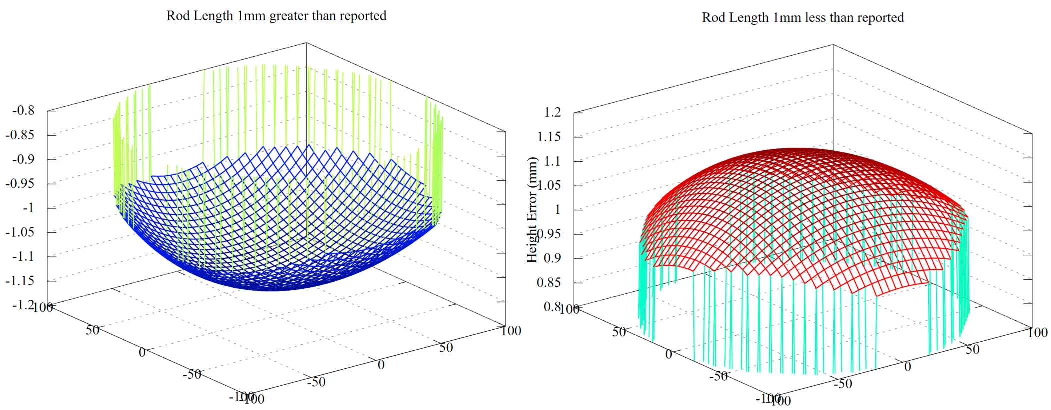

Figure 7.15 Rod length deviation [27]

7.14 Rod assembly tool

I have designed this tool for easier rod assembly. It uses a 20x20 or a 20x40 aluminium profile from a frame construction as a base. Both sets have to be tighten to the profile at desired axis-axis distance. After that a set screw is installed into each join and epoxy glue is applied on the screw and into the rod. Both joints are inserted into rod and the whole assembly is mounted to both tools. M3 screw is put inside the bearings and tighten to ensure that both joint bodies are at the same plane.

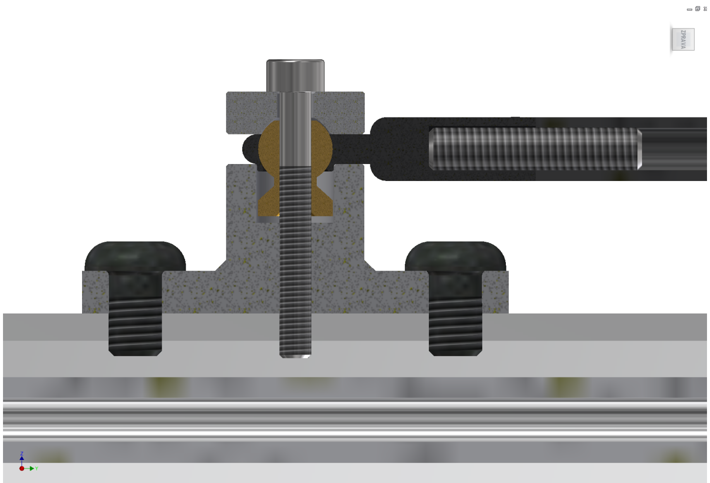

Figure 7.16 Rod assembly tool

7.15 Mobius extruder for bowden setup

LP Delta ver. 1.0 is capable of using two extruders and switching between them. Lightweight effector with a filament bowden tube will be used with a Mobius 3.1 extruder. It uses a standard Nema17 motor, BMG all metal gears with inner bearings and the rest is 3D printed from ABS. Gear ratio is 4:1 for a more precise filament dosage [34].

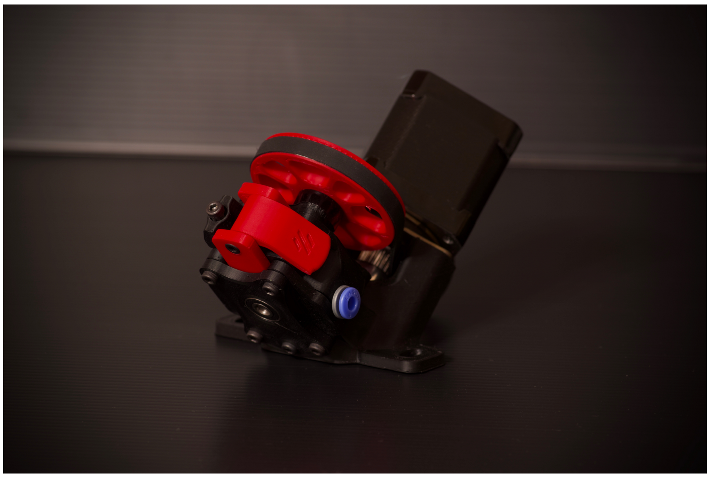

Figure 7.17 Mobius 3.1 extruder [34]

7.16 G5 Flex extruder

Due to the long filament bowden tube, I have decided to design a high flow effector with a bowden driven extruder. There are only two options on the market right now - Flex3drive [35] and Zesty Nimble [36]. Nimble V3 or V2 has been unavailable for months, so I have decided for a F5 Flex from Flex3drive. 30:1 worm gear set eliminates bowden backlash - it is simply divided by 30, so there is no major affect on the flow consistency

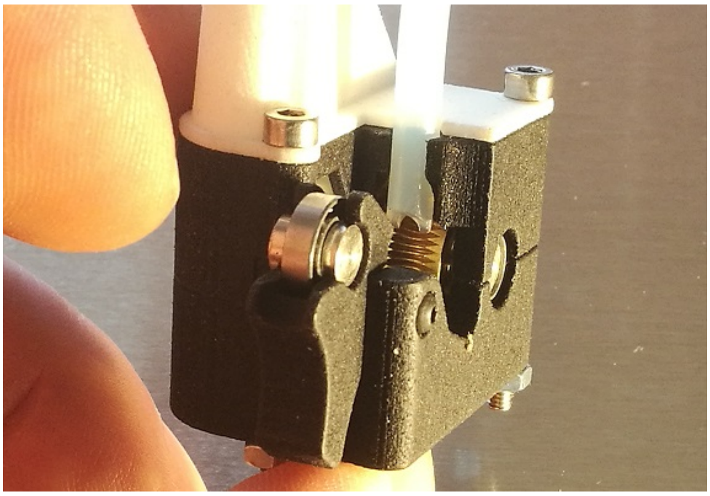

Figure 7.18 G5 Flex extruder [35]

7.17 Calibration probe

I have tried multiple probe types over the years [37] and each of them has it's advantages and disadvantages. First effector design used an inductive probe with a thermistor that solves thermal dilatation problems. However this design required a special probe mount or a hot-end heat-sink installation above the effector plus it has X, Y offset. Detachable mechanical switch is also a good solution, but it requires manual action before and after every calibration. BL Touch would also require special mount and it's tip has an offset from the nozzle in X, Y or both directions.

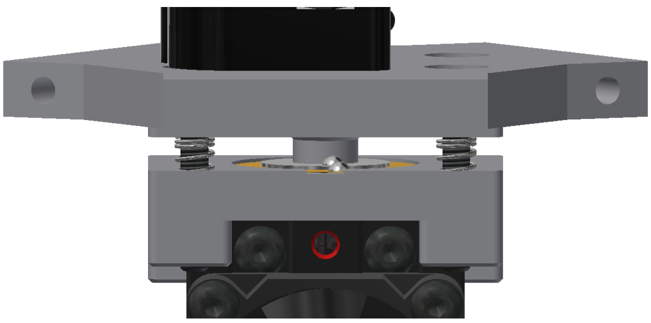

Figure 7.19 Effector with a piezo levelling sensor

I have decided to focus on a piezo probe due to these facts. It uses tip of the nozzle to probe, and there is also no problem with X, Y offsets. It's sensitive can be adjusted on the board with trimmers to the point where the tip of the nozzle will not be damaged by force while probing the bed. It is also possible to use 3 piezo probes under the build plate, but it is not recommended, because the piezo ring can work just up to

70°C. Connection to the motherboard is the same as any other end-stop - VCC, GND, Signal.

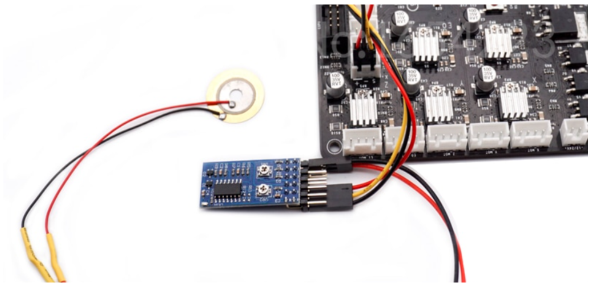

Figure 7.20 Precision Piezo Z-probe
Universal Kit [38]

7.18 Control board

The most widely used control boards are from a SKR family. I also have a few of them - SKR 1.3, SKR 1.4. But they have one major disadvantage - just one fan PWM output and three thermistor inputs. This project counts with the fact that the 3D printer will be fully enclosed with a main chamber for printing and another box for filament. I will also use multiple PWM controlled fans for driver cooling, electronics cooling and chamber temperature control. Extra driver slots and pins can be used as SPI and UART IO. Extra hot-end outputs with PWM function can also be used for fans or any other high current electronics.

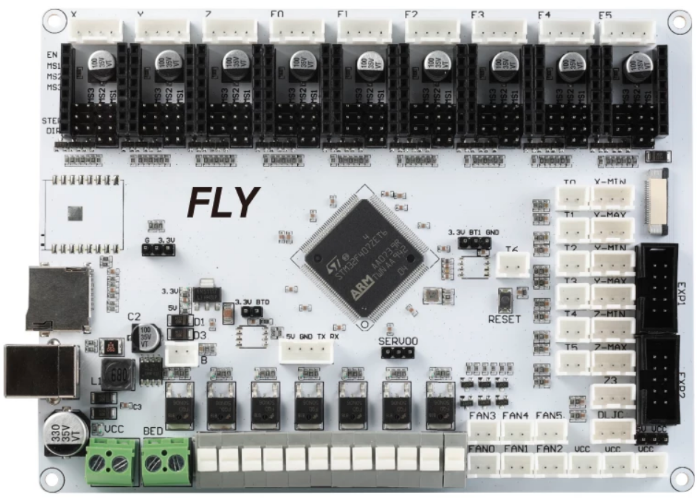

Figure 7.21 Mellow Fly-F407ZG motherboard [39]

Table 7.2 Mellow Fly-F407ZG specification

Supply voltage	Logic voltage	Driver count	Fan PWM outputs	Thermistor inputs	CPU Frequency	Hot-end outputs
12-24 V	3-5 V	9	6	6	168MHz	6

7.19 Drivers

NEMA23 23HM22-2804S stepper motors take up to 2.8A per each phase, so standard A4988, TMC2208 or TMC2209 drivers cannot be installed. I have decided to use TMC5160 drivers from BigTreeTech that can be controlled via SPI interface. External Mos-FETs are soldered on top of the board of each driver allowing higher working current and better thermal dissipation. They are capable of up to 256 micro-stepping. 8-35V can be used to control motors with a maximal 3.0 A RMS current. It also supports StealthChop2 mode for a very quiet motor operation. Aluminium heat-sink will be applied on the external Mos-FETs on top of the board and active cooling tunnel will be installed for all drivers to keep them under 60°C. The installation is very similar to TMC2130 [40].

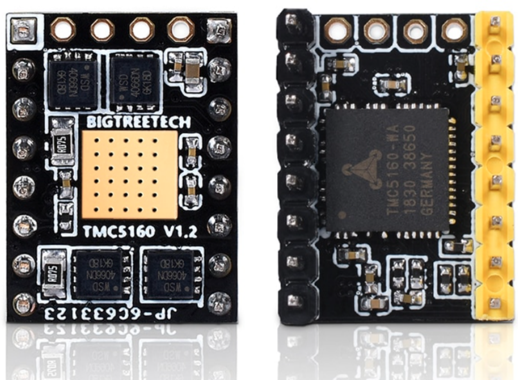

Figure 7.22 Bigtreetech TMC5160 SPI stepper driver [41]

Table 7.3 TMC5160 specification

Max. current	Logic voltage	Supply voltage	Micro stepping	Stealth Chop2	SPI Mode
3A RMS	3-5 V	8-35 V	256	Yes	Yes

7.20 Power supplies

I have decided to use 24V as a printer's main voltage. It makes possible to use thinner cables, because the current is half against a standard 12V voltage. Stepper drivers also work better with 24V and can achieve bigger motor torque. There is also a smaller chance of damaging circuits on motherboard, which is a very common cause of problems with high current setups. The printer will require only about 130W on 24V in this state, but the next step will be a chamber temperature control, so more power for fans and electronics will be needed.

Figure 7.23 Mean Well RSP-320-24 [42]

Raspberry Pi 4 requires 5V and minimal 3A. It is possible to use a step-down DC-DC module, but it is not recommended. A separate 5V 25W power supply for Raspberry is the way to go. Another relay can be used with this setup to enable power for motherboard from a Raspberry's web UI as another safety measure.

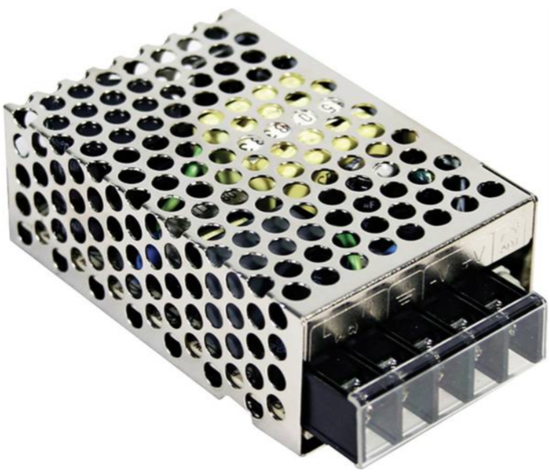

Figure 7.24 Mean Well RS-25-5 [43]

8 ASSEMBLY

8.1 Rod assembly

The first step is to complete a rod assembly due to the fact that we are going to use tower aluminium profiles used in the final assembly. I will use 4 rod assembly-tools at the same time for 2 rods, because I am in a hurry, but a preferred way is to use two tools for one rod at the same time. Insert and tighten M4 set screw into joints. Cut tubes to defined length, clean the inner wall with a sand-paper. Apply epoxy glue on set screws and a bit into the tube. Insert both joints into tube, put a M3 screw into ball bearing and tighten both of the screws into the assembly tool.

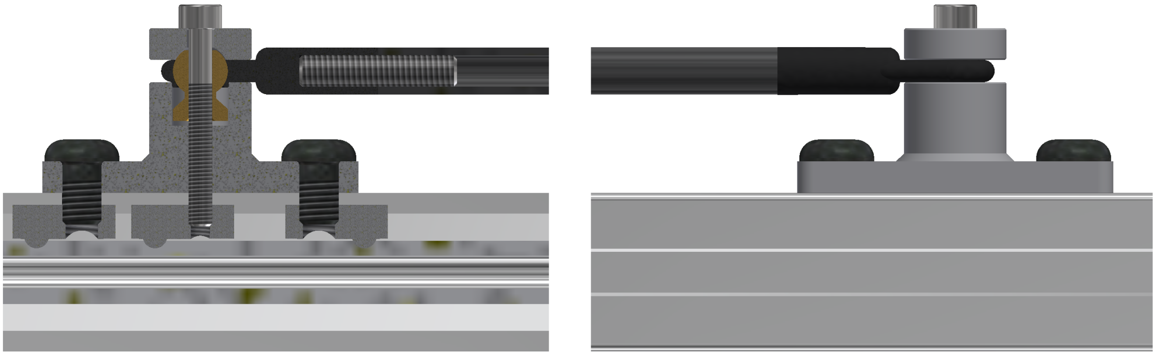

Figure 8.1 Rod assembly - cross-section (left), assembly (right)

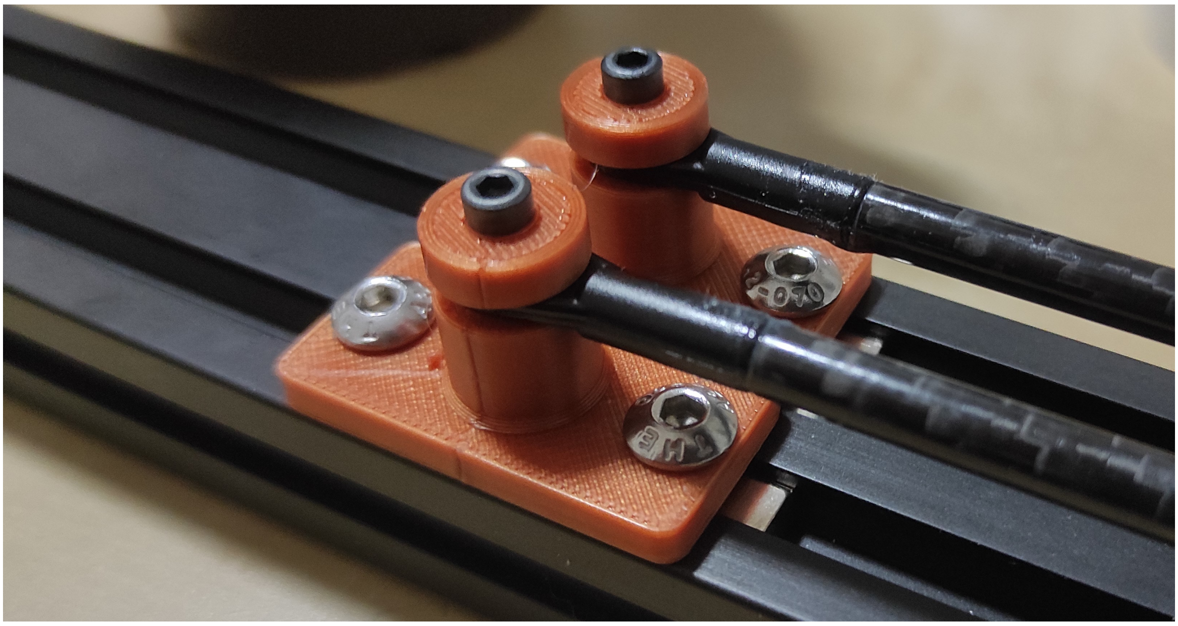

Figure 8.2 Rod assembly

8.2 Base

Base has a hexagonal shape with three belt-tensioner, two standard and one blind corners. Outer wall is made of 20x40 mm aluminium profiles. Bed will be installed on knurl-nuts tighten to the bed base - 3x 20x20 mm profiles. Poly-carbonate cover ensures that no printed parts will fall down under bed and it also works as a assembly plane and a thermal insulator. Rubber compressor-foot is attached to each corner compensating any vibrations and floor inaccuracy.

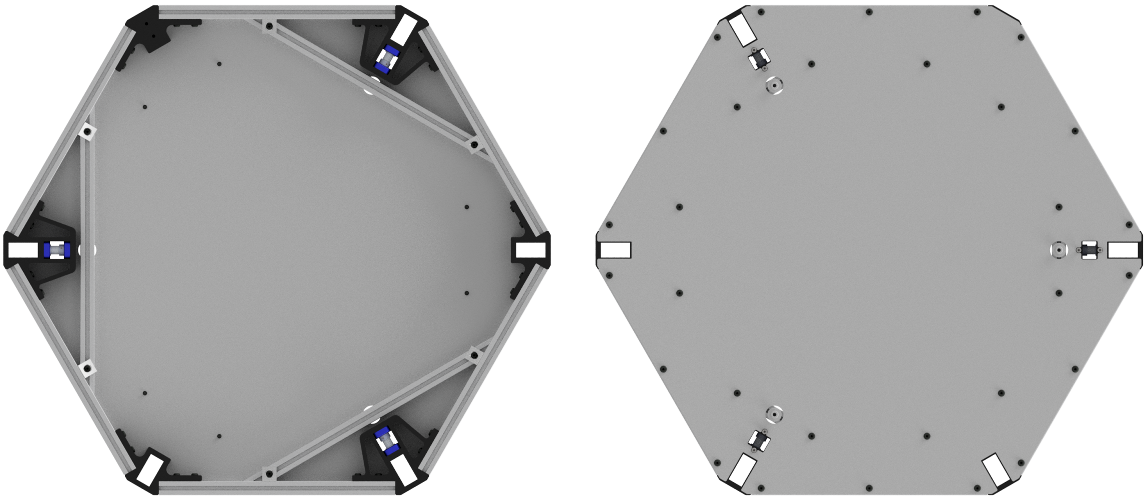

Figure 8.3 Base - render

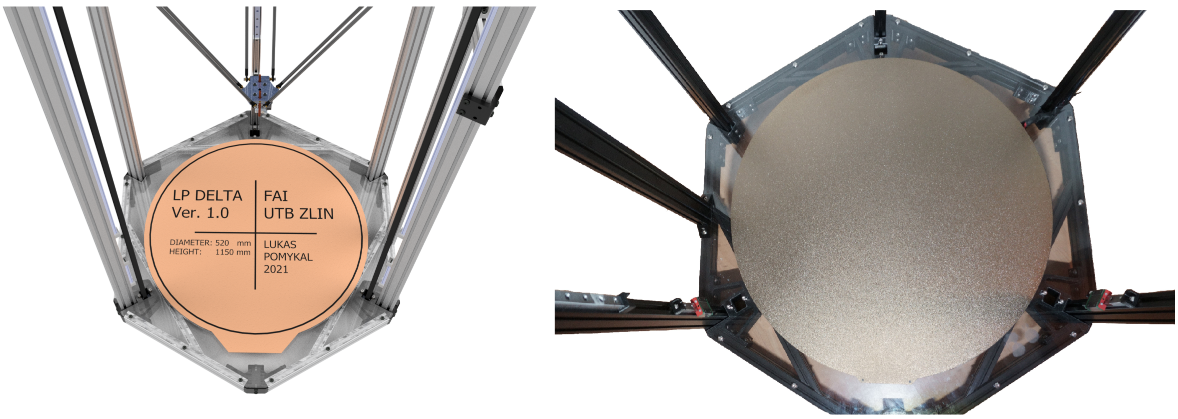

Figure 8.4 Base with build plate assembly render (left) vs reality (right)

8.3 Bed

Bed surface must be cleaned and degreased before installing heater. After this step a Keenovo heater with a 3M sticker is applied and all possible air bubbles must be removed with pressure. The same procedure must be done on the other side before installing magnetic base. As a final step a thermal protection as a safety backup of the bed thermistor should be mounted and connected.

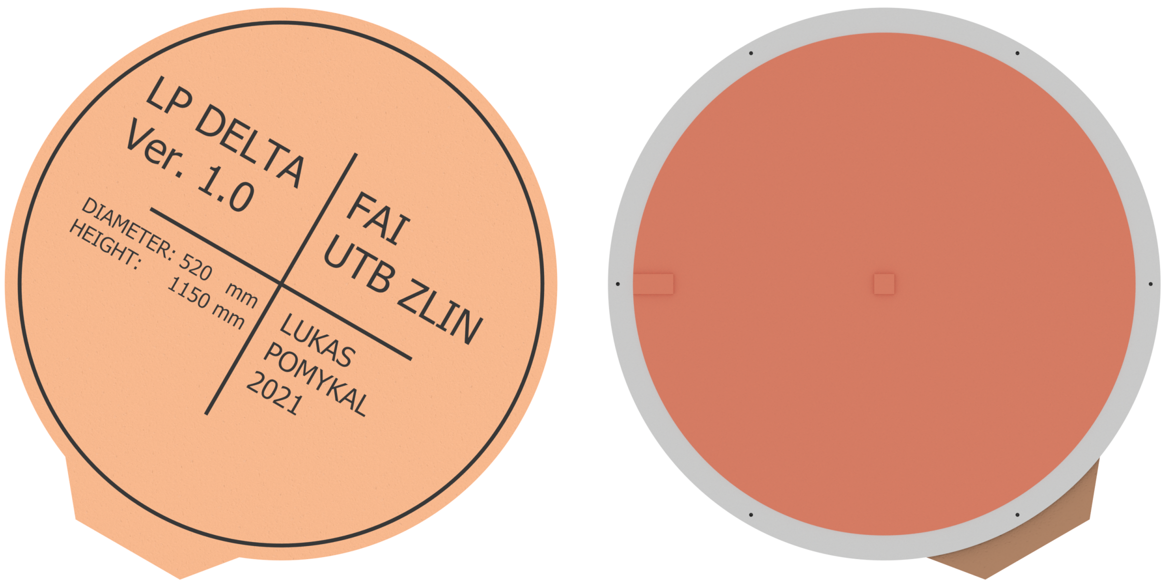

Figure 8.5 Bed - render top side (left) bottom side (right)

Figure 8.6 Bed - assembly top side (left) bottom side (right)

8.4 Electronics compartment

Common delta printers have MCU under the bed, but I have decided to move all electronics to top of the printer for a better cooling. This compartment will be fully enclosed with 4 inlet and 2-4 outlet fans. These 60x60 mm 24V fans will provide necessary air flow and cold air. Their placement is based on electronics location - one pair is used for driver cooling, the other one for Raspberry Pi 4B. Outlet fans will push out air from compartment and they are located near PSUs for a better cooling effect. SSR relay uses passive-cooling - the frame works as a heat conductor. Construction of the electronics compartment is made of 20x20 aluminium profiles in pairs with a 35 mm gap.

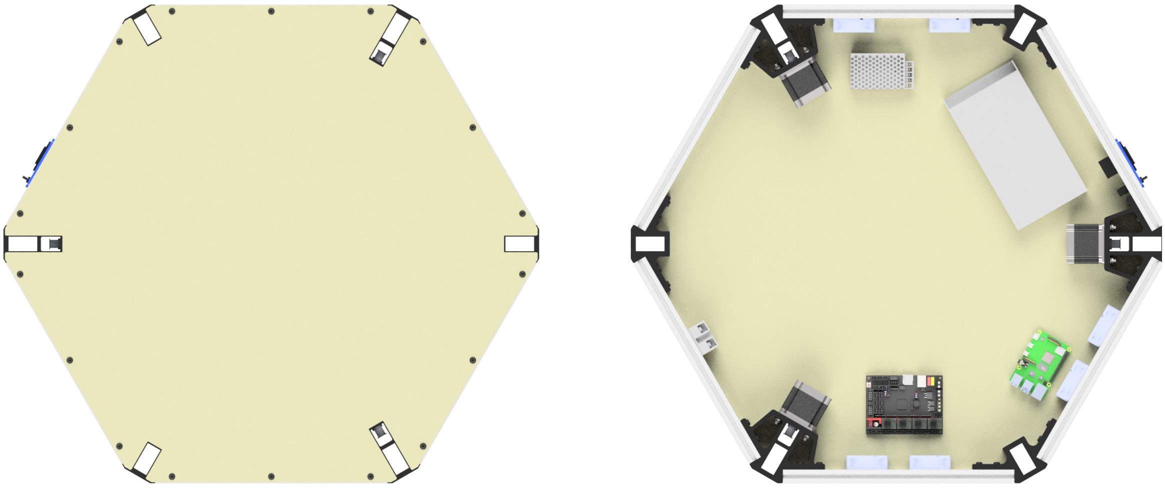

Figure 8.7 Electronics compartment

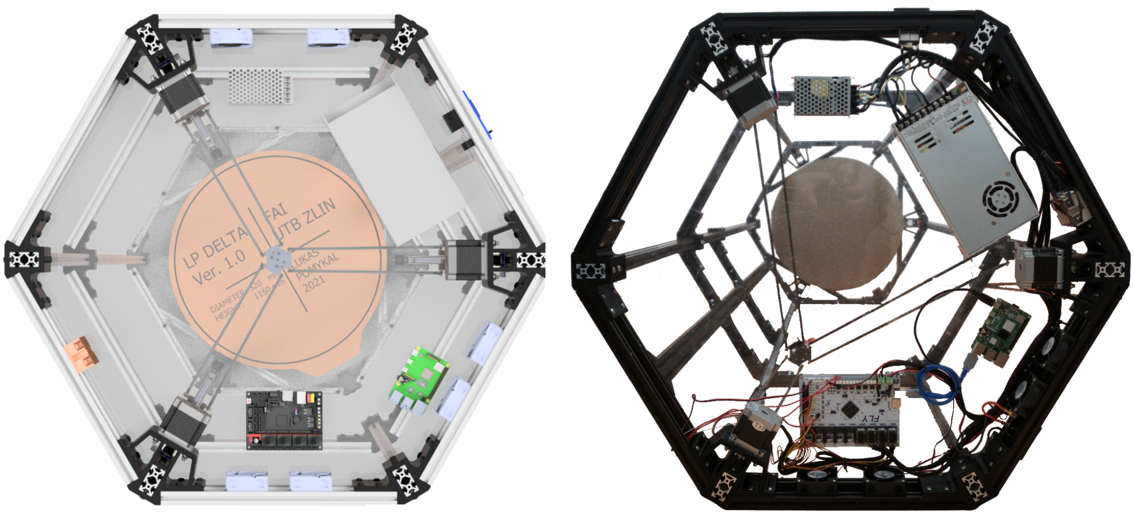

Figure 8.8 Electronics compartment render (left) vs reality (right)

8.5 Towers

Three towers with MGN12 linear rails should be assembled before installing them into base and electrics compartment assemblies. Every tower assembly consists of a 20x40x2000 mm aluminium profile, 1500 mm MGN12 rail, 100 mm MGN12 rail, three secure-stops and one end-stop mount. MGN assembly tool secures correct alignment in the center of each tower.

Two center tools were installed at each MGN rail end and a third one was moved to every mounting point. Distance between screws is about 100 mm. End-stop mount

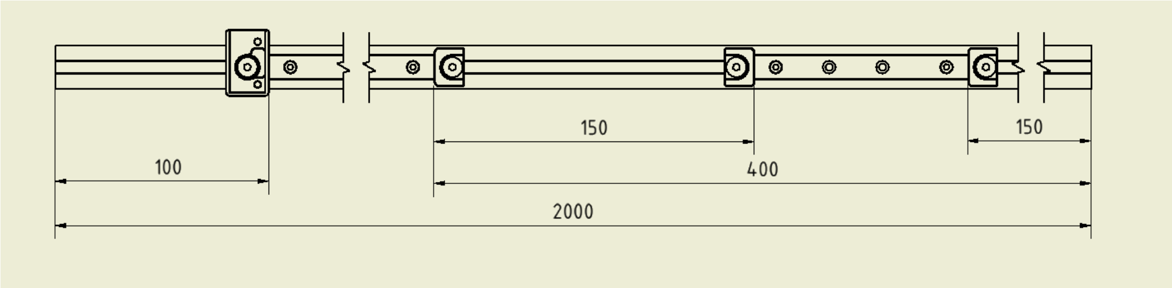

Figure 8.9 Tower assembly drawing

works also as a secure-stop and is tighten with a M5 screw instead of a M3 screw at rails. MGN carriage movement is tested after and lube is applied after the complete printer assembly.

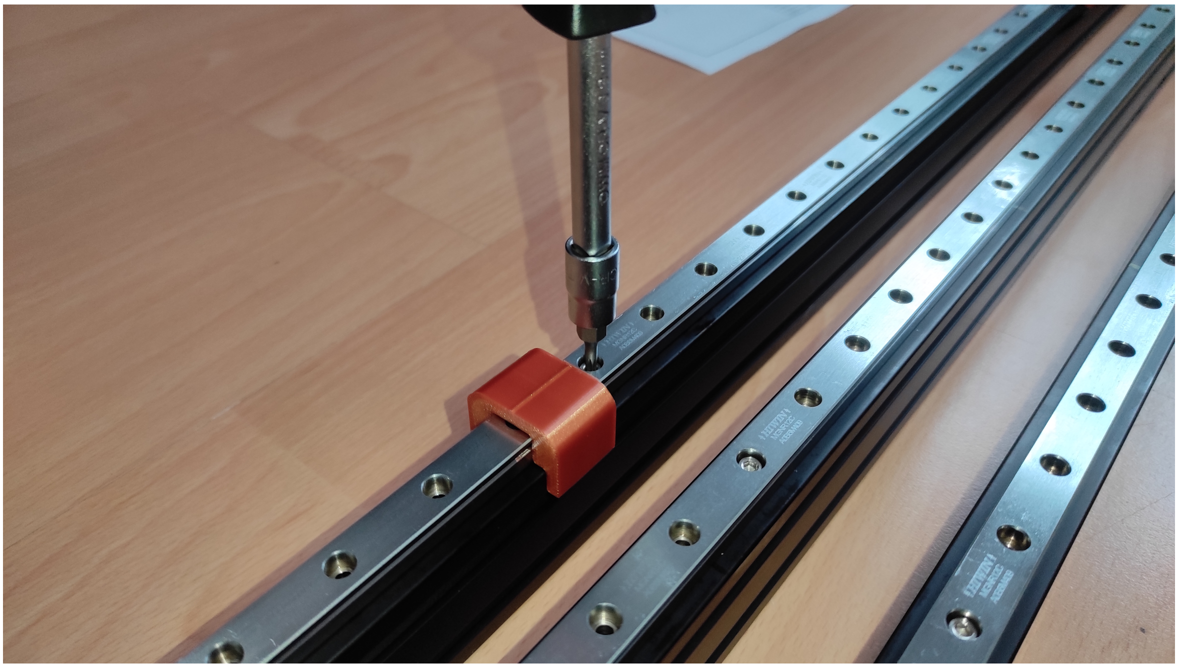

Figure 8.10 Tower assembly

8.6 Hot-end assembly

NF Crazy hot-end was assembled due to manufacturer's instructions with a 40W 24V heater and a 104GT2 thermistor. 30x30x10 24V fan was mounted on back of the heat-sink providing enough air flow to cool down heat break under 50°C at the top. Another one can be installed on the other side for a better cooling effect in a fully enclosed 3D printer. Hot-end assembly was installed into the holder with a piezo ring and a voltage comparator was installed on the side of the holder. Please note that plastic threads do not work well, so heat inserts must be installed.

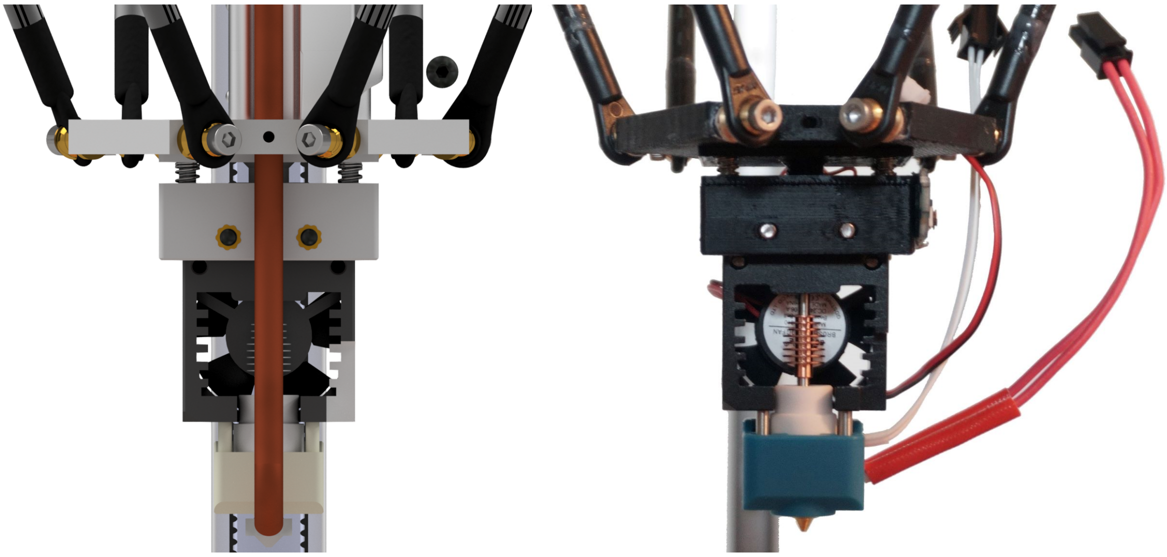

Figure 8.11 Hot-end assembly render (left) vs reality (right)

8.7 Piezo probe test

Piezo probe test should be done before installing effector on rods. Conductive layer on the piezo ring is very fragile and it is better to test it before complete assembly. 5V and GND must be connected to the board and comparator sensitivity adjusted with trimmers on the board.

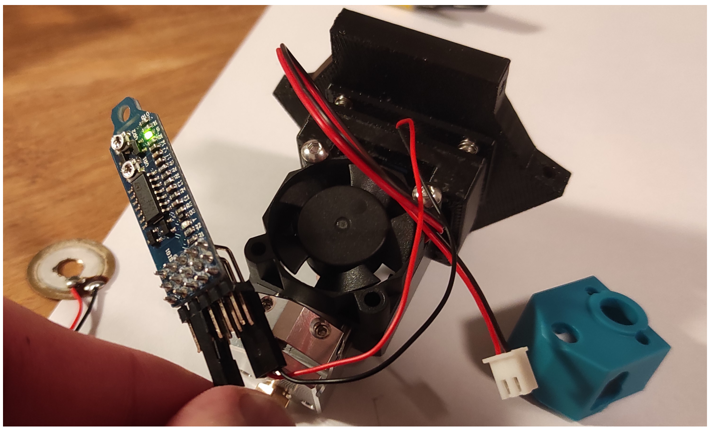

Figure 8.12 Piezo probe test

8.8 Complete assembly

Printer was fully assembled starting with a base and an electronics compartment. Towers were inserted into the base while a middle assembly was being put together. Electronics compartment was put on the top of towers and each profile was inserted into selected corner. Whole assembly was measured, towers adjusted and each screw tightened.

Figure 8.13 LP delta assembly render (left) vs reality (right)

9 DESIGN TEST AND VERIFICATION

9.1 Build plate assembly

9.1.1 Bed PID calibration

The first step was test thermal protection - a bi-metal temperature switch mounted under the bed . This type is rated for 130°C that means when the bed exceeds this temperature, the switch turns off, control board senses a problem and performs an emergency shutdown. After that the bed was PID calibrated for 125°C which is an optimal temperature for ABS 3D printing and the surface was tested with a UNI-T 260B thermal camera for heat dissipation and any temperature problems.

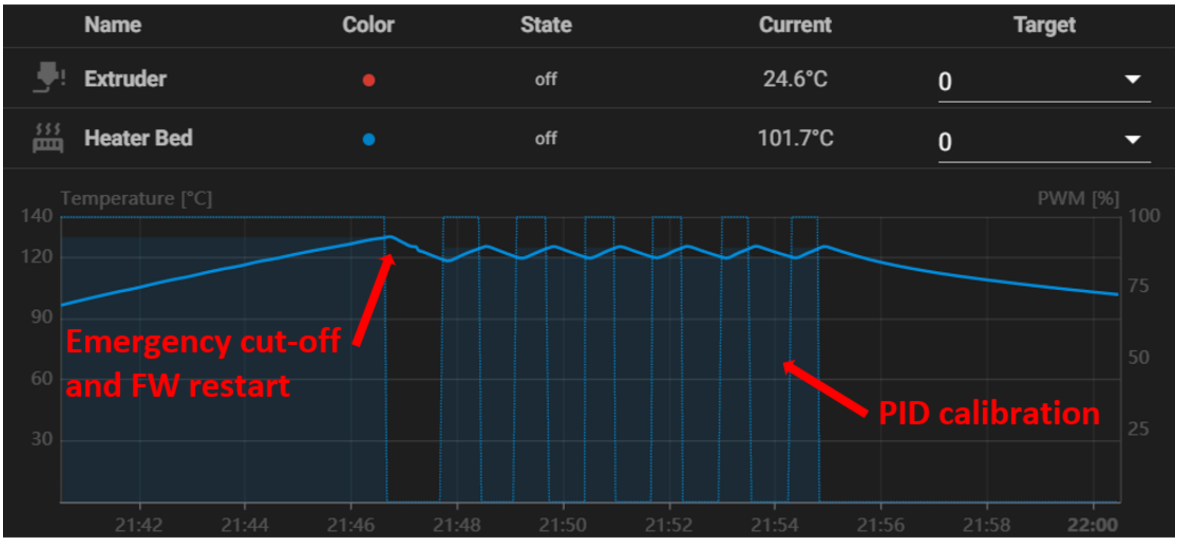

Figure 9.1 Bed heater emergency cut-off and PID calibration

9.1.2 Bed thermal camera test

Thermal conductivity, distribution and ability to reach target temperature must be tested. 10 mm thick ALQAL plate guarantees the best possible thermal distribution. Bed heater with a 3M self-adhesive plate is attached to bottom of the plate and must be thermally tested to determine a good bond without any air gaps. Powder coated flex-plate - printing surface uses magnetic force to stay on the aluminium plate which a magnetic base with a self-adhesive 3M tape installed on top of the bed provides. Same problem with air gaps can appear here to. I have used UNI-T 206B professional thermal camera with a 256x192 px resolution to test both surfaces. Maximal measured temperature was around the center 112.2°C and minimal at the side 106.3°C.

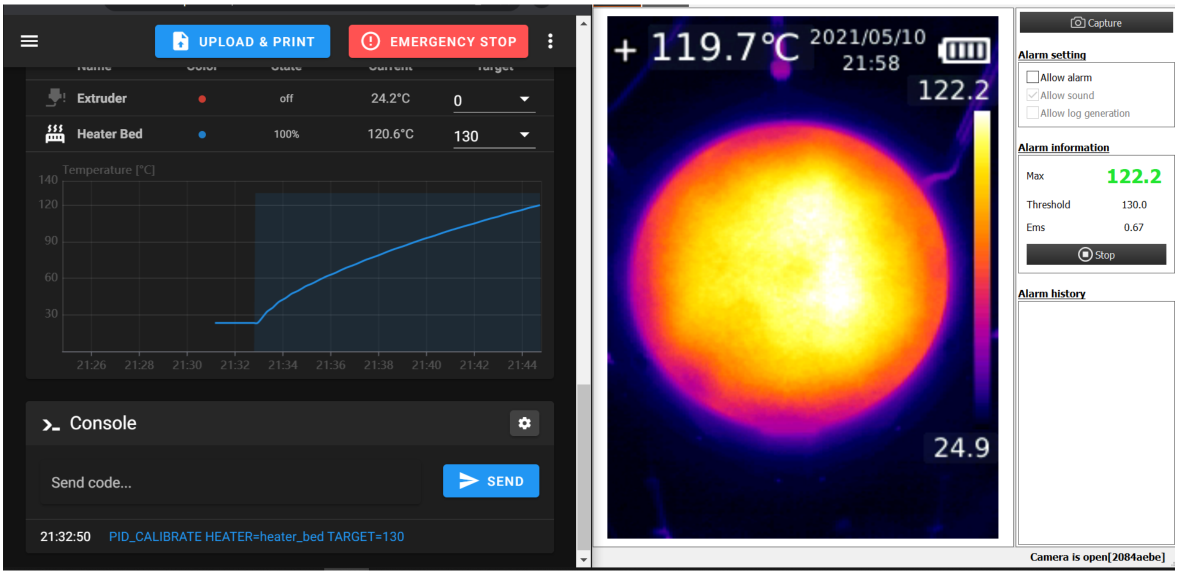

Figure 9.2 Bed assembly temperature graph and thermal view from UNI-T 260B

9.2 Hot-end assembly

9.2.1 Hot-end PID calibration

Motherboard uses a MOSFET and PWM control to keep the nozzle at target temperature. Hot-end assembly has it's own thermal capacity and cooling capabilities. To be able to keep the temperature at desired level with a minimal deviation, a PID calibration must be performed. This printer will use PLA, PETG, ABS filaments, so my calibration target temperature was set to 240°C. I have performed this calibration three times to ensure perfect result and P, I, D constants were saved after each PID calibration.

Figure 9.3 Hot-end PID calibration

9.2.2 Hot-end thermal camera test

Hot-end assembly surface temperature was measured and being captured by a thermal camera during PID calibration to visualize fan cooling and heat-break performance.

Figure 9.4 Hot-end temperature graph and thermal view from UNI-T 260B

9.3 Test part

9.3.1 3D test part design

This testing object was designed for accuracy and precision measurements with a probe CNC machine. Overall dimension results can show any problems with X, Y, Z axis settings and thermal expansion. Round shapes control the printer's ability to interpolate circle. Holes and groove test material expansion, cooling and leaking over desired shape.

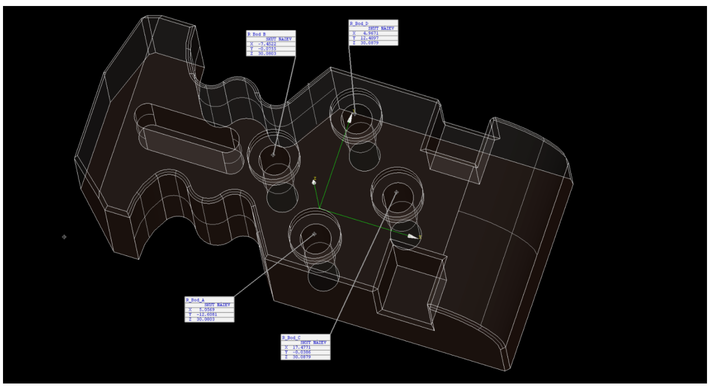
Figure 9.5 3D CAD model of a test part

9.3.2 Drawing and probing positions

This drawing shows probing positions over the whole object. Desired parameters and dimensions were marked as CS. Other positions were measured too, but they are not included in the table below. Large number of measuring points helps with surface deviation interpretation. Periodical outer wall inconsistency would show too large infill overlap or insufficient wall count. Relatively equal differences in positions 13 and 19 would stand for thermal expansion. Jerk settings can be easily evaluated at each point where the line segment ends.

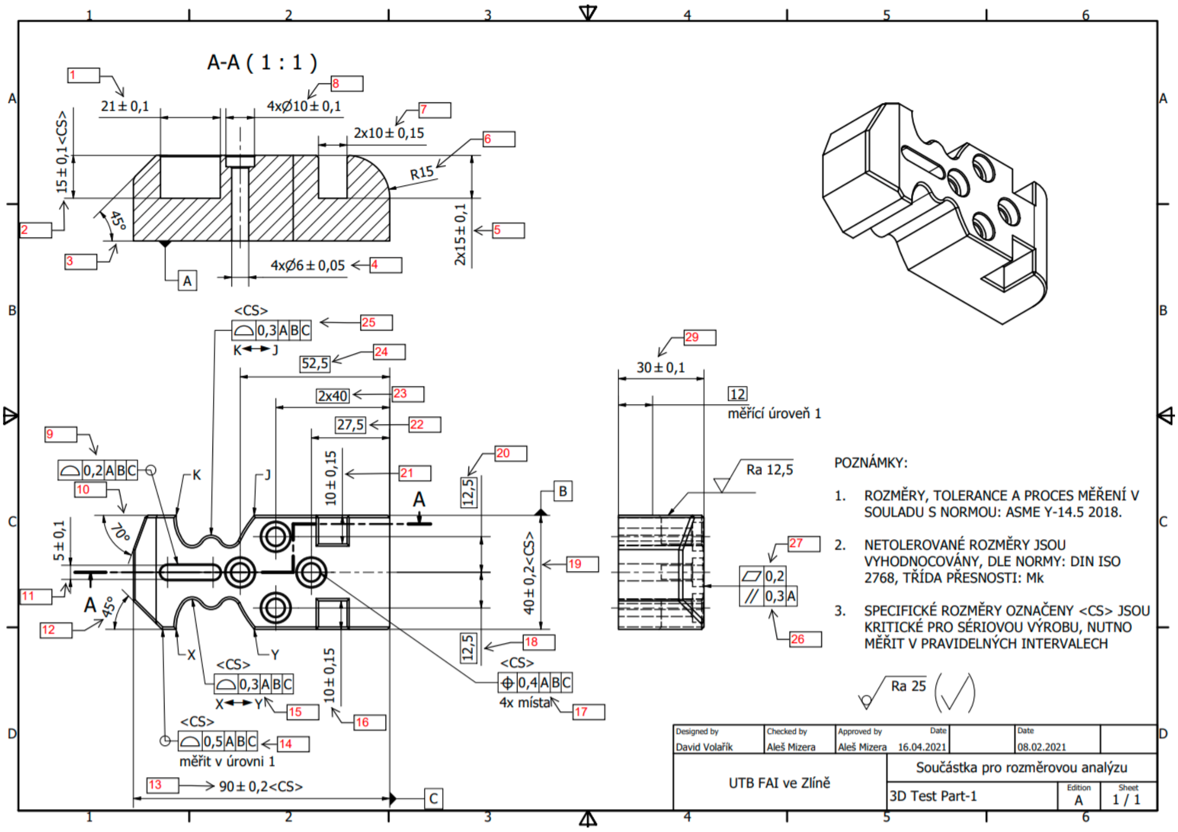

Figure 9.6 Test part - drawing with probing positions

9.3.3 3D deviation visualization

This picture shows deviations in X, Y axis at each probing point. The majority of larger deviation is caused by thermal expansion - contraction in our case. This deviation is visible on almost all sides of the printed object aiming into the cente /opposite side. Differences in round shapes show interpolation errors. Jerk effect can be seen in every corner or on places where the path changes.

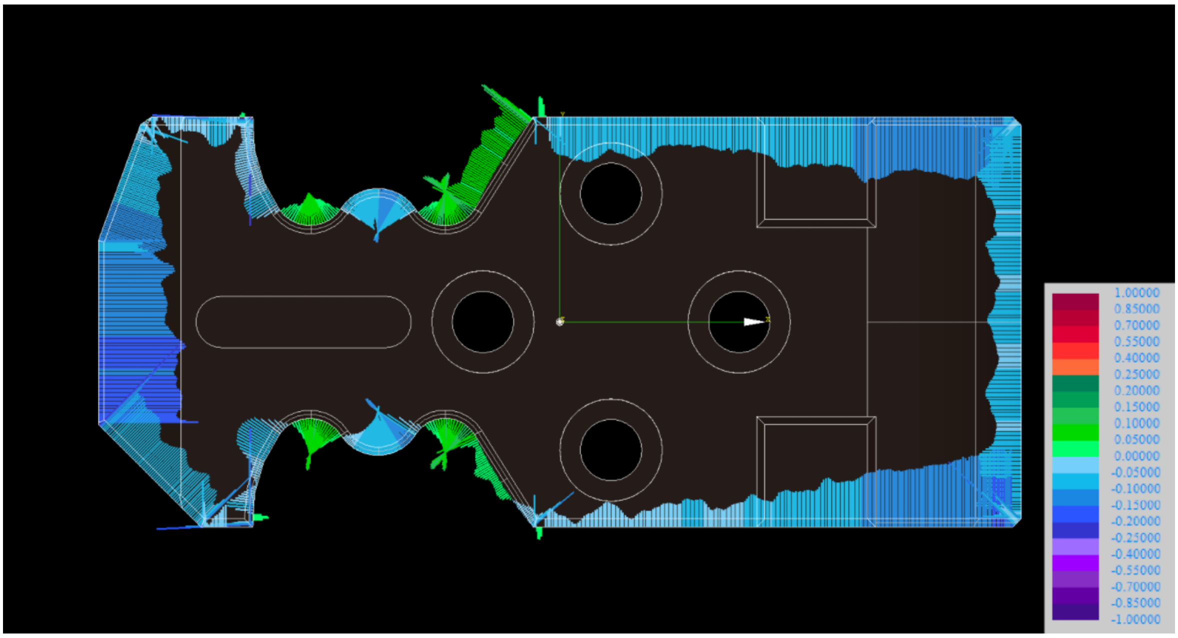

Figure 9.7 3D model - visualization of outer surface measured deviations

9.4 Precision

Table below shows evaluated measurement results from a Werth Scope-Check MB 650 machine and 6 identical 3D printed test models that can be seen above. Stepper micro-stepping was set to 16 and interpolation to 256 internal micro-steps, calibrated delta rod length is 655 mm. Majority of measured positions show less than 0.1 mm variances from desired - nominal dimensions, which is far better than most of the hobby-grade 3D printers. The biggest issue is thermal expansion, shrinkage at this case, that is visible in positions 2, 13, 19. Variances in surface and round shapes are minimal, usually between 0.027-0.097 mm. Even better results could be achieved by repeated enhanced delta calibration. Individual settings for flow and thermal expansion could also be applied for each material.

Table 9.1 Measured dimensions

Position number	Measured values [mm]					
	Nominal	Min	Max	Variance	Average	Median
2	15.00	15.016	15.034	0.0018	15.025	15.027
13	90.00	89.876	90.011	0.0865	89.9685	89.871
14	0.40	0.421	0.492	0.071	0.457	0.454
15	0.30	0.235	0.262	0.027	0.245	0.251
17	0.40	0.174	0.231	0.057	0.201	0.198
19	40.00	39.815	39.862	0.097	39.832	39.845
25	0.30	0.254	0.294	0.035	0.273	0.274

9.5 Accomplished parameters

I have summed up accomplished 3D printer parameters into this table. I was able to achieve desired printable radius 500 mm and add extra 50 mm. Printable height is 1165 mm and could be even approved to about 1180 mm with different end-stop position and shorter delta rods. The hot-end and remote extruder are capable of 45 mm^3/s material flow with retraction under 1 mm. Measured probe accuracy and end-stop accuracy is between 0.005-0.07 where the large variation is caused by a cheap piezo disc that will be improved in the next version. Maximal speed is 400 mm/s with 9000 mm/s^2 acceleration.

Table 9.2 Accomplished parameters

Parameter	Value
Printable height	1165 mm
Printable diameter	550 mm
Accuracy X,Y	0.015 mm
Accuracy Z	0.0025 mm
Maximal speed	500 mm/s
Maximal acceleration	9000 mm/s^2
Nozzle size	0.25 - 2 mm
Input power	1500 W (230V)
Input voltage	230V

CONCLUSION

I have managed to finish a delta kinematics 3D printer design in CAD application Inventor. Majority of the used parts were either designed to be 3D printed without supports or bought in international shops and markets. Aluminium profiles, build plate and covers were locally sourced and custom-made from selected materials. Whole frame was assembled from custom-cut profiles, ABS plastic parts and connecting material. Mechanics and actuator assemblies were mounted after that and tested for any unwanted friction and backlash. Electronics has been installed, wired and tested before applying input voltage. Circuit breaker and power switch was mounted at front of the frame for easy access and security. Klipper firmware with printer configuration was uploaded and modified for this kinematics and used electronics.

All temperature calibrations were also executed with a thermal camera to help with problem identification and heat dissipation. 3D printer was calibrated afterwards with multiple iterations and calibration procedure modifications. Each value set was stored, flashed and used in next iteration. 6 test models were printed for accuracy, precision and variation measurements. Results were elaborated and recommendation for a better outcome was suggested.

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LIST OF ABBREVIATIONS

RP	Rapid prototyping
MSLA	Mask stereolithography
SLA	Stereolithography
SLS	Selective laser sintering
IPA	Isopropyl alcohol
FFF	Fused filament fabrication
FDM	Fused deposition modeling
ALQAL	CNC milled aluminium plate made by Alcom Alval
CAD	Computer aided design
PLA	Polylactic acid
SC	Specific control
etc	Et cetera

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