NTNU
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Science and Technology

A modular CNC machine

Runar Weidemann Simonsen

Subsea Technology
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Supervisor: Knut Sørby, MTP

Norwegian University of Science and Technology
Department of Mechanical and Industrial Engineering

Preface

Since childhood I have had a great interest in technology, and in the later years the interest has moved towards automation and programming as well. I have completed a few home automation projects, and acquired knowledge on related subjects both through education and hobbies. I also have some knowledge about CAD modelling from my time in trade school, and also education as a mechanical engineer at HiST.

Before this semester i contacted my supervisor at NTNU regarding my master thesis and choice of subject, and we agreed on a modular CNC-machine as a topic. I was excited about this as I am interested in the subject, and it provided a great opportunity for me to learn more about designing and prototyping. It would also give me a more detailed insight in evaluating design properties through CAD.

I would like to thank my supervisor Knut Sørby at NTNU for his guidance throughout the project.

Trondheim, June 2018

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Runar Simonsen

Abstract

This report assesses different design solutions for a modular CNC-machine with capabilities for additive production, CNC-milling and laser engraving. The design is meant for a target group where hobbyists and home-enthusiasts are in focus. Because of this the design is a relatively lightweight bench model with modular capabilities for ease of use. Based on target group and component prices a budget of 13 000 NOK is set.

A suitable design is chosen and modelled using CAD software.

A prototype is built based on the chosen design, and tested for relevant properties of how well it performs within the three modes. The results are then evaluated and possible upgrades are suggested.

Sammendrag

Denne rapporten vurderer ulike designløsninger for en modulær CNC-maskin med muligheter for additiv produksjon, CNC-fresing og lasergravering. Designet er ment for en målgruppe hvor hobbybrukere og hjemme-entusiaster er i fokus. På grunn av dette er designet en relativt lett benkmodell med mulighet for modulært bytte av produksjonsmetode. Basert på målgruppe og komponentpriser er et budsjett på 13 000 NOK satt.

Et egnet design er valgt og modellert ved hjelp av CAD-programvare.

En prototype er bygget basert på valgt design, og testet for relevante egenskaper, og hvor godt den presterer innenfor de tre produksjonsmetodene. Resultatene blir til slutt vurdert og mulige oppgraderinger foreslås.

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Abbreviations

CNC	Computer numerical control
CAD	Computer aided design
FEM	Finite element analyses
HSE	Health, safety and environment
FDM	Filament deposition modeling
SLA	Stereolithography
PLA	Polylactic Acid
ABS	Acrylonitrile Butadiene Styrene
HIPS	High Impact Polystyrene
PVA	Polyvinyl Alcohol
G-Code	Grey code
PDCA	Plan do check act
TTL	Transistor-transistor-logic
VFD	Variable frequency drive
PSU	Power supply unit
LCD	Liquid crystal display
RAMPS	RepRap Arduino Mega Polulu Shield
Arduino IDE	Arduino Integrated Development Environment
GUI	Graphical user interface
UGS	Universal G-code Sender
RPM	Rounds per minute

1 Introduction

1.1 Background

During the last decade, progress in technology and research has made production, automation and computational power cheaper and more efficient. Industrial technology and equipment get more advanced, which results in equipment and components practically available for the public also get more advanced. Concepts as 3D-printing and home automation has arisen and is currently publicly available. Computer chips has become smaller, cheaper and more efficient, allowing the production of relatively cheap microchips for different types of controller boards and microcomputers.

With the increase in component availability and open source 3D-modeling software; a large DIY-community has emerged styling themselves as ''makers''. This has resulted in a new market for 3D-printers and smaller CNC-machines. This technology has allowed a new level of prototyping and production both for industrial purposes, and also smaller DIY-projects. It also opens for new educational possibilities within production, programming and automation.

One of the new concepts are multi-machines, which have capability of several functions, where the most common one is 3D-printing and laser engraving. These can be found online, though many of them are replicas made in china with cheaper components and as a result a varying degree of functionality/quality. Some of them also includes CNC-milling as an option, but with some limitations, and at a higher cost. The milling of materials requires a sturdier frame and more powerful motors, where the printing and laser engraving can be made much simpler. Most common is the linear motion design where the machines move the tool along linear guides in the X, Y and Z-axis. For the 3D-printing and laser engraving there are some delta models available as well but these usually don't have a CNC-milling functionality due to the extra forces applied when milling.

There are several options on software available, where some are free and based on an open source license. Most of the versions are based upon similar programming where it uses cartesian coordinates to move the tool in the work area.

1.2 Problem description

A modular CNC-Machine.

The objective is to design and build a CNC machine which, using a modular system, can perform various processing operations. There are simple requirements for processing accuracy and stability, and analyzes of these properties must be performed, based on practical testing.

The task should include:

- Planning and design of CNC machine, with focus on the modular system. Various processing methods should be considered implemented, such as additive production, milling and laser machining engraving.

- Preparation of CAD model of the machine. The need for a structural calculation or simulation should be considered.

- Calculation for critical components, feed rate and other characteristics of the CNC system

- Manufacture of parts and assembly of the CNC machine

- Practical testing and discussion of the results.

The thesis is edited as a research report with a summary in both Norwegian and English, conclusion, reference list, table of contents etc. In the preparation of the text, the candidate will emphasize making the text transparent and well-written. It is important that the necessary references for corresponding places in text, tables and figures are entered in both places. The assessment places great importance on the results being thoroughly processed, that they are tabulated and / or graphically presented in a transparent manner and discussed in detail.

Materials developed regarding the project such as software or physical equipment are part of the answer. Documentation for the correct use of this shall as far as possible also be attached to the answer.

1.3 Method and execution

The method chosen in this thesis is first to identify different possible basic designs, and choose the one which best suites the objectives and requirements. The necessary calculations are made to ensure the components uphold the required properties, while ensuring the design keeps within the budget.

The design is then modelled in detail using CAD software.

When a suitable design is completed the parts are ordered and the machine is put together, and the necessary software installed.

A HSE analyses is written for use of the machine, and the finished prototype is then tested and evaluated with regards to production quality and ease of use.

In the end the result is presented and evaluated, and possible upgrades are considered.

All CAD models have been made by the author of this report.

2 CNC machine tools

2.1 CNC system

2.1.1 Open loop/Closed loop

CNC production systems can be defined in two main categories; open loop and closed loop systems. When the CNC system operates a PC or controller board reads instructions, normally from a from a G-code file. It then sends movement signals to the motor drivers, which in turn drives the motors a certain amount. The system has no feedback and so, no way of detecting if the programmed motion was carried out correct. This is called an open loop system [1].

A closed loop system indicates the controller or pc gets feedback from sensors in the motors, which verifies the exact movement that is being executed. These systems are able to correct for errors in acceleration, velocity and movement real-time.

2.1.2 Stepper vs servo

There are currently two types of motors commonly used in CNC operations; stepper motors and servo motors. They each have advantages and drawbacks dependent on the usage. Stepper motors utilizes permanent magnets and a stator which carries the windings. A stepper motor usually has a minimum of 50 poles, and energizes them in a sequence to make the motor turn a certain number of steps. Since the rotation angle between the individual poles are quite small it can lose or gain a step every now and then. However, this translates to a small degree of error in the linear movement of the machine.

Usually stepper motors are used in an open loop configuration, and is therefore considerably cheaper than servos, and require a less complex controller unit. Stepper motors is capable at delivering high torque at lower speeds, but the torque output is decreasing at higher RPM's.

Servo motors are built on the same principle as the steppers but with a lower number of poles. They are often used in closed loop-configurations as feedback is needed to accurately measure rotation of the motor. They run smoothly with approximately the same torque output throughout the operating range, and are often used in combination with a gearbox [2].

In conclusion a servo motor will outperform a stepper motor in both accuracy and repeatability, but will however cost considerably more to implement. The stepper motors do however deliver acceptable performance for most cost-efficient systems.

2.1.3 Linear motion

A common factor for all CNC machines is the linear motion system. Many are based upon similar frame-design with actuators for moving the tool in workspace. Although other variants exist, most use cartesian coordinates and can be controlled from a computer or a designated controller board. Differences are that CNC-mills or routers have a more rigid frame which can handle the extra forces involved, and the more powerful lasers have protective shielding.

The linear motion system is based on electric motors that uses either a belt or a ball screw to transform rotation to linear movement. In combination with linear rails the accuracy of these machines can become quite good, dependent on component quality.

2.1.4 Software/User interface

There are several programs used to convert a design from a digital file to the finished part. Most convert the part file into G-code which is the most widely used numerical control programming language. The G-code is used to tell the individual motors to move, and when. For 3D-printing, laser engraving and milling the finished part is ''sliced'' into layers, and the movement path for each layer is described using G-code.

The steps from scratch to finished part will be 3D-modelling through CAD software, then slice the part and convert into G-code the controller board can interpret. The transfer to a controller board can be via SD-card, wired connection or Wi-Fi/Bluetooth etc.

The user interface should be easy and intuitive. Most existing printers and engravers need only a G-code file, and some calibrating and can then start the work with the push of a button. For milling operations its more common to have a designated computer or an advanced real-time controller, and this can be implemented for the other processes as well.

2.2 Manufacturing processes in a CNC machine

2.2.1 Additive production

Additive production is based on technology that lets us build three-dimensional object from a digital file. The process uses different techniques to build successive layers of the model, until the part is complete. Each of these layers are thinly sliced cross-sections of the model.

This method can be used with numerous different materials, such as plastic and metal. However, printing in metal generally brings a huge increase in related costs and is for now mostly associated with high-end industry. Plastic printers on the other hand is currently commonly available for the public users [3].

Some applications of the technology today include educational, automotive, aviation and aerospace. Even in construction the possibility for printing houses using a special concrete is under development [4].

The two most common additive production methods are FDM and SLA.

FDM feeds a filament of plastic or metal through a nozzle, which melts it and deposits it on the work area. As the filament hardens again it creates the layers of the finished product. The nozzle, worktable or a combination of these move along the different axis to allow the printer to work in all three dimensions.

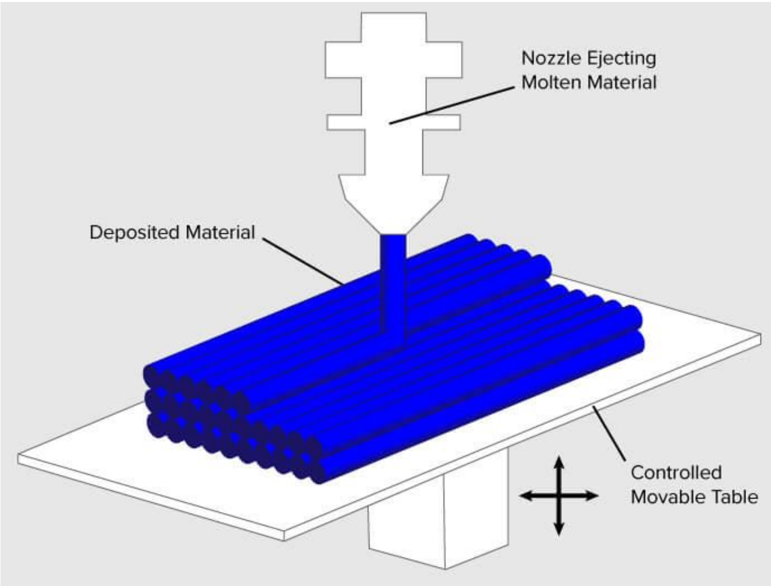

Figure 1. FDM Production

Stereolithography (SLA) uses a container filled with liquid filament, which is curable when exposed to ultraviolet light. A laser is used to precisely cure the specific areas within the cross section of the part. The part is then lowered into the liquid between 0.05 to 0.15mm, and the next layer can be cured.

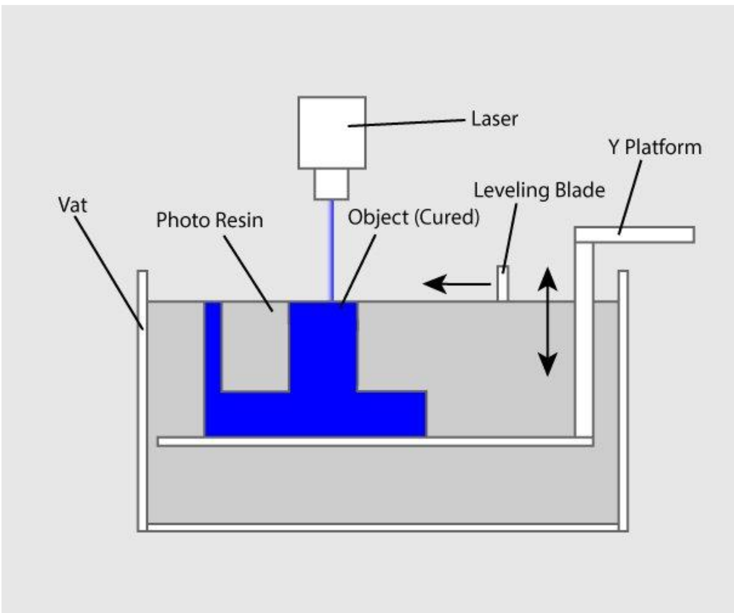

Figure 2. SLA Production

For the consumer market the plastic printers using FDM technology are the clear market leader, due to low component costs and accessibility. This type of printer typically has a lightweight design which is suitable for a benchtop model.

Some of the available printing materials for FDM printers are [5]:

PLA.

- The most common plastic material.
- Inexpensive and a wide variety of applications.
- Renewable and biodegradable.

ABS

- Higher melting point = temperature resistant.
- inexpensive.
- Used for tougher applications, outdoor use etc.

HIPS

- Dissolvable in d-Limonene, used as support material for complex geometry.
- durable and lightweight.

NYLON

- Some degree of flexibility.
- tough material, high impact resistance.

CARBON FIBER

- a base infused with carbon fiber to increase strength.
- printing properties very similar to base product used.

WOOD

- Base material infused with wood derivatives as dust, cork etc.
- Creates a wooden texture to the printed part.

PVA

- Dissolvable in water. Support material for complex geometry.
- No special solvent or equipment required.

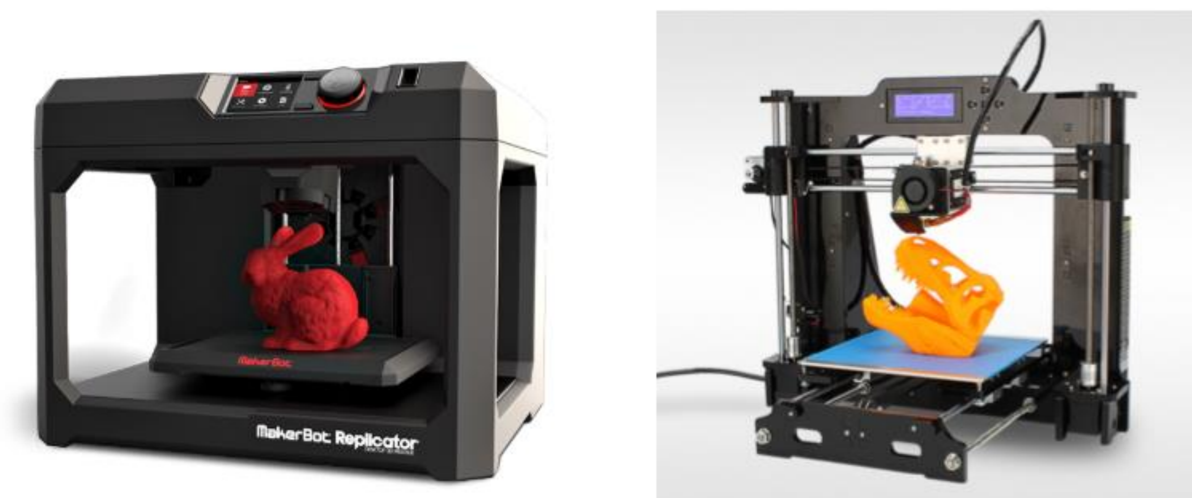

Figure 3. Examples of typical consumer 3D-printers.

2.2.2 Laser engraving

Lasers can be used to cut, etch or mark different materials. This is utilized in form of engravers with can draw permanent markings on different products.

Laser engravers/cutters typically uses the same basic design as most printers, but with shorter Z-travel and sometimes a larger XY-plane.

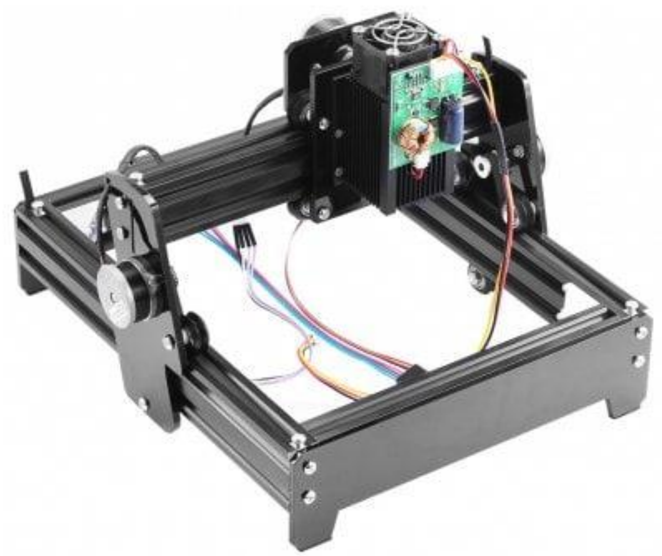

Figure 4. Example of inexpensive laser engraver.

The inexpensive models come with laser modules based on diodes ranging from a few hundred milliwatts up to about 15W. These are suitable for engraving on materials such as plastics and wood.

To make permanent marks on metal usually requires a more high-powered laser, but there are chemical coatings which allows less powerful lasers to engrave on metal as well. The same range of lasers can cut thin plastic, cardboard and wood, depending on power and focus of the laser.

Laser cutters also comes in much more powerful and effective versions such as CO2 and Fiber-lasers. These machines are also much more expensive, and requires more equipment. The risk involved using these are also considerably higher as the damage potential is greater. They are more reserved for industry and more specific projects than what normally is required by the average consumer. They can however be used to cut a wider selection of materials as they are much more powerful.

Figure 5. Example of a powerful laser.

2.2.3 CNC-milling

CNC-milling is a production method that has been known for a long time, but only recently been introduced in a hobbyist-friendly package to the private market. CNC-milling features a rotating drill bit which can cut or drill most materials. The machines are normally named in categories of number degrees of freedom. The minimum is translation along the three axes plus the rotating drill bit, however they come with up to five degrees of freedom. As with the other concepts the more advanced machines are much more expensive and therefore not compatible with a normal consumer market.

Figure 6. Example of a router.

A concept that on the other hand is continuously more attractive for a normal consumer market is the CNC-router. The router can cut through wood and plastics, but not most metals. This is primarily due to two factors; the added cutting force and vibrations that is induced with metal working, where the vibrations are the biggest challenge.

3 Design

3.1 Target user group

To choose a suitable design for a modular CNC-machine it must be clear who the typical user of the equipment is. It is big differences in a machine designed to work in a large production factory, or at a bench in someone's garage.

As technology has progressed a new market has developed with it. The hobbyist, DIY-enthusiasts, creators and makers now represent a much larger group than before. The tools and resources available are growing at an exponential rate, and is likely to continue to expand in the coming years. People are sharing their projects, from software to design through open source-based communities.

The 3D-printing technology has made it possible for people to design and prototype at home. The DIY-enthusiast can produce parts and components, be it a new wheel for the tray in the dishwasher or parts for the new cosplay costume. Creators and makers can make complex geometry prototypes or components to the latest robotics project.

Laser engraving is used to decorate different materials and components, with anything from company logos to art.

CNC-milling is also a part of this DIY group, as smaller machines is available at a reasonable cost. Some has capability of machining metal, as well as plastics and wood. This brings yet another aspect to the home mechanic.

Another use of a lightweight printing/engraving/CNC-machine is in education. From high school to universities these types of machines can be utilized in workshops for education in designing, machining, prototyping and programming.

Even for some industrial purposes this type of machine is valuable, where some companies have a need for prototyping and displaying their designs without the need for a full-sized workshop.

A modular design which incorporates the three functions in one machine would result in a product that is desirable for a large span of users.

3.2 Desired specifications

To ensure the design is an attractive option for the user there are some requirements that must be met. Parameters such as accuracy and repeatability are always present in these types of designs. However, since the target group consist of the hobbyist rather than the expert, ease of use is also a large focus area. Ideally a plug-and-play solution would be desired over an extensive manual setup process.

3.2.1 Modularity

The finished prototype will have capabilities for 3D-printing, laser engraving and CNC-milling of non-metals (plastics, wood etc.). These three production methods require different tools, so a type of tool exchange will be necessary. The method for switching between production methods needs to be simple to execute for the user, without having a negative impact on accuracy of the product. A modular tool mounting mechanism will have to be designed.

3.2.2 Accuracy

Accuracy of the machine would depend on the production method in use, as well as the frame and linear guides. For 3D-printing there are several factors that will affect the final accuracy of the print. These include linear motion precision, temperatures on heat bed and filament, type of filament and printing speed. For the most part they can be tuned depending on geometry of the part and type of filament used for the print.

However, there are a few which will be dependent directly on the choice of design such as the linear motion accuracy and rigidity of the frame. These will be governing factors for laser engraving and CNC-milling as well. To obtain the necessary accuracy on the final part, the positional accuracy requirements for the design should be less than $100\mu m$ across the work area. The rigidity and strength of the frame and other components will be dimensioned according to loads from the CNC function as this will have higher requirements than printing or engraving.

3.2.3 Price

As the machine is not meant for industrial purposes it needs to be affordable to be competitive with existing solutions. The total cost should not exceed 12-14 000 NOK. An open loop CNC system is chosen to keep the cost low, and still achieve the desired accuracy.

This implies a relatively small and light frame, suitable for a bench-model.

3.2.4 Ease of use

The machine should be easy to use, and have a user interface which is understandable and intuitive. The software should be able to let the user operate the different modes with ease, while maintaining options to allow more advanced users to fine-tune parameters if they wish.

3.3 Basic design

There are several options as to the basic design of the frame. As discussed earlier the three different functions have the same criteria to the frame, only the CNC-operations need a stronger, more rigid frame than the others.

For additive production and laser engraving there is no heavy components compared to the CNC spindle, and they could therefore have smaller motors and linear guides as well.

The placement of the three axis of motion varies between models. Normally the tool holder itself can move in all three axes, or the work table can take movement in X or Y-direction while the tool itself moves in the remaining two, as seen in fig.3. The latter provides less stress on components as there will be less moving weight connected to the first axis of motion.

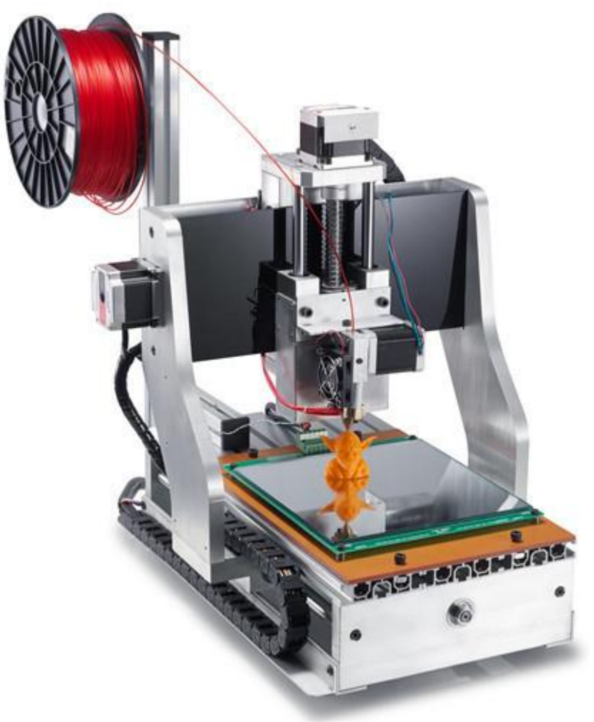

Figure 7. Example of configuration of axes.

As seen in figure 7 the weight of the tool, X- and Z-axis is all resting on the mounts in the Y-axis. In the example in figure 3 the work table itself takes care of motion along the Y-axis. The first solution does not present a problem for printing or engraving, but for a machine capable of routing and light metal milling the extra weight of components will have a considerable impact.

Therefore, a design with moving worktable in Y-direction is chosen. That leaves two options left; The X-axis mounted on Z-axis or vice versa. Both have certain advantages and drawbacks.

Z-on-X solutions: Here the Z-axis motion system is mounted on the X-axis. The advantages here is that the Z-axis only require one motor, and linear rail guide. On the other hand, if a larger work volume is desired the momentum from both cutting forces and weight of components would be considerably higher when working in the lower area, as one would usually do when using the CNC-mill/router. Also, the linear motion system for the X-axis would carry the weight of the tool itself, and the weight from the Z-axis guides, ball screw, motor etc.

X-on-Z solutions: This way momentum from cutting forces are minimized, and stays the same through the whole height of the work area. This design requires two motors and linear rails for the Z-axis, they can however be smaller since the loads are divided between them.

As for the linear motion system both ball screws and belts can be used, coupled to a stepper motor. They do have some different characteristics though which is discussed in the component selection section. The same applies for linear rails, where round shaft or profiled rails are available.

3.4 Frame

The frame will have to be strong and rigid enough to support CNC milling. It will also have to meet economic requirements, and be easy to assemble.

Possible material options for the frame is steel or aluminum. A steel frame could be stronger and more rigid than one in aluminum, but would also be heavier and require welding to achieve high rigidity. Extruded aluminum profiles are cheap and accessible, and easy to assemble. Mounted with correct supports a frame of aluminum profiles will also achieve high rigidity and strength. All three functions will benefit from a large work volume, although rigidity will be increasingly harder to maintain the bigger the work volume is.

Based on the discussion above a frame design in aluminum profiles are chosen, with a work volume of 400 x 400 x 200 mm.

Figure 8. 3060 Aliminum profile.

Extruded 3060 aluminum profile in quality 6063-T5 has a mass of 1.85 kg/m.

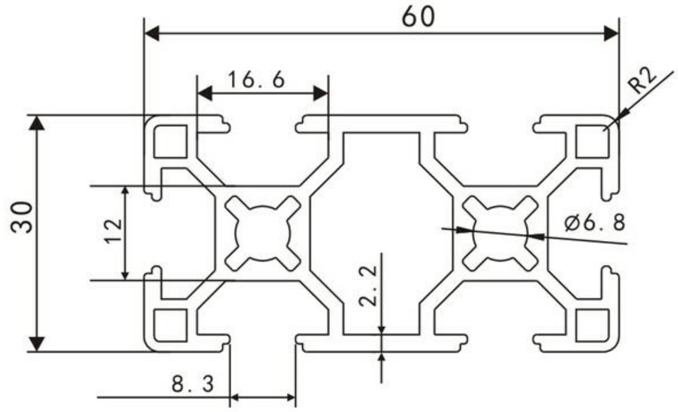

Figure 9. 3060 Aluminum profile cross section.

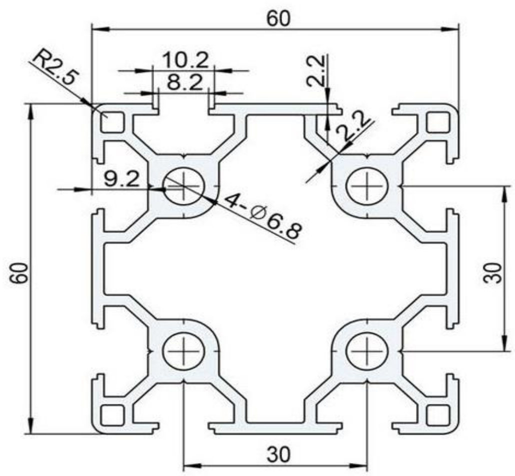

Figure 10. 6060 Aluminum profile cross section.

As discussed above the frame design will be with a moving worktable which moves in the y-direction, and two towers that carry the X-axis along the Z-axis.

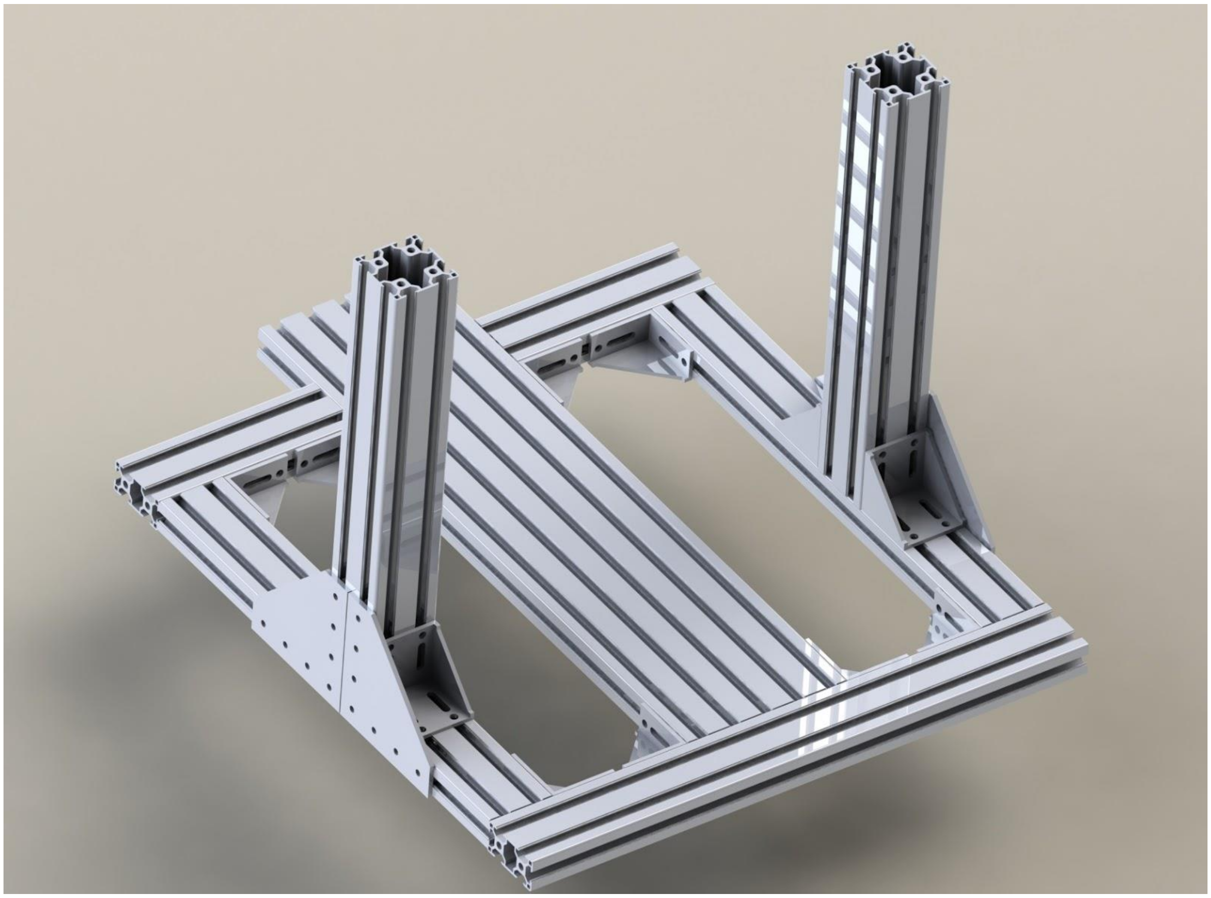

Figure 11. Frame design.

The frame design is shown in picture1, with brackets in joints for higher stability and rigidity. The Y-axis and worktable are mounted on the larger aluminum profile in the middle of the bottom frame, and the two Z-axis are mounted on the two towers as seen in figure 12. Calculations and discussion for motor size, ball screws and linear rails can be seen in the component selection.

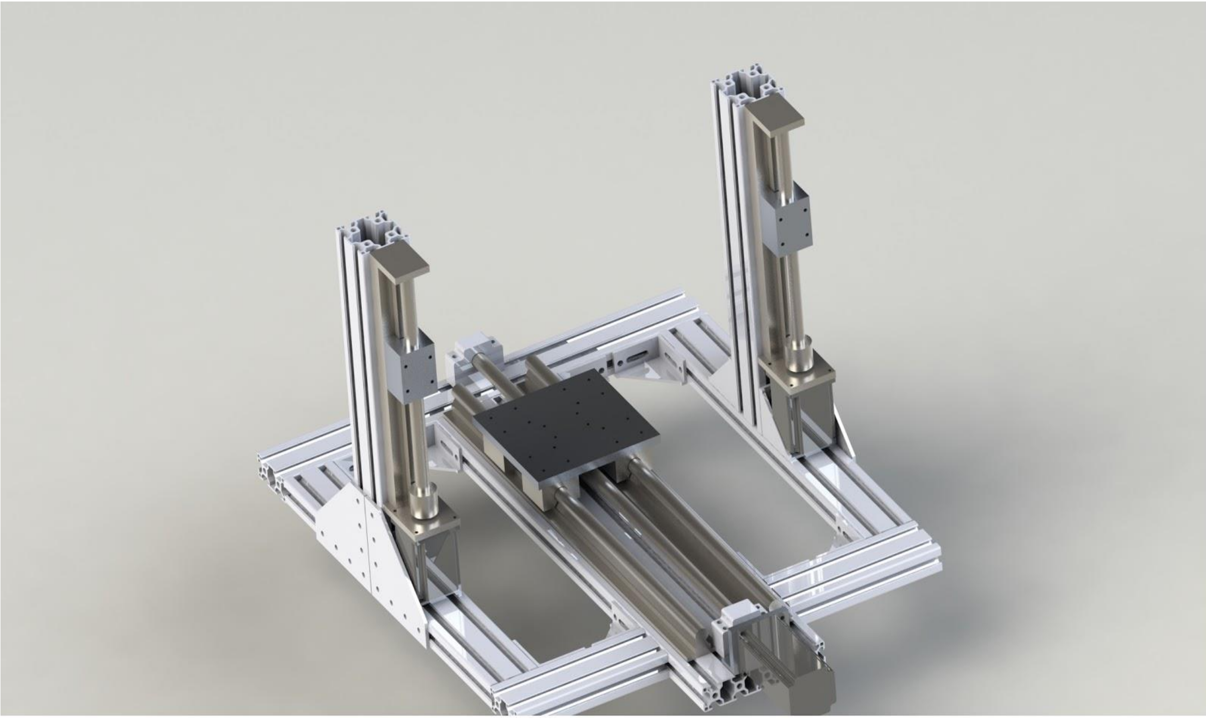

Figure 12. Frame design with Y- and Z-axis.

On the Y-axis there are two rounded linear rails with two rail bearings per rail for increased stability. The ball nut is mounted in the middle, and a aluminum plate are connecting them all via screw connections.

Both Z-axis are also connected via screw connections to the two frame towers. Both have the stepper motor mounted below the ball screw which gives a cleaner design. The ball nut on the Z-axis are also mounted on the linear rail bearing which is located below the ball screw, mounted on the frame tower.

The X-axis is mounted on the two ball nuts/bearings which moves along the Z-axis.

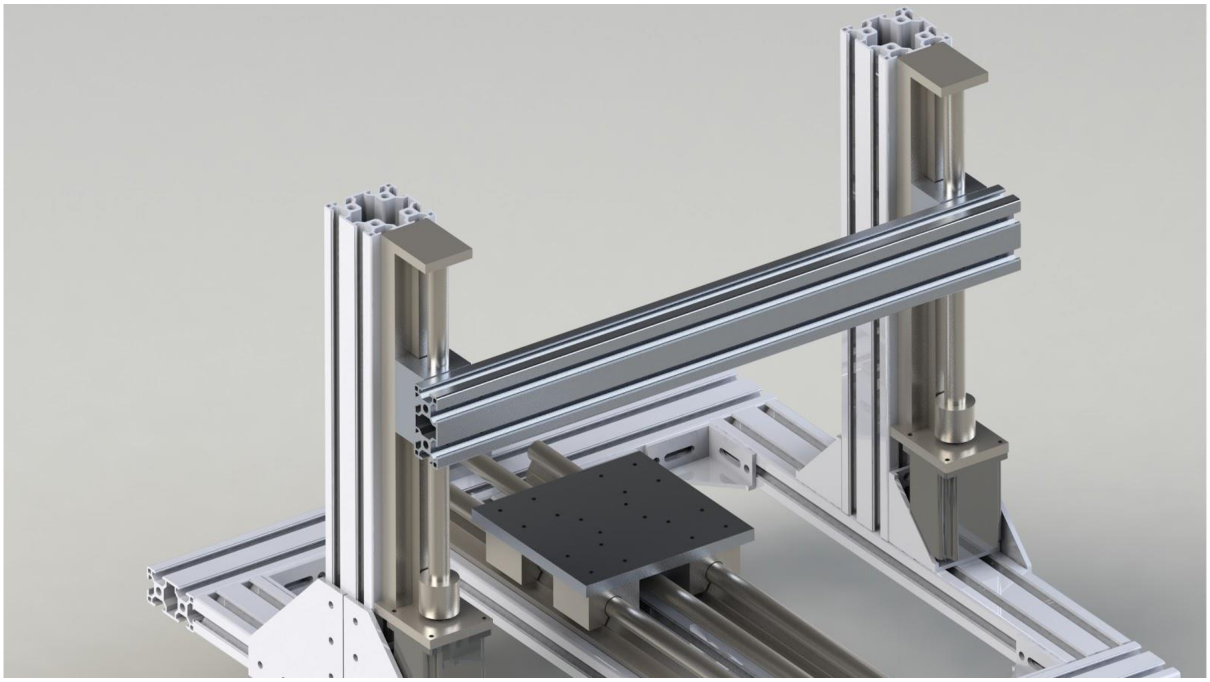

Figure 13. Mounting of X-axis.

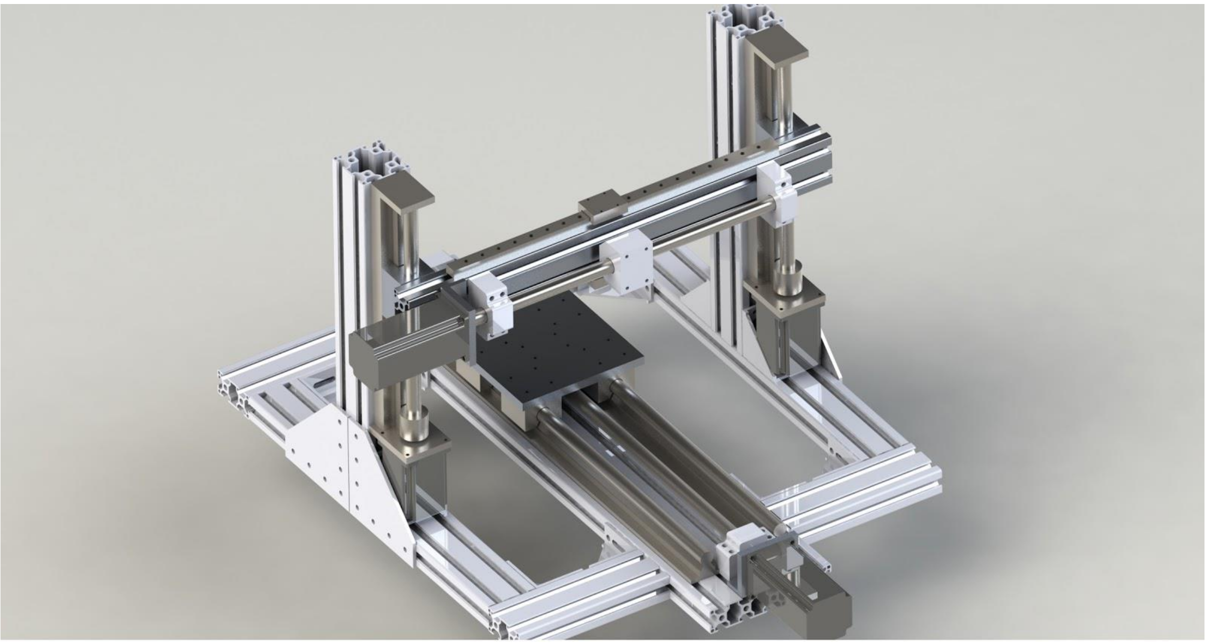

Figure 14. X-axis with linear guides, ball screw and stepper motor.

The X-axis linear guides are mounted on the beam across the two actuators along the Z-axis as shown in picture2.

When CNC milling either wood, plastic or metal there will be chips and dust flying around and attach to the linear rails and ball screws. This is countered by installing protective covers made from Plexiglass on the sides, and a flexible plastic cover on the linear rails and ball screws on the other two axes.

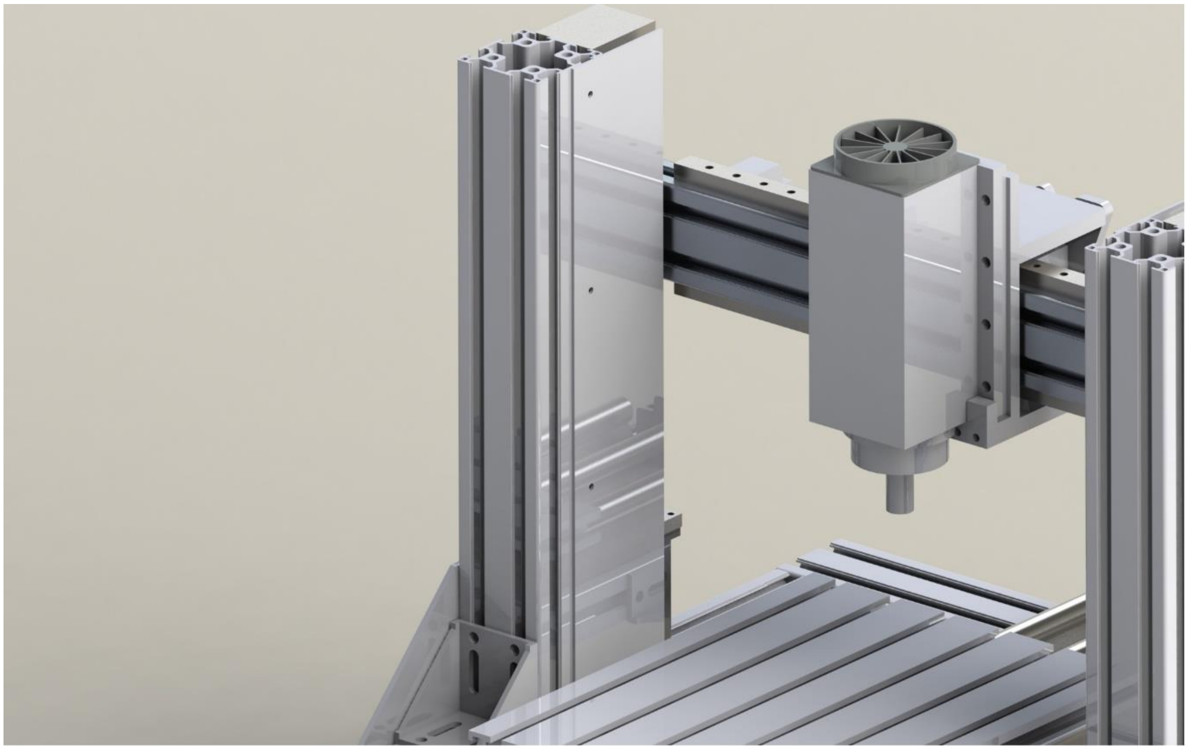

Figure 15. Protective cover on Z-axis.

3.5 Rigidity and vibration

3D-printing or laser engraving does not produce much vibrations, compared to CNC milling. However, there are some coming from turning stepper motors, but this is well within what the frame is designed to handle without an impact on production results.

The first thing to do to minimize vibrations when milling, is to ensure the machine is running at the correct speed for the workpiece material and the tool that is in use. A lot of vibrations and machine chatter can be minimized by tuning parameters such as cutting depth, feed rate and spindle RPM [6].

Brackets and screw connections will provide some rigidity, however the aluminum frame is susceptible for vibrations and to completely counter them will be very hard, if not impossible.

However, there are some actions that can be taken to further improve the effects of vibrations. The brackets and screw connections make a rigid enough coupling for engraving operations in wood/plastics etc., but even light milling of relatively soft metals will generate much more and stronger vibrations that could impact accuracy and the final result.

It is at this point assumed that the frame construction is rigid enough to handle 3D-printing, laser engraving and wood/plastic engraving with a CNC spindle, which is the main work scope of this machine. With this many moving parts, connections and materials, it is difficult to accurately calculate how vibrations will affect the operation during metal milling and to which degree.

A few ways to better vibration damping performance are still mention here. As a rule of thumb, there are some factors that normally are considered and/or manipulated when dealing with vibrations; mass and rigidity. Increasing one or both of these will to some degree result in less errors due to vibrations in most CNC-machines [7].

3.5.1 Increasing rigidity

To add rigidity the aluminum frame can be glued together with strong epoxy, in addition to the brackets. The same applies for the linear rails, in all three axes. An obvious drawback with this solution is that you lose the ability to easily adjust frame connections, and it would impact assembly/disassembly of the machine.

Increasing the size, and number of mounting points on the brackets where possible will contribute to a higher rigidity for the frame. It may be considered to make custom brackets if needed to better suit the purpose.

3.5.2 Increasing non-moving mass

one way to increase non-moving mass would be to fill the hollow aluminum frame profiles with a specialized sand, which will act as a buffer and absorb some of the energy from vibrations. This would probably lessen the impact of vibrations, but also to some degree defeat the purpose of a lightweight benchtop machine. Other materials can also be used, such as a special epoxy mixture.

Another way to partially handle vibrations is through vibration damping gaskets between the stepper motors and the frame.

3.6 Component selection

Components will be chosen to meet the required specifications. The full component list can be seen in appendix A.

3.6.1 Linear motion

Linear rails.

There are two types of linear guides available; rounded and profiled.

Figure 16. Rounded and profiled linear rails.

The profiled rails have a larger contact area then rounded, for a given size, and thus a higher load bearing capacity. They are also better suited for moment loads, and typically have equal load bearing capacity in all directions. The load capacity for rounded rails depend of the direction of loading, which is the direction of the load to the ball bushing as seen in figure 16.

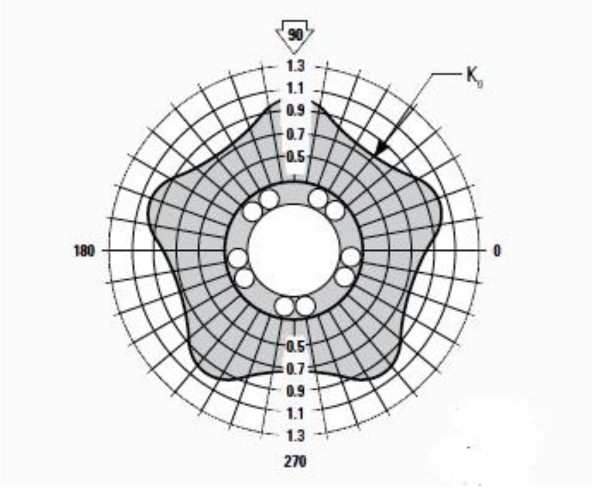

Figure 17. Rounded rail load bearing capacity.

Profiled rails have a higher speed limit than rounded, due to the circulation method of the ball bearing, but for this purpose they are both capable of sufficient speeds. Profiled rails also offer better accuracy and rigidity.

Generally rounded rails are more resistant in harsh environments, and require less maintenance. They are also cheaper to manufacture than profiled rails [8].

To meet the requirements for this machine and considering availability and price, rounded rails are chosen for the Y-axis, and profiled for X-, and Z-axis.

Profiled linear rails.

The profiled linear rails chosen is the MGN15H, with the following properties:

The full list of specifications can be seen in appendix A.

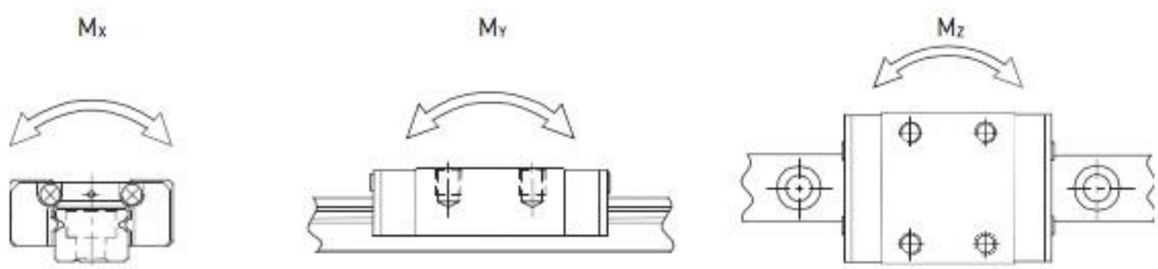

Figure 18. Profiled linear rails, direction of moment.

Table 1. Linear rails load rating.

Description	Value	Unit
Dynamic load	6,37	kN
Static load	9,11	kN
Dynamic moment M_x	52	N
Dynamic moment M_y	41	N
Dynamic moment M_z	41	N
Static moment M_x	73,5	N
Static moment M_y	57,8	N
Static moment M_z	57,8	N

As discussed further up in the report it is the CNC operation which will be the dimensioning factor for the frame components. To maintain the option for light CNC milling of metal, it is assumed a maximum cutting force of 600N can be applied in calculations.

Calculations to ensure the rails in Z-axis will withstand maximum expected momentum:

Assumptions:

- A maximum cutting force of 600N, which act on the tool in the XY-plane.
- A Z-distance of 110mm from the cutting force to the linear rail block.
- Mass from the spindle and all other connecting parts are located close to the moment axis and partially cancel each other out, and thus will have a small impact compared to the cutting force.

$$M = 600 * 0.11 = 66\ Nm$$

Applying a safety factor of 1.2:

$$M = 66 * 1{,}2 = 79{,}2\ Nm$$

Since the rails in Z-direction are mounted vertically, this corresponds to the dynamic moment M_y in table 1 above.

Rated moment for the two Z-axis linear rails:

$$M = 2 * 41 = 82\ Nm$$

With a cutting force of 600N and a safety factor of 1.2, the linear rails in the Z-axis will have sufficient moment rating for the application.

Calculations to ensure the rails in X-axis will withstand maximum expected momentum:

Assumptions:

- A maximum cutting force of 600N, which act on the tool in the XY-plane.
- The parts and connectors are rigid bodies with a homogenous transfer of forces.

Due to symmetry in the design, the resulting axis of moment and distance will be equal to the calculations in Z-axis. However, the orientation of the linear guides indicates this corresponds to Mx in table 1.

Rated moment for the two X-axis linear guides:

$$M = 2 * 52 = 104\ Nm$$

With a cutting force of 600N and a safety factor of 1.2, the linear rails in the X-axis will have sufficient moment rating for the application.

For the worktable in Y-axis, SBR16 rounded linear rails is selected. They are more cost-effective and provide enough strength for this application. From the datasheet provided by the manufacturer [Appendix B] the linear guide blocks have a dynamic load rating at 774N and a static load rating at 1180N. Due to the design they don't take moment forces, but as seen in figure 13 it will be used four of these on two rounded linear rails, which can be seen from the values in the previous calculations will be more than enough.

Lead screw or Belt drive.

To transfer the rotational motion of the motor to linear motion of the axis, either a lead screw or a belt driven system can be chosen. Both are applied to the same function, but are different in the way they operate.

The belt drive uses two circular pulleys and a timing belt to transfer rotary motion to linear motion. Usually the timing belt is made from an elastomer with fiber reinforcement, but several material options are available, depending on the application. The belts teeth interact with the pulleys to transfer torque and prevent slipping. It is required to have the correct belt tension to avoid teeth slipping on the pulleys [9,10].

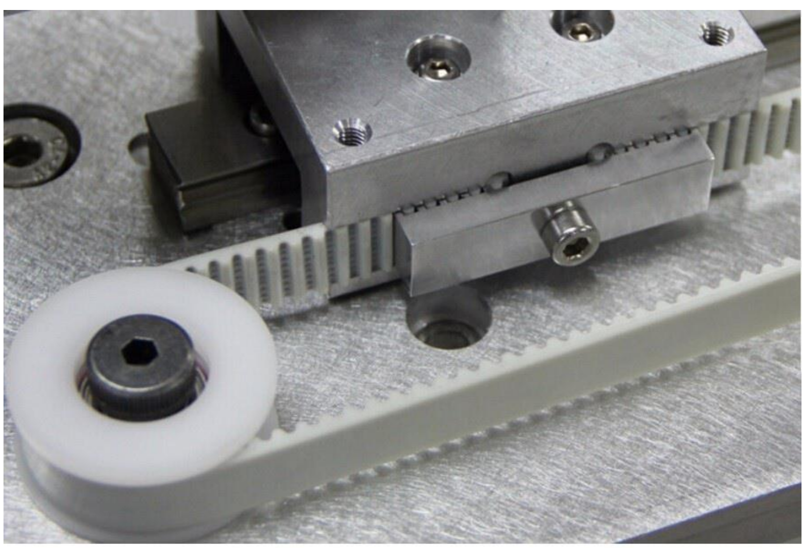

Figure 19. Example of a belt drive.

The ball screw uses a ball nut to drive the carriage along the axis as the screw rotates.

Figure 20. Example of a ball screw.

The ball screw system is heavier but generally offers greater accuracy and load capabilities than a belt drive, due to the possible elongation of the belt over time. The belt drive on the other hand is capable of higher speeds and is often chosen for greater distances as they can achieve this more cost effective than a ball screw.

In summary the belt drive is generally used for lighter loads and greater distances, and the ball screw for higher loads which require high positional accuracy [11].

For this design the ball screw is a good choice as it is relatively short distances with the higher loads of CNC machining, combined with the accuracy they provide.

The specific ball screw selected are the RM 1605-3. It has a 16mm diameter, 5mm lead and three number of threads. It is classified as a C7 accuracy screw which corresponds to a travel error at 50 m per 300mm. See Appendix C for full table. The same type of screw will be used for all three axes. The load capacity is given from the manufacturer and is as follows [12]:

Table 2. Ball screw load rating.

Description	**Value**	**Unit**
Static load rating	13.2	kN
Dynamic load rating	7.65	kN

As we can see the load rating are well beyond what would be inflicted by the normal operations of the machine. It is however not recommended to exceed 80% of the design load rating to prolong the lifetime of the ball screw.

To calculate for this the total maximum mass being moved by each axis is needed, in addition to the length of each screw:

The X-axis includes the spindle with mounts, the bearings on two linear guides and the ball nut on the axis.

The Y-axis includes the bearings and ball nut, work table with clamps and the workpiece itself.

The Z-axis include the x-axis with mounts on an aluminum profile, and two bearings with ball nuts.

Table 3. Ball screw calculation properties.

Mass on X-axis	10 kg
Mass on Y-axis	10 kg
Mass on Z-axis	18 kg
Length of ball screw X-axis	400 mm
Length of ball screw Y-axis	400 mm
Length of ball screw Z-axis	200 mm

Assumptions and details:

- As cutting forces will depend on cutting speed, work material etc, a cutting force of 600 N during drilling or milling is assumed.
- The Z- axis is driven by two motors, linear guides and ball screws.
- masses on moving axis are rounded up.
- Assuming maximum mass for the workpiece is 5 kg.

If we calculate for the Z-axis, with 18 kg of mass being lifted by two ball screws we get:

$$F = m * a$$

$$F = 18 * 9{,}81 = 176{,}58 \cong 177\ N$$

When drilling a hole with the CNC spindle the resulting forces on the two Z-axis ball screws are:

$$F = 600 - 177 = 423\ N$$

Which is far below the load rating:

$$F_{LR} = 7650 * 2 = 15300 = 15{,}3\ kN$$

Since the X- and Y-axis has the same moving mass, we calculate forces during milling operation only for X:

$$F = m * m * \mu + 600 = 10 * 9{,}81 * 0{,}02 + 600 = 601{,}96\ N$$

Which also is well within the limit.

The critical speed for the ball screw must also be verified.

This is given by: [13]

$$n = f * \frac{d_r}{L^2} * 10^7 * S_f$$

Where n = critical speed (RPM)

f = Ball screw mounting coefficient

d_r= Ball screw root diameter (mm)

L_2= Distance between supports (mm)

S_f= Safety factor = 0.8*

*Note that a safety factor of 0.8 has been added in the equation.

Calculating for the ball screw in X- and Y-axis:

$$n = 15{,}1 * \frac{14}{400^2} * 10^7 * 0{,}8 = 10\ 570\ RPM$$

Calculating for ball screw in Z-axis:

$$n = 15{,}1 * \frac{14}{200^2} * 10^7 * 0{,}8 = 42\ 280\ RPM$$

Even though the critical RPM for the shorter screw is much higher, both are way higher than what is to be expected from normal operation of the machine.

Motors.

The Nema stepper motor is a commonly used stepper motor for machines of this kind from smaller 3D-printers to larger CNC-systems. A stepper motor is a brushless DC motor that divides a full rotation into several steps, which can be controlled by a motor driver. The driver tells the motor to move a certain number of steps and it can stop and hold at any of these steps without any feedback.

To calculate the required size and torque requirements of the motors there are some factors which should be considered:

- Rate of acceleration and movement velocity during operation.
- Weight and inertia of components and workpiece
- cutting forces from CNC operation

As discussed earlier it is the CNC function that has the highest requirements to this machine as the tool weighs more, and there are cutting forces involved during operation. Therefore, we will choose stepper motors based on calculations from the CNC function.

There are two modes of movement that needs to be calculated for, rapid movement of the tool in the work area and movement during machining. The rapid movement can be higher to save work time as there are no machining involved.

During CNC machining the following parameters are set:

- Rapid movement = 300 mm/s = 0.3 m/s
- Machining movement = 50 mm/s = 0.05 m/s
- Machine acceleration time = 0.5 s

Moving mass on the axis:

Table 4. Moving mass on axes.

Mass on X-axis	10 kg
Mass on Y-axis	10 kg
Mass on Z-axis	18 kg

Assumptions and details:

- As cutting forces will depend on cutting speed, work material etc, a cutting force of 600N is assumed.
- The Z- axis is driven by two motors, linear guides and ball screws.
- masses on moving axis are rounded up.
- Assuming maximum mass for the workpiece is 5kg.
- Maximum torque situation is calculated (acceleration + cutting force)
- A safety factor with the value 2 is used

Formulas [14]:

Torque when moving at constant speed:

$$T_c = T_d + T_p + T_f$$

Where T_c= Torque at constant speed

T_d= Torque required to drive the load

T_p= Torque due to preload ball nut

T_f= Torque due to friction of seals/bearings

$$\frac{F_a * P}{2 * \pi * \eta}$$

Where Fa = Total axial force

P = Screw Lead (Pitch)

η = Efficiency of the ball screw

$$F_a = F + m * g * \mu$$

Where F = axial force from machining process

m = Mass of moved objects

g = Gravitational acceleration

μ = Friction coefficient of linear guides

Torque when accelerating:

$$T_a = T_c + T_{acc}$$

Where T_{acc} = Torque from acceleration

$$T_{acc} = J * \alpha$$

Where J = System inertia

α = Angular acceleration

$$\alpha = \frac{2 * \pi * \omega}{60 * t}$$

Where ω = Angular velocity

t = Time of acceleration

$$J = J_m + J_s + J_l$$

Where J_m = Motor inertia

J_s = Screw shaft inertia

J_l = Load inertia

$$J_l = m * \left(\frac{P}{2 * \pi}\right)^2$$

Additional data needed to calculate maximum torque requirements for the stepper motors:

Table 5. Stepper motor calculation data.

Description	**Value**	**Unit**
Efficiency of the ball screw	0,9	n/a
Profiled linear guide friction coefficient	0,01	n/a
Rounded linear guide friction coefficient	0,02	n/a
Angular velocity	50	RPM
Time of acceleration	0,5	s
Ball screw lead (pitch)	0,005	m
Motor inertia (Nema 23 112mm)	0,000075	kg*m^2
Motor inertia (Nema 23 76mm)	0,000039	kg*m^2
Ball screw shaft inertia X-axis	0,000032	kg*m^2
Ball screw shaft inertia Y-axis	0,000039	kg*m^2
Ball screw shaft inertia Z-axis	0,000027	kg*m^2
Torque from preload ball nut	0,12	Nm
Torque due to friction from seals/bearings	0,05	Nm

An excel spreadsheet is made to easily see how different masses and cutting forces affects the total motor requirements.

Calculation results for the X-axis motor:

Table 6. Stepper motor X-axis calculation results.

inertia of the load	0,000006338999554	kg*m2
Inertia of the system	0,0001083389996	kg*m2
Angular acceleration	10,46666667	rad/s2
Torque due to acceleration	0,001133948195	Nm
Total axial force	600,981	N
Torque due to load	1,063306794	Nm
Total torque	1,234440742	Nm
Torque requirement motor with safety factor	2,468881485	Nm

Required torque for the X-axis motor = 2.5 Nm

Calculation results for the Y-axis motor:

Table 7. Stepper motor Y-axis calculation results

inertia of the load	0,000006338999554	kg*m2
Inertia of the system	0,0001203389996	kg*m2
Angular acceleration	10,46666667	rad/s2
Torque due to acceleration	0,001259548195	Nm
Total axial force	600,981	N
Torque due to load	1,063306794	Nm

Total torque	1,234566342	Nm
Torque requirement motor with safety factor	2,469132685	Nm

Required torque for the Y-axis motor = 2.5 Nm.

Calculation results for Z-axis motors:

Table 8. Stepper motor Z-axis calculation results.

inertia of the load	0,0000114101992	kg*m2
Inertia of the system	0,0001134101992	kg*m2
Angular acceleration	10,46666667	rad/s2
Torque due to acceleration	0,001187026752	Nm
Total axial force	601,7658	N
Torque due to load	1,064695329	Nm
Total torque	1,287069383	Nm
Torque requirement motor with safety factor	2,574138765	Nm

As there are two motors driving the Z-axis the required torque per motor will be:

$$\frac{2,574}{2} = 1,287 \cong 1,3\ Nm$$

Based on these calculations the Nema 23 112mm is chosen for the X- and Y-axis, and two Nema 23 76mm for the Z-axis.

Nema 23 112mm	**Nema 23 76mm**
Holding torque: 3.0 Nm	Holding torque: 1.9 Nm
Current 4.2 A	Current 3.0 A
Step angle: 1.8 degrees	Step angle: 1.8 degrees
Phase: 2	Phase: 2

To run the stepper motors separate drivers are needed as the controller board itself cannot deliver the current required to achieve the torque needed. For this purpose, the cost-effective DM542 motor driver is chosen.

Features of the DM542 driver [15]:

- Anti-Resonance provides optimal torque and nulls mid-range instability
- Motor auto-identification and parameter auto-configuration technology, offers optimal responses with different motors
- Multi-Stepping allows a low-resolution step input to produce a higher micro step output, thus offers smoother motor movement
- 15 selectable micro step resolutions including 400, 800, 1600, 3200, 6400, 12800, 25600, 1000, 2000, 4000, 5000, 8000, 10000, 20000, 25000
- Soft-start with no “jump” when powered on
- Input voltage 18-50VDC
- 8 selectable peak current including 1.00A, 1.46A, 1.91A, 2.37A, 2.84A, 3.31A, 3.76A, 4.20A
- Pulse input frequency up to 200 kHz, TTL compatible and optically isolated input
- Automatic idle-current reduction
- Suitable for 2-phase and 4-phase motors
- Support PUL/DIR and CW/CCW modes
- Over-voltage, over-current protections

Figure 21. DM542 Stepper driver.

The DM542 stepper motor driver requires an input voltage from 18-50V. Based on availability and price two power supplies which delivers up to 360W at 36V are chosen. They will each drive two of the motors.

Figure 22. 36V/360W power supply.

Calculations to make sure these are sufficient:

$$P = U * I$$

Where P = Power (W)

U = Voltage (V)

I = Current (A)

$$P = 30 * 4{,}2 + 36 * 3{,}0 = 259{,}2\ W$$

one power supply is more than capable to drive on 4.2A motor and one 3.0A motor, which sums up to 260 W

3.6.2 Additive production

To print object in 3D using the FDM method requires an extruder, a hotend and a surface suitable for printing on.

Note: All the printer components will be powered and driven directly from the controller board, and the combined power supply will be discussed in Controller/Software.

Extruder.

The extruder is feeding the filament at a certain rate through the hot-end. It uses a small stepper motor and gears to drive the filament. There are two variants of extruders that has proven effective; Bowden and Direct drive. The Bowden design are mounted on the frame, instead of on the hot-end. This means less moving weight, and normally gives more accurate printing results than a direct drive on the same printer [16].

As the direct drive is mounted on the hot-end itself, it increases responsiveness and requires less torque from the extruder motor.

Figure 23. Mk8 dual extruder with hotend.

The mk8 dual extruder is a direct drive, with capability for printing two filaments in the same print. This allows easier use of a support material for complex prints. The hot-end are mounted directly under the drive, and includes cooling fans to manage excess heat. The weight of the extruders will not impact accuracy in this case as the frame and linear motion system is dimensioned to handle a light CNC-mill.

The full specifications for the mk8 extruder:

- Nozzle: 0.2mm/0.3mm/0.4mm/0.5mm
- Material of print: 1.75 mm PLA / ABS
- Sports shaft speed: 40 mm/s
- Voltage: 12V
- Thermistor: 100K NTC
- Temperature: 190°-230°
- Cooling fan: 4010, 12V
- Stepper motor: NEMA17
- Weight: 980 grams

This will be sufficient to effectively print in most filaments.

The printing surface also affects the quality of the print, and is usually made of glass of plastic. However, a heated bed has been known to have positive effects on the print, improving adhesion of the first layer, which is critical for the rest of the print. It also minimized negative effects from warping as the print cools down.

For this project a MK2B heat-bed is chosen, with a glass plate on top.

Figure 24. MK2 Heat bed.

3.6.3 Milling

The milling function of this machine requires a spindle, controller/PSU and some tool to hold the workpiece while machining.

The spindle chosen for this build is an air cooled 1.5kW module, with a ER11 collet.

Figure 25. 1.5kW air cooled spindle.

The 1.5 kW spindle can handle all types of engraving, and CNC milling of some metals as well. Specifications of the spindle given by the manufacturer are as follows [17]:

- Power: 1500W
- Voltage: 220V
- Frequency: 0-400Hz
- Speed:0-24000rpm
- ER11 collet
- Runout: less than 0.005mm

The spindle controller is a variable frequency drive, which controls the spindle speed. It also contains a RS485 communication port which can be used to control spindle parameters directly from the main controller board or computer.

VFD parameters:

- Input voltage: 220V
- Output voltage: 220VAC
- Input frequency: 48-63 Hz
- Output frequency: 0-400 Hz
- Input phase: 1 or 3 phase
- Output phase: 3 phase

The workpiece holder for the milling function is a standard clamp made from aluminum which is mounted directly on the table. This can double as a holder for the Laser engraving function as well. If the workpiece does not fit in the clamp, or a stronger fixture is needed it it easy to use smaller individual clamps fixed directly in the profiles on the worktable itself.

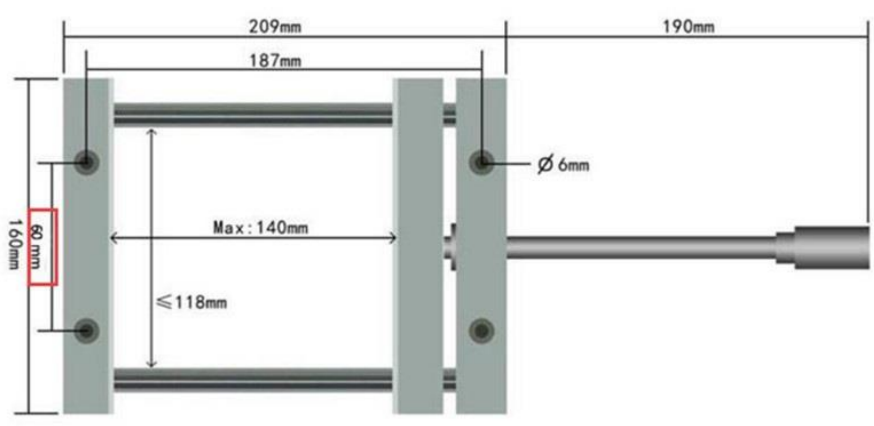

Figure 26. CNC clamp.

3.6.4 Laser engraving

A laser used for engraving wood and plastics does not require much power. Available in the price range for this machine they range from about 0.5W to 15W. A laser module at 2.5W, with adjustable focus is chosen. It will be enough power to engrave on most materials except metal. I will also cut thin acrylic, paper etc. with multiple passes.

Figure 27. 2.5W laser module.

The 2.5W laser has a wavelength at 445nm and features a TTL modulation function. The laser module is controlled and powered directly via the controller board.

3.6.5 Modular tool exchange

To achieve capabilities as a multi-machine and the set requirements, the modularity will have to be rigid and strong enough to cope with the forces involved in wood engraving with a CNC-spindle, as well as light metal milling. It also need to be easy to use and let the user exchange the tool between CNC milling, laser engraving and 3D printing.

The three modes have very different criteria to both the machine, and the modular mounting mechanism. Laser engraving and 3D-printing have no and very small external forces acting on the tool, and can therefore manage with a much lighter mechanism than CNC operations. All three will need to be attached to the machine with screws, but the CNC spindle will need a more rigid mount.

Other requirements to the mounting mechanism is that it should guide the tool and preferably hold it in place to allow the user to secure it.

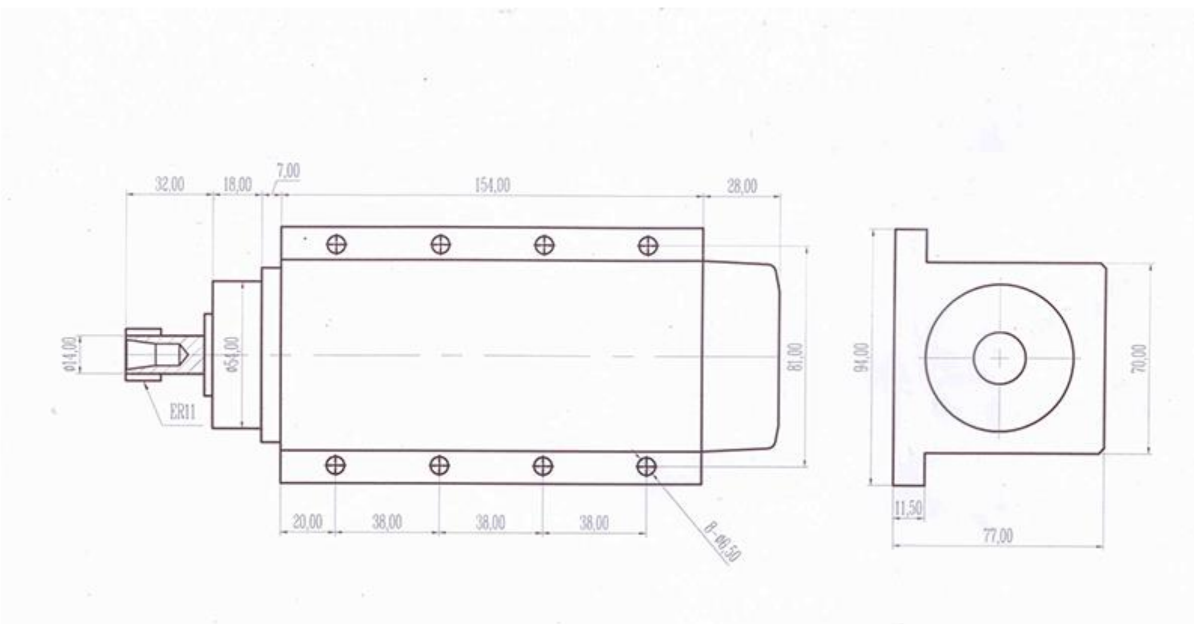

Figure 28. Machine drawing of the CNC spindle.

As seen from figure 27 [17], the CNC spindle has a squared profile. As the spindle has the highest priority in strength/rigidity from the mounting mechanism, it will be designed to fit the spindle. The laser engraver and 3D-printer components will be permanently mounted on two mounting plates which has the same fit as the spindle and is easily interchangeable in the same mounts.

As seen in figure 28 below, two small brackets are installed to guide and assist in holding the tool in place while the user can properly secure it.

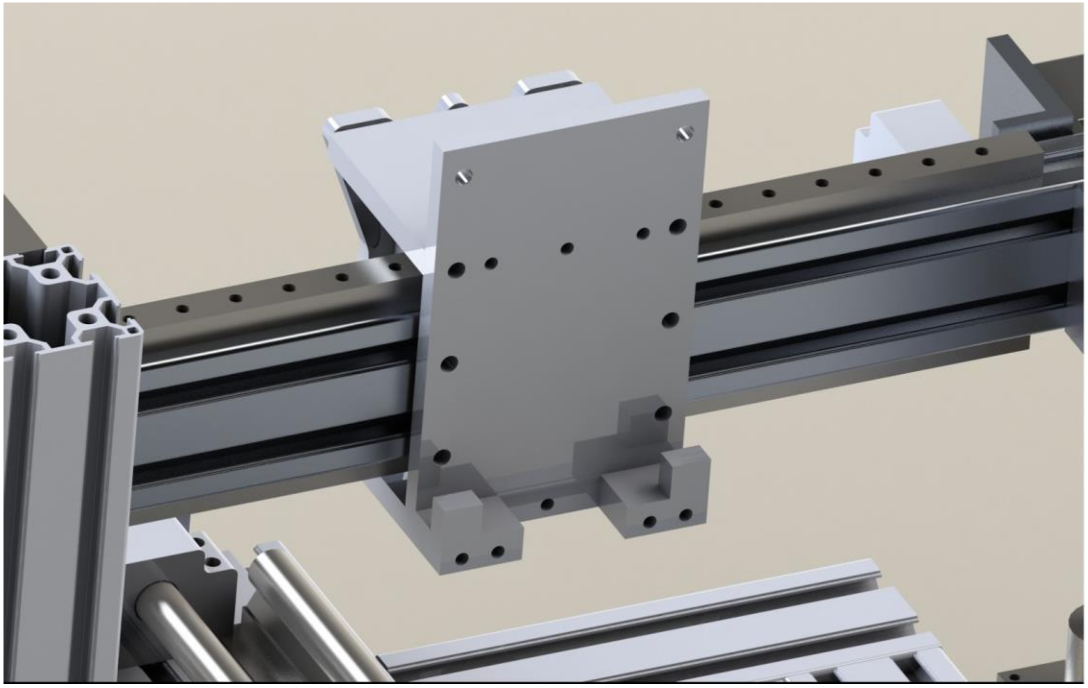
Figure 29. Modular tool mount.

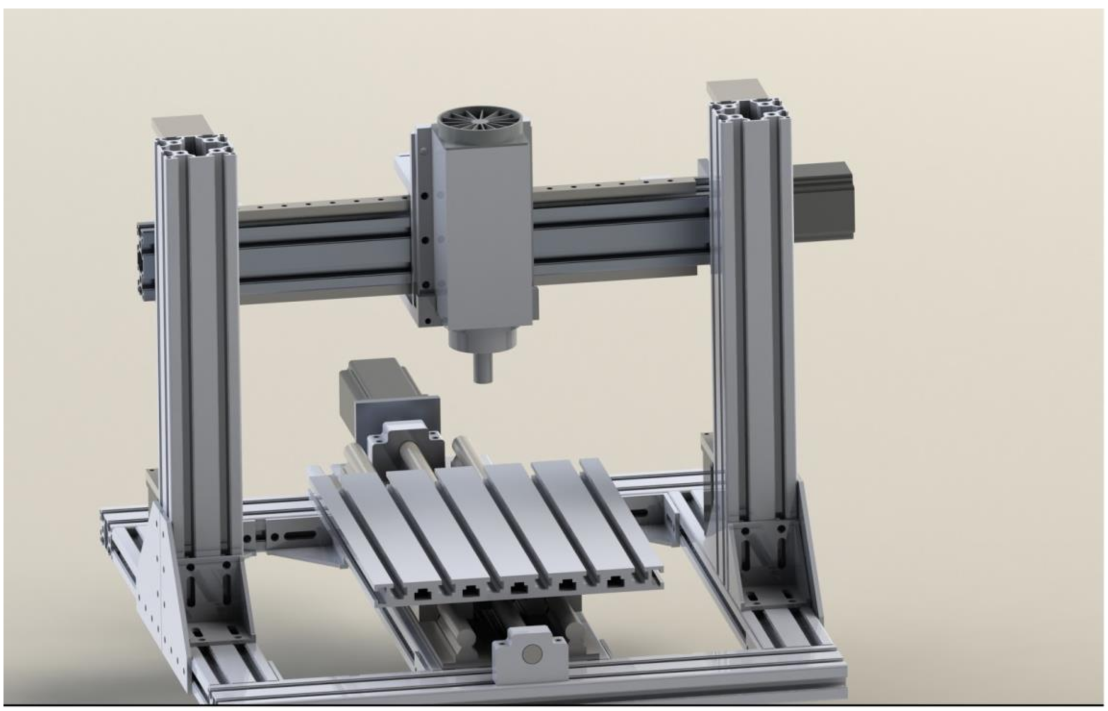
Figure 30. CNC spindle modular tool mount.

3.6.6 Controller and software

The main controller is the RAMPS 1.4, which is an Arduino-based controller board that work in pairing with the Arduino Mega 2560. This uses an Atmega 2560 microprocessor to calculate motor speeds etc. from G-code.

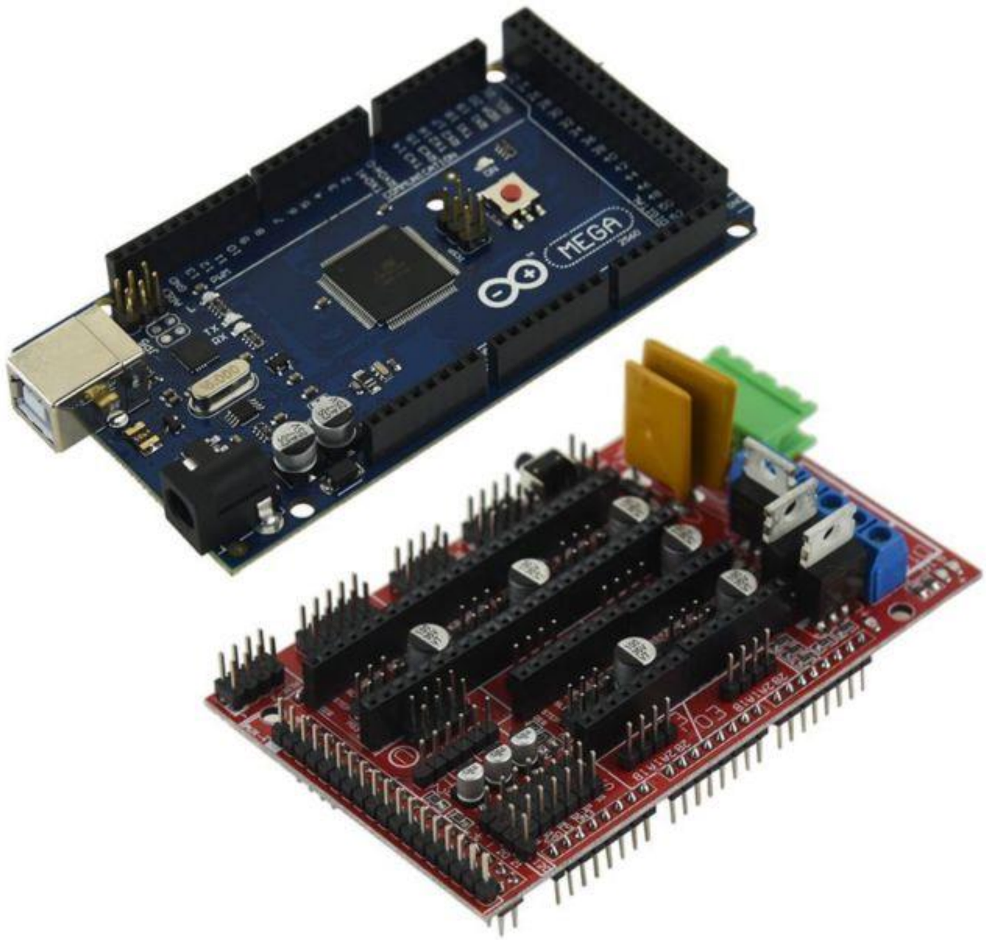

Figure 31. Arduino mega + RAMPS 1.4 controller board.

The RAMPS board contains signal outputs for stepper motors, drives the hotbed and extruders, output for the laser driver board and possibilities for later expansions such as a Bluetooth or Wi-Fi module. It can print parts directly from the SD-card reader, or connect to a PC via USB for live control over the features. The latter is often more suitable for CNC-milling as one might want a bit more control. If used via the SD-card it is necessary to upload the G-code file to the SD-card and then to the Arduino. The controller is connected to a small LCD screen where simple calibration can be made, and which file on the SD card to print/engrave.

A 12v power supply is coupled with the Arduino/RAMPS setup to power both the microprocessor and all the peripherals connected via the board. This includes the hotbed, extruder and the hot-end when printing, or the laser when engraving.

Power consumption is as follows:

Table 9. 3D-printer power consumption.

Hot-end	30W
Hotbed	180W
Extruder	20W
Laser	2.5W

As seen in table 9 the 3D-printing function will require considerably more power than laser engraving. As the machine has capabilities of dual extruding, the total power consumption is up to 280W when printing. This does not include the consumption of the microchip itself and the small LCD display. Due to availability a power supply rated at 360W at 12V is chosen.

Figure 32. 3D-printer PSU.

End stops and probes.

The RAMPS extension board has connections for up to six end stop switches/probes. These protect the machine from crashing due to bad programming or other user errors. It is also used in calibration and homing of the tool.

This build will feature four mechanical end stops, two minimum and maximum on the X- and Y-axis. On the Z-axis a capacitance proximity sensor switch is used, to measure the distance from the tool to either the worktable or the workpiece.

Figure 33. Capacitance proximity switch and mechanical end stop.

The proximity switch is capacitive, which means it will detect the distance to most materials and is not limited to conductive ones. Specifications of the capacitive proximity switch from manufacturer are as follows [18]:

- Capacitive sensor
- NPN NO (Normally open)
- Detecting distance: 1-10mm
- Input voltage: 6-36V
- Current output: 300mA
- Response frequency: 100Hz

On the software side there are several options available, from paid solutions to free versions based on open source licenses. The latter will be chosen for this machine, as the option to upgrade later is always present. On the controller board the firmware interprets G-code to send motion signals to the different motors and other components. For this task Marlin is chosen, which is a popular open source program written for the Arduino. It has a large number of users and is continuously developed for better performance and expandability. It can also be adjusted to fit any printer or CNC-machine, and include most operations that are in use today.

Repetier was also considered as firmware on the controller board, but as Marlin has a larger user base it is easier access to support if needed. In most other aspects they are very similar. [19]

Configuration of Marlin firmware to suit this specific machine is done in Arduino IDE. it features a clean and understandable setup which is easy to learn even for beginners. It will need to be configured to use two steppers in the Z-direction, and set temperature targets for the extruder and hotbed and some movement restrictions.

As for the live controller software on the PC-side, there are also several options.

For the printing operations, Pronterface is a good alternative, with most options one would need. In addition to running a complete program one could send individual G-codes for testing etc. See Appendix D for G-codes.

For CNC and laser operations BCNC or UGS are proper controllers which contain all the functions needed for mid-level to advanced CNC operations in an easy to use GUI.

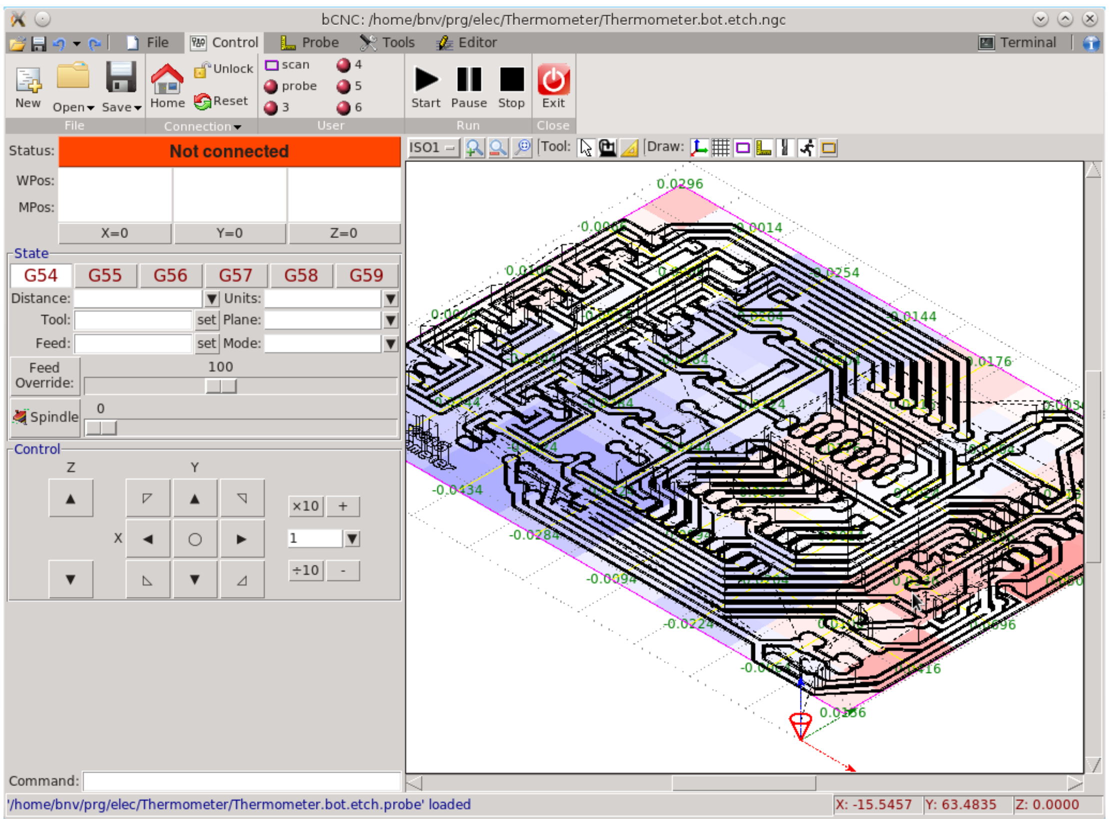

Figure 34. Example of BCNC GUI.

For wireless control there are also multiple apps that can be downloaded to android or Ios devices, for management and live status of the machining process.

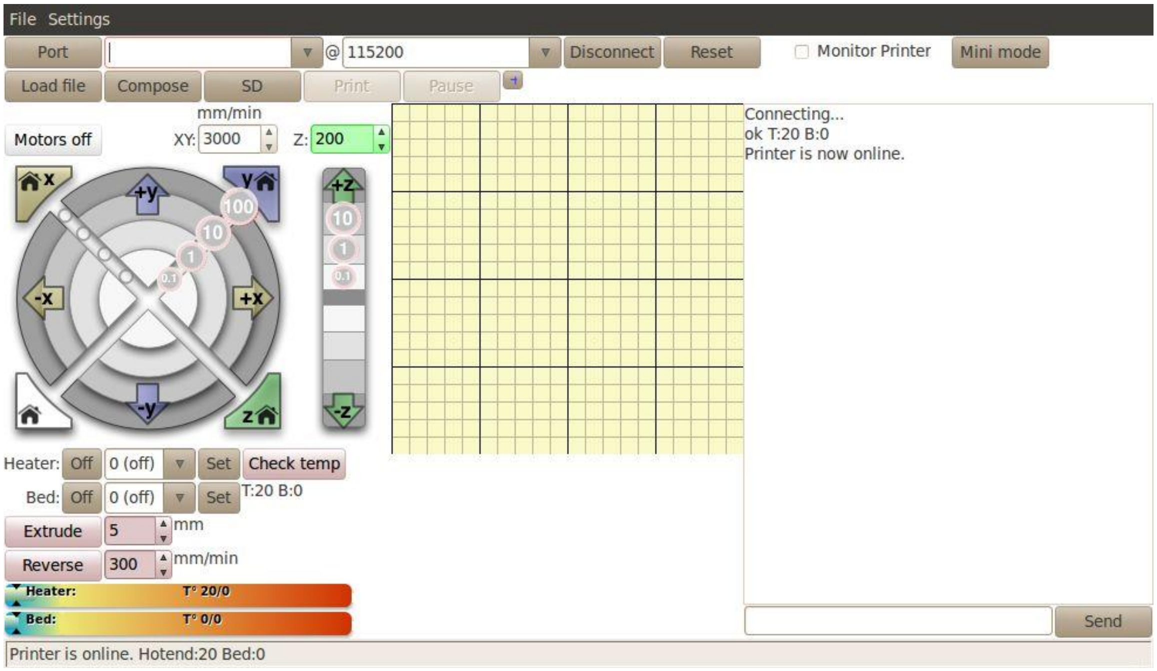

Figure 35. Example of Pronterface GUI.

Marlin is originally written to control 3D-printing and laser engraving, but not CNC-milling or CNC engraving. It can however be configured to do this as well. In the test phase it will be considered if another firmware is better suited to complete all three functions or not.

When engraving with the laser a program that compile any picture in to G-code is needed. For this purpose, LaserGRBL is chosen. It can compile readable G-code for either Marlin or most other GRBL-based firmware.

The CAM software for the CNC milling operation chosen is CamBam.

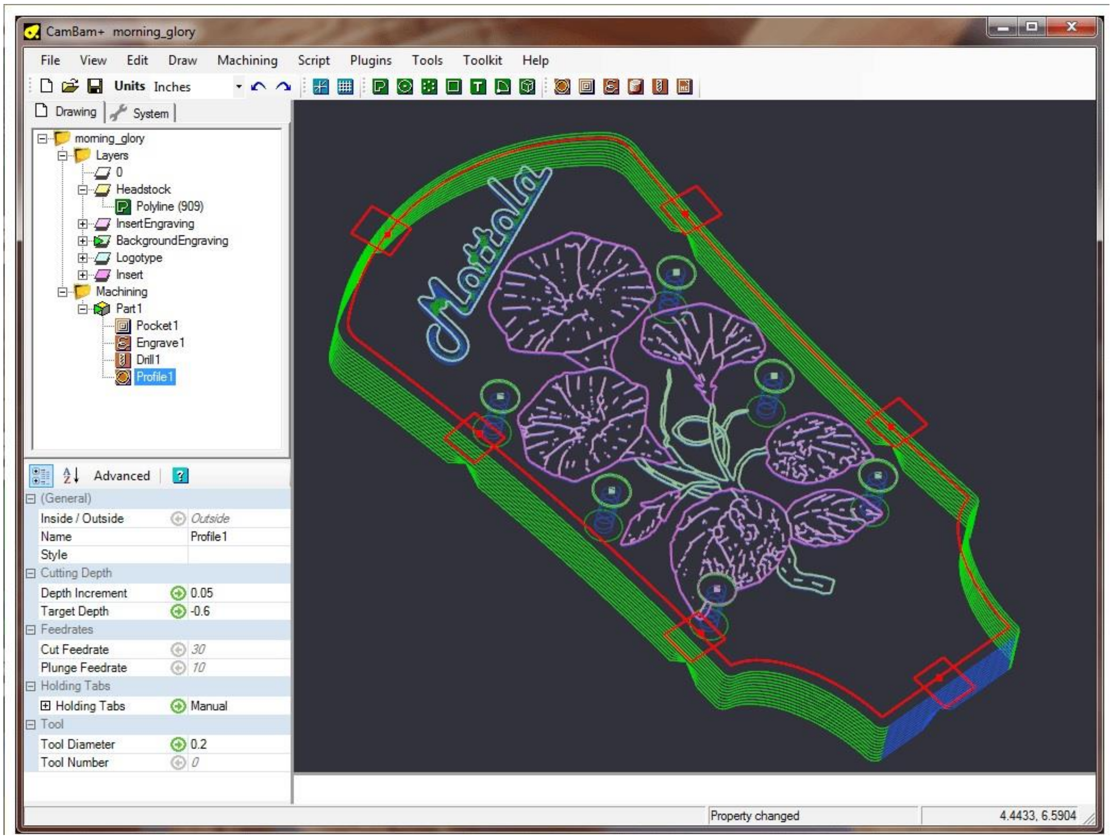

Figure 36. Example of CamBam GUI.

The RAMPS extension board has an input option for a LCD screen, with SD card reader as well. This option allows the control directly from the combined turning knob/push button on the LCD controller panel. This way it is possible to calibrate the machine and start a job directly from the SD card, without connecting a dedicated PC. This is especially a good feature for 3D-printing or laser engraving operations, but can be used for CNC operation as well.

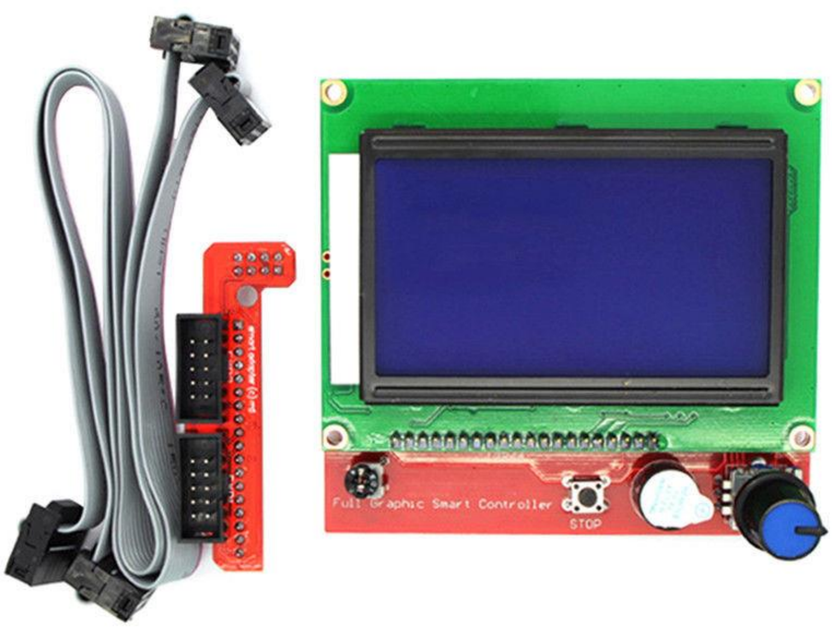

Figure 37. LCD panel with pushbutton and SD card reader.

3.6.7 PSU

To keep everything tidy a control box containing all the power supplies and the controller board is designed. To keep within the budget, it is designed in plexiglass, which is cost-effective and sturdy enough for the purpose. It must be big enough to contain 3 power supplies, the 4 stepper motor drivers, and the controller board with the LCD screen on top. For a cooler look carbon fiber film can be applied to all or some surfaces.

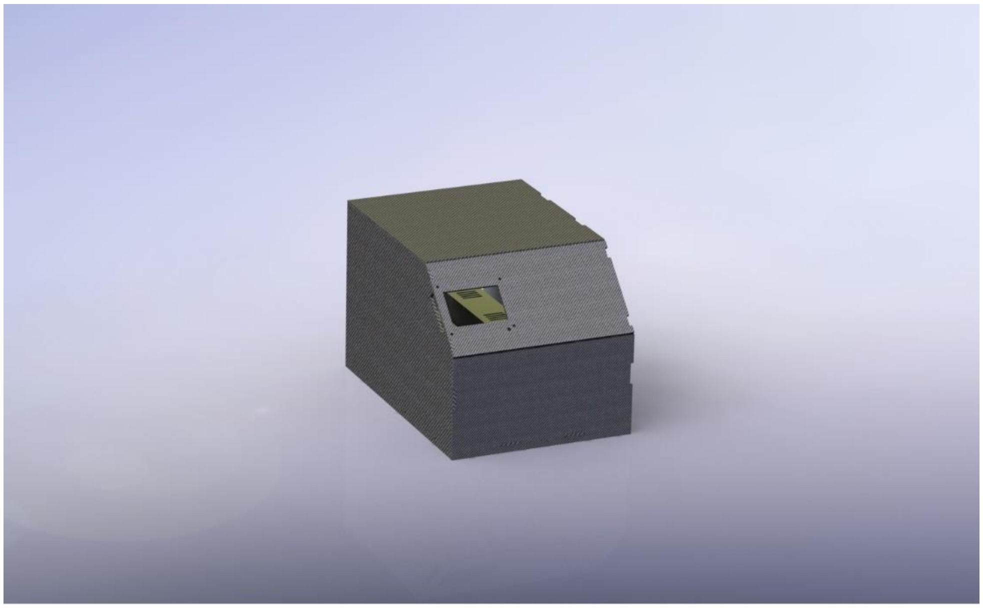

Figure 38. PSU box front view.

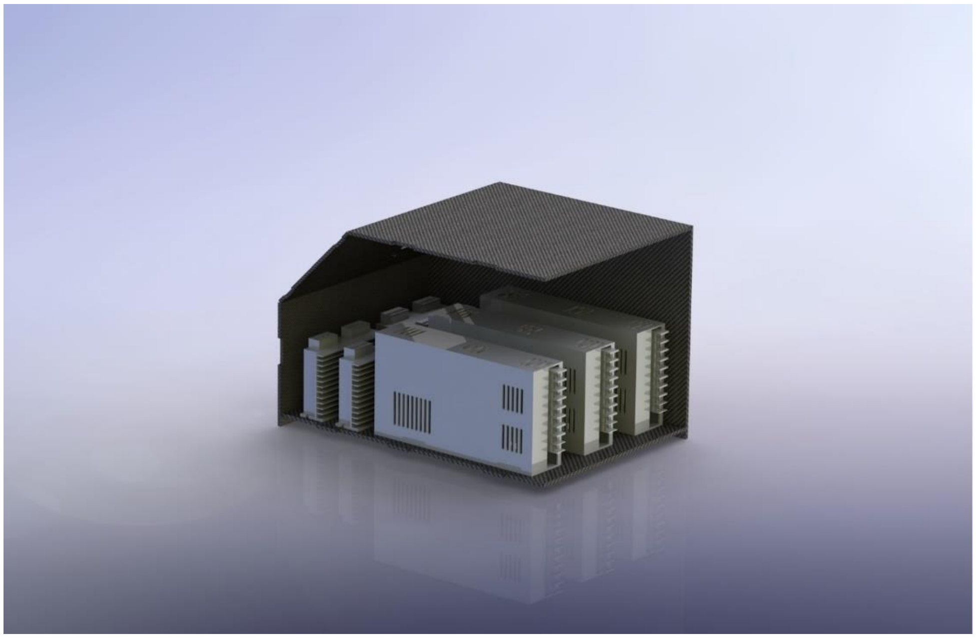

Figure 39. PSU box side view.

3.7 Budget

With the chosen design and components discussed above, the total cost for the machine is estimated to cost 1676 USD or about 13 500 NOK. This is an acceptable result in regards of the budget target of 13 000 NOK. The full parts list and cost with shipping can be seen in Appendix E.

4 HSE

ISO 45001 - Occupational Health & Safety

The HSE-analysis is done according to the PDCA-principle presented in ISO 45001 [20]. The Plan - Do - Check - Act cycle is an iterative process that can be implemented in management systems to minimize the risk of accidents and unwanted events as follows:

- Plan: Determine and assess the different OH&S risks and establish OH&S objectives and processes to deliver the wanted results.

- Do: Implement the planned processes.

- Check: Monitor processes and activities according to OH&S policies and report results.

- Act: Take necessary actions to improve processes as needed

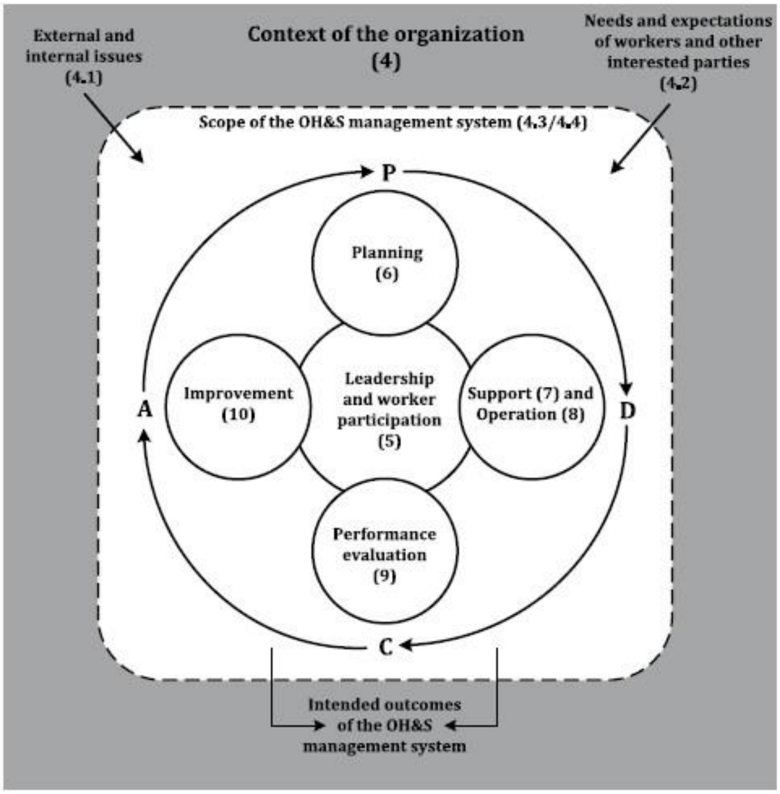

Figure 40. PDCA cycle.

4.1 Identifying potential Hazards and risks

Identifying potential risks and hazards will be done separately for the three functions.

CNC

- Rotating equipment;
- Contact with revolving cutter
- Jackets, gloves etc can be entangled in the machine
- Trapping fingers between moving parts and frame/workpiece
- Burn skin or clothes on hot metal/tool
- Inhaling dust/particles from milling operation
- Work pieces, broken cutting tools, swarf etc can be violently ejected from the milling machine
- Damage due to tool crashing in workpiece/frame

3D-printing

- Burn skin or clothes on hot equipment
- Trapping fingers between moving parts and frame/workpiece
- Inhaling toxic fumes from certain filaments
- Damage due to tool crashing in workpiece/frame

Laser engraving/Cutting

- Eye or skin damage from class 4 445nm laser beam
- Trapping fingers between moving parts and frame/workpiece
- Inhaling toxic fumes
- Damage due to tool crashing in workpiece/frame
- Fire hazard

Risk assesment CNC function

Activity	Potential hazard	Probability (1-5)	Consequence (A-E)				Risk Value	Comments/Actions
			Human	Environment	Economical/Material	Reputation/External		
CNC-Milling/Routing	Contact with revolving cutter	1	C	A	A	A	C1	- Proper instruction/training how to use the machine - Keep hands out of work area while running
	Entangle gloves, jacket etc in rotating equipment	2	C	A	D	A	C2	- Proper instruction/training how to use the machine - Keep hands out of work area while running
	Trapping fingers between moving parts and frame/workpiece	2	C	A	A	A	C2	- Keep hands out of work area while running
	Burn skin or clothes on hot metal/tool	2	B	A	A	A	B2	- Use heat resistant gloves or wait until workpice/tool has cooled down before touching
	Inhaling dust/particles from milling operation	3	C	A	A	C	C3	- Ensure good ventilation, especially when milling wood/plastic
	Work pieces, broken cutting tools, chips etc can be violently ejected from the milling machine	2	B	B	A	A	B2	- Secure protective screens before running
	Damage due to tool crashing in workpiece/frame	2	A	A	C	A	C2	- Ensure correct program is used - Proper instruction/training

Probability
1. Very low
2. Low
3. Medium
4. High
5. Very high

Consequence
A. Very low
B. Low
C. Medium
D. High
E. Very high

Risk assesment 3D-printing function

Activity	Potential hazard	Probability (1-5)	Consequence (A-E)				Risk Value	Comments/Actions
			Human	Environment	Economical/Material	Reputation/External		
3D-printing	Burn skin or clothes on hot equipment	3	B	A	A	A	B3	- Proper instruction/training how to use the machine - Keep hands out of work area while running
	Trapping fingers between moving parts and frame/workpiece	1	B	A	A	A	B1	- Keep hands out of work area while running
	Inhaling toxic fumes from certain filaments	3	C	B	A	C	C3	- Ensure good ventilation, especially when printing materials that emits potentially dangerous fumes
	Damage due to tool crashing in workpiece/frame	1	A	A	C	A	C1	- Ensure correct program is used - Proper instruction/training

Probability

1. Very low
2. Low
3. Medium
4. High
5. Very high

Consequence

A. Very low
B. Low
C. Medium
D. High
E. Very high

Risk assesment laser function

Activity	Potential hazard	Probability (1-5)	Consequence (A-E)				Risk Value	Comments/Actions
			Human	Environment	Economical/Material	Reputation/External		
Laser engraving/cutting	Eye or skin damage from class-4 445nm laser beam	1	C	A	A	A	C1	- Proper instruction/training how to use the machine - Keep hands out of work area while running - Use protective glasses when laser is on
	Trapping fingers between moving parts and frame/workpiece	1	B	A	A	A	B1	- Keep hands out of work area while running
	Inhaling toxic fumes	3	C	B	A	C	C3	- Ensure good ventilation, especially when engraving/cutting materials that emits potentially dangerous fumes
	Damage due to tool crashing in workpiece/frame	1	A	A	C	A	C1	- Ensure correct program is used - Proper instruction/training
	Fire hazard	2	B	A	C	C	C2	- Ensure correct program is used - Only engrave/cut appropriate materials - Ensure good ventilation - Have fire suppressing system available

Probability
1. Very low
2. Low
3. Medium
4. High
5. Very high

Consequence

A. Very low
B. Low
C. Medium
D. High
E. Very high

5 Testing

The test phase will be divided in three categories, one for each function of the machine. In each category there will be described simple tests to assess the quality of the work produced by the machine, and the results will be discussed in the Results chapter. The discussion will include how the measured results compared to expected values of the machine.

5.1 Milling

The main purpose of the milling function is engraving, in wood or plastics. The first test will be engraving a standard nameplate in wood. Here CamBam is used to generate the g-code file needed for the controller to execute the right toolpath.

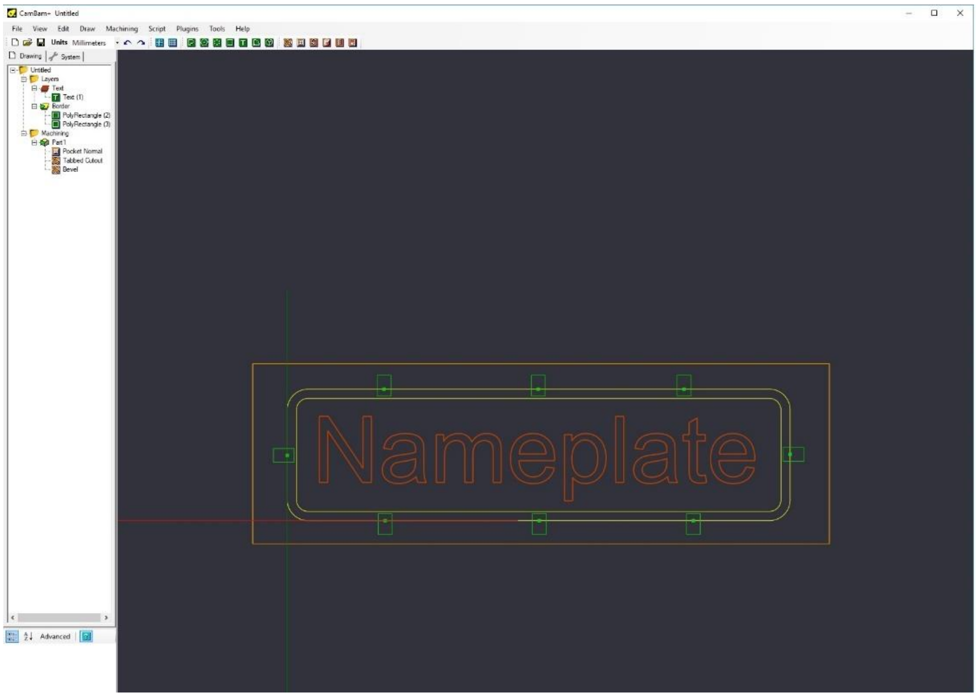

Figure 41. Example of CamBam.

As a second test the machine will produce the same nameplate, but in aluminum. This will test the rigidity and accuracy under higher loads than with wood or plastics. For both tests it is measured if the cuts are according to the CAD file that was used as input.

5.2 Additive production

To test the 3D printer the machine must first be calibrated. The X- and Y-axis are calibrated using the end stop switches, and Z-axis using the proximity switch. The Z-axis calibration is visually inspected as well to ensure it is correct. The heated bed should already be level, but four measurements are made, one in each corner to verify that it is. If it is not level, this can be compensated for, either in software or by manually levelling the bed via the attachment screws.

The print test will be printed in PLA, which means the heat bed will be set to 40-50 degrees Celsius, and the hot end to 190 degrees.

The print file is a small boat designed by Creative Tools, and is an open free-to-use test file specifically designed to test the different parameters of the 3D-printer.

It can be downloaded from Thingiverse [21].

Figure 42. Example of test print.

The boat contains overhangs, corners and small details designed to push any 3D printer, and is a suitable test object to get the printer properly calibrated, and evaluate results.

5.3 Laser engraving

The main purpose for the laser engraving function is to engrave pictures/designs on wood and some plastics.

Therefore, the testing of this function will be to see if sufficient resolution and quality can be achieved, when engraving on wood. However, a 2.5W laser should also be able to cut thin plastics, cardboard etc. A test will be run to cut cardboard, and a 4mm plastic plate, however the latter will likely be pushing the limits for the laser, and will require multiple passes.

Figure 43. Laser engraver test image 1.

As seen in figure 40 the first test image will be a map of Norway, with the text ''Norway'' besides it. This image includes a lot of contours and tight corners in the map, and also some text to see how well the laser performs in both areas.

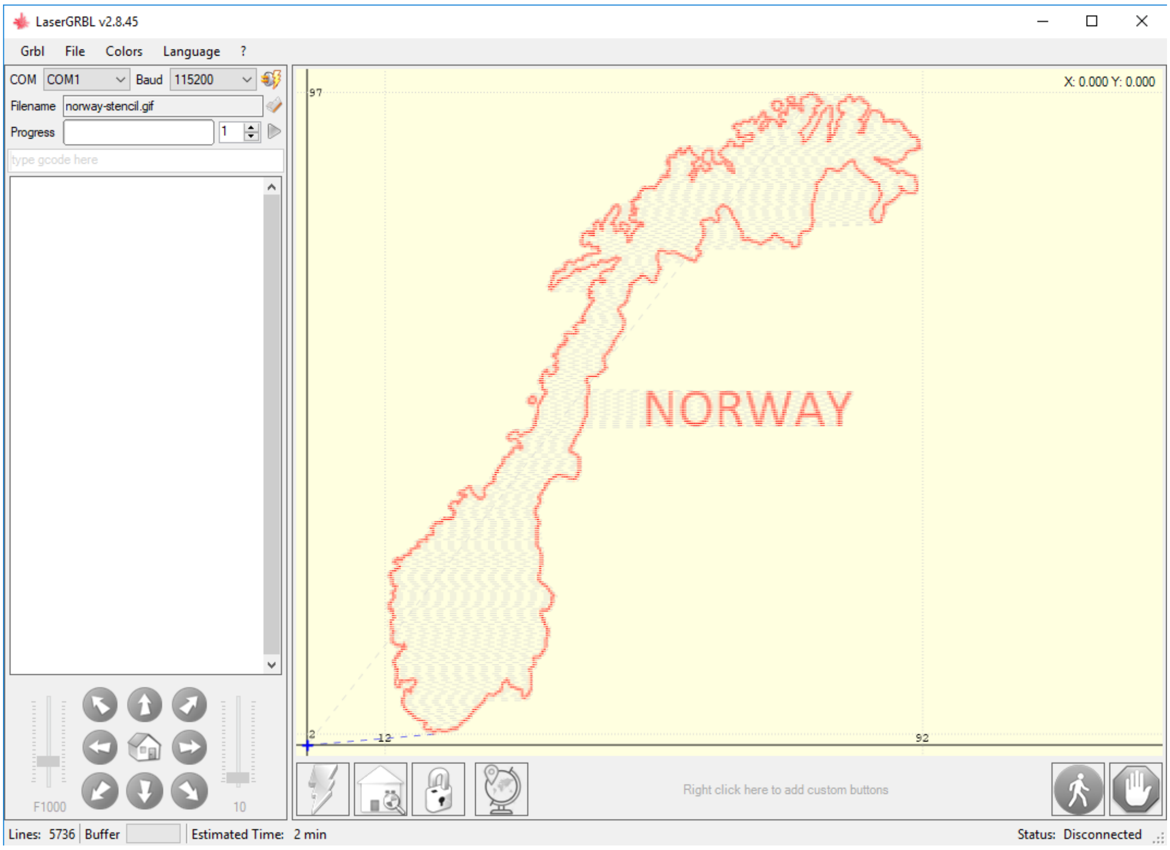

Figure 44. Test image 1 compiled in LaserGRBL.

The test image is compiled in LaserGRBL, and converted to G-code which the Arduino can read and translate to motor movement and laser power.

The laser is powered through TTL modulation, which means the power output from the laser can be adjusted in steps from 0 to 255. In the first test the laser will utilize the M4 command to power the laser as needed when engraving.

Parameters for test image:

- Image size: H=105mm W=100mm
- Engraving direction = horizontal
- Resolution = 3 lines/mm
- Engraving speed = 16.66 mm/s

The second test is to engrave a picture. This test will require to fully use the power modulation of the laser since it's not just black lines.

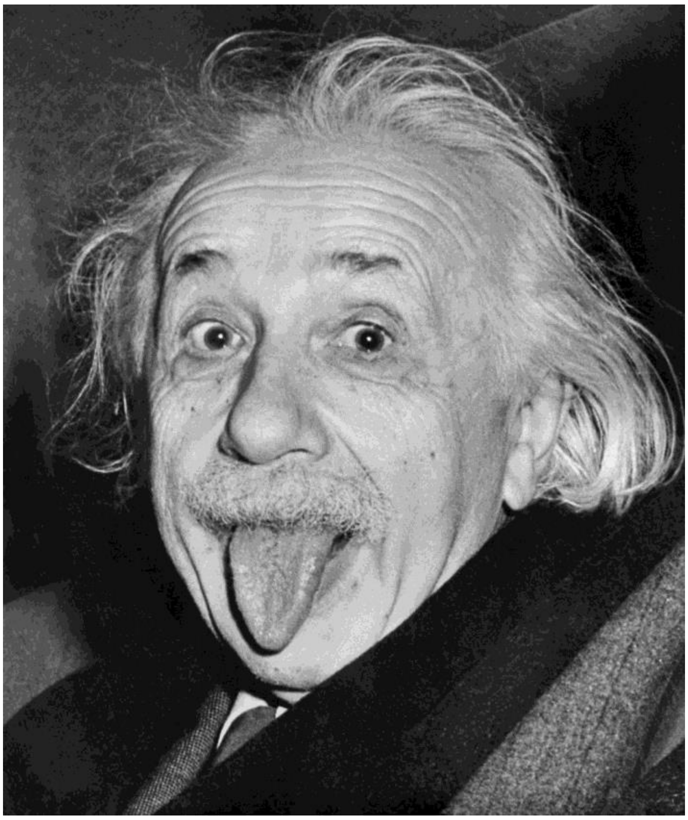

Figure 45. Laser engraving test image 2.

For the image test a picture of Einstein is chosen. This picture will require the laser to engrave grayscale, as opposed to just black and white.

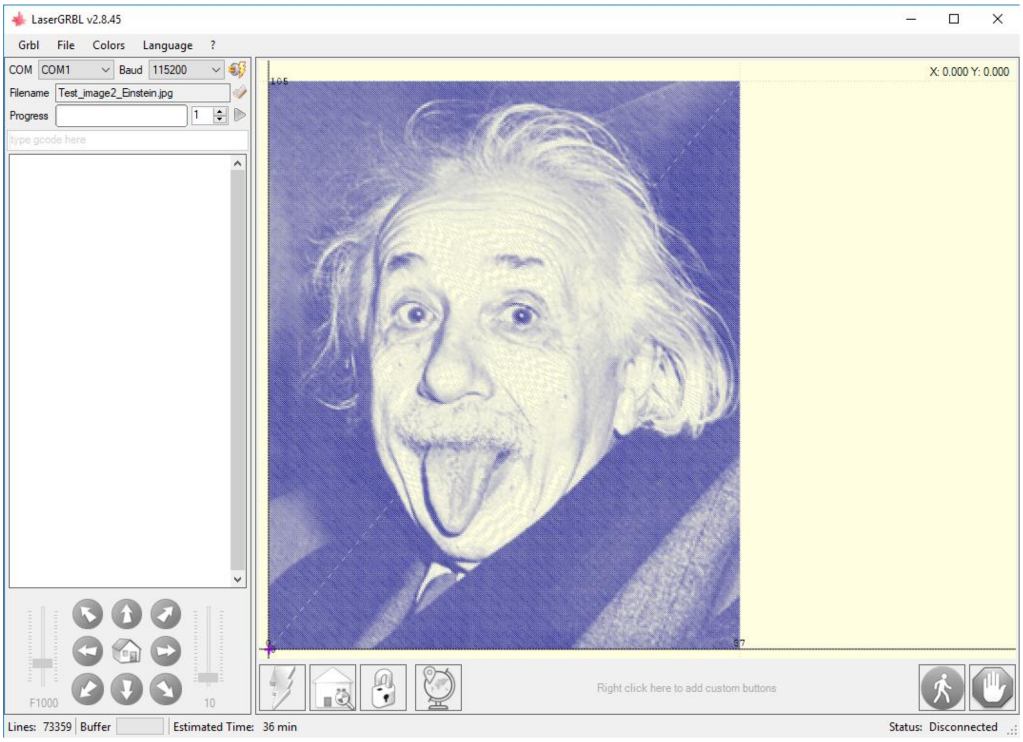

Figure 46. Test image 2 compiled in LaserGRBL.

As seen in figure 43 the image is processed and ready to send to the engraver. Contrast and brightness has been slightly adjusted up to increase quality of finished product.

Test parameters for image_02:

- Image size: H=87mm W=105mm
- Engraving direction = diagonal
- Resolution = 3 lines/mm
- Engraving speed = 16.66 mm/s

5.4 Accuracy

To test the accuracy and repeatability of the machine a dial gauge can be mounted on the worktable, and the tool positioned besides it. The tool is then moved 150mm away from the gauge and back again multiple times and we can see if the dial gauge displays the same distance from the tool each time. This can be repeated for all three axes.

6 Results

Some of the tests have been completed and the results will be displayed and discussed in this chapter.

*Notes: During the testing and setup of the machine, it was early discovered that one of the motors did not run as it should. It malfunctioned and would seemingly random drive at a slower speed than it should, and the fault was traced to one of the stepper motor drivers. As the time for delivery on these parts are very long, it was not possible to order a new one in time. The solution to this was to run the two stepper motors in the Z-axis on the same driver, which means they would each get a maximum of 2.1A each, instead of 3A as they should. Therefore, they will have less torque than what is calculated earlier in the report. They can however complete the testing with slower acceleration rates than what was originally dimensioned for. This allowed for some testing to be done.

Sadly, after completing a few test prints with the 3D-printer, and in the middle of the first run with the laser, the motor coupling on the X-axis broke. The coupling on the X and Y-axis are of a flexible type to allow for small misalignment errors if they should occur, while the coupling on the Z-axis are solid couplers and not interchangeable with X and Y. Both couplers on the X and Y-axis are rated for torque up to 3.2 Nm and should have no problem withstanding the forces involved during testing, which was done with conservative accelerations and speeds. However, this occurred in the first test run with the laser engraver, and before any testing with the CNC function had started. Due to this the milling and accuracy tests will have to be postponed until the manufacturer can replace the part, and thus not included here.

Figure 47. Broken motor coupling.

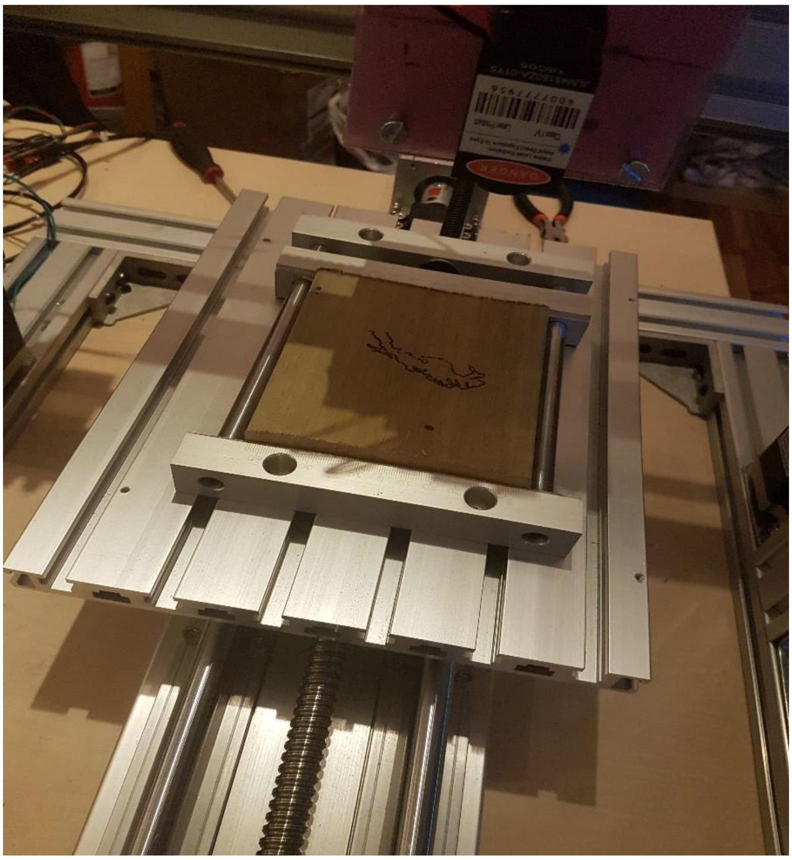

Figure 48. The CNC machine working with laser engraving.

6.1 Additive production

The printer has been calibrated and tested with the following parameters:

- Printing speed: 50mm/s
- Printing material: PLA
- Nozzle temperature: 190°C
- Bed temperature: 45 °C
- Layer height: 0.1mm

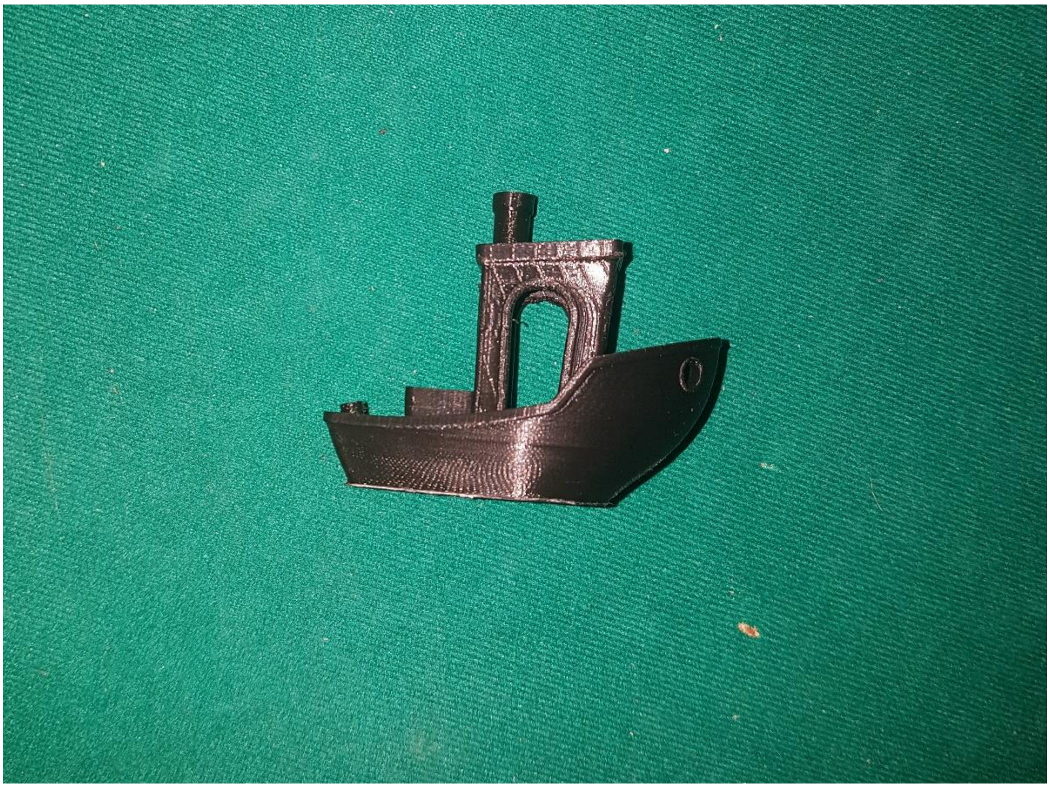

Figure 49. Finished test print.

As seen from figure 49 the finished part came out good, with all corners sharp and no deformations due to warping in overhangs. When printing with PLA, the finished part will shrink a bit due to temperature changes, and this must be compensated for in the CAD process. This is especially important when printing tight fittings, holes etc. The finished part has the correct dimensions, and nice flat surfaces.

6.2 Laser engraving

The laser engraving test was not completed, but did complete about one third of the first test image before the motor coupling failed.

A piece of wood was secured on the worktable using the clamp. It was positioned in the middle of the work area, and the laser is set to display the outlining square of the picture frame using only a few percent of the available power. It is then possible to visually confirm that the picture is aligned and within the engraving piece before starting engraving.

Figure 50. First test run with the laser.

The engraving seen in figure 50 was done with the following parameters for the machine:

- Maximum output by the laser: 40%.
- Engraving speed: 1500mm/min
- Maximum acceleration rate: 300mm/s^2
- Image size: 100xmm x x98mm
- Engraving height: 120mm
- Focus: Manually adjusted on the laser

As mentioned above this was the very first test run with the laser, and the test parameters was set to what was assumed to be reasonable values from where to start optimizing. It is therefore likely one or more of the parameters can be optimized for an even better result, as it was planned before the motor coupling broke.

6.3 Suggested improvements

Since some of the testing have been postponed due to parts malfunctioning, one obvious improvement would be to better assure quality of components delivered by all manufacturers. Based on the testing which is completed, the design itself is seemingly performing as it should.

A feature which can be added is a form of active dust collection system for the milling function. When engraving or cutting with a CNC spindle a lot of dust is created and spread around the workspace. Even though the linear rails and motors are relatively protected, it would be an advantage to have a more effective dust collection. The same feature can also function as an exhaust system for gasses produced when 3D printing certain plastics, or using the laser engraver. In both scenarios the result would be a cleaner, safer workspace.

Another extension could be a Bluetooth or Wi-Fi module, to enable wireless communication. This way it is possible to start, for example, a long print and check the status on the machine via an app on your smartphone or tablet. It also enables you to upload files wirelessly.

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[18]	Capacitive proximity switch manufacturer. https://www.aliexpress.com/store/2953256
[19]	RepRap, 2018. List of Firmware. https://www.reprap.org/wiki/List_of_Firmware
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8 Appendix

8.1 Appendix A.

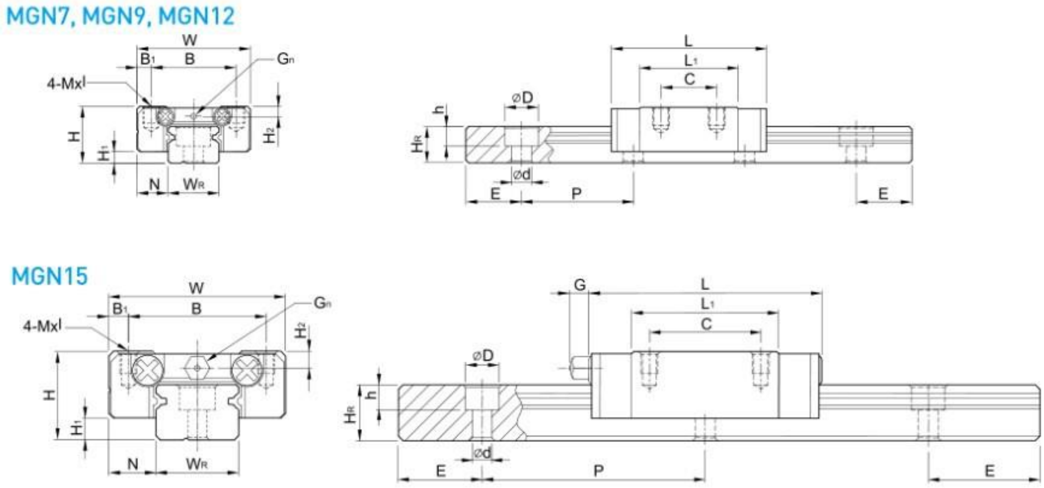


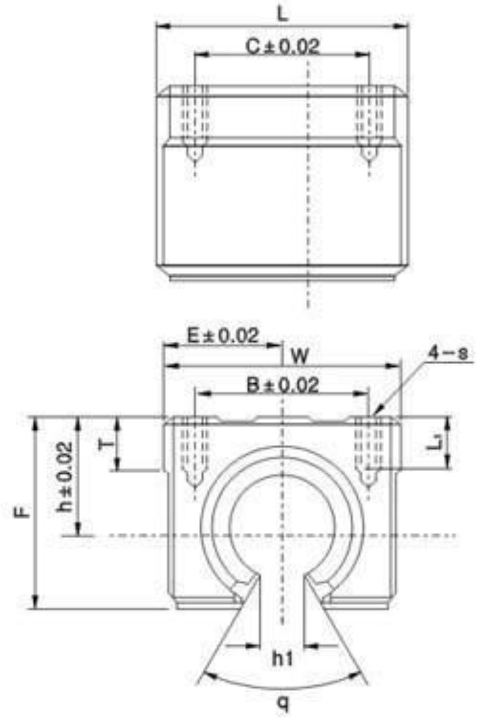
Figure 51. MGN15 linear rail machine drawing.

Model No.	Dimensions of Assembly (mm)			Dimensions of Block (mm)										Dimensions of Rail (mm)							Mounting Bolt for Rail	Basic Dynamic Load Rating	Basic Static Load Rating	Static Rated Moment			Weight	
	H	H_1	N	W	B	B_1	C	L_1	L	G	G_N	Mxl	H_2	W_R	H_R	D	h	d	P	E	(mm)	C(kN)	C_0(kN)	M_R N-m	M_P N-m	M_Y N-m	Block kg	Rail kg/m
MGN5C	6	1.5	3.5	12	8	2	-	9.6	16	-	Ø0.8	M2x1.5	1	5	3.6	3.6	0.8	2.4	15	5	M2x6	0.54	0.84	2	1.3	1.3	0.008	0.15
MGN7C	8	1.5	5	17	12	2.5	8	13.5	22.5	-	Ø1.2	M2x2.5	1.5	7	4.8	4.2	2.3	2.4	15	5	M2x6	0.98	1.24	4.70	2.84	2.84	0.010	0.22
MGN7H							13	21.8	30.8													1.37	1.96	7.64	4.80	4.80	0.015	
MGN9C	10	2	5.5	20	15	2.5	10	18.9	28.9	-	Ø1.4	M3x3	1.8	9	6.5	6	3.5	3.5	20	7.5	M3x8	1.86	2.55	11.76	7.35	7.35	0.016	0.38
MGN9H							16	29.9	39.9													2.55	4.02	19.60	18.62	18.62	0.026	
MGN12C	13	3	7.5	27	20	3.5	15	21.7	34.7	-	Ø2	M3x3.5	2.5	12	8	6	4.5	3.5	25	10	M3x8	2.84	3.92	25.48	13.72	13.72	0.034	0.65
MGN12H							20	32.4	45.4													3.72	5.88	38.22	36.26	36.26	0.054	
MGN15C	16	4	8.5	32	25	3.5	20	26.7	42.1	4.5	M3	M3x4	3	15	10	6	4.5	3.5	40	15	M3x10	4.61	5.59	45.08	21.56	21.56	0.059	1.06
MGN15H							25	43.4	58.8													6.37	9.11	73.50	57.82	57.82	0.092	

Note : 1 kgf = 9.81 N

Figure 52. MGN15 Linear rail datasheet.

8.2 Appendix B.



Unit Type	Dimensions (mm)												Slide bush			Weight (kg/m)
	h	E	W	L	F	h1	q	B	C	S	L_1	T	Type	Basic load rating Dynamic C(kgf)	Basic load rating Static Co(kgf)	
SBR 10UU	15	18	36	32	24	6	80°	25	20	M5	10	7	LM10UU-OP	372	549	65
SBR13UU	17	20	40	39	27.6	8.5	80°	28	28	M5	10	8	LM13UU-OP	510	784	100
SBR 16UU	20	22.5	45	45	33	10	80°	32	30	M5	12	9	LM16UU-OP	774	1180	150
SBR 20UU	23	24	48	50	39	10	60°	35	35	M6	12	11	LM20UU-OP	882	1370	200
SBR 25UU	27	30	60	65	47	11.5	50°	40	40	M6	12	14	LM25UU-OP	980	1570	450
SBR 30UU	33	35	70	70	56	14	50°	50	50	M8	18	15	LM30UU-OP	1570	2740	630
SBR 35UU	37	40	80	80	63	16	50°	55	55	M8	18	18	LM35UU-OP	1670	3140	925
SBR 40UU	42	45	90	90	72	19	50°	65	65	M10	20	20	LM40UU-OP	2160	4020	1330
SBR 50UU	53	60	120	110	92	23	50°	80	80	M10	20	25	LM50UU-OP	3820	7940	3000
SBR 16LUU	20	22.5	45	85	33	10	80°	60	60	M5	12	9	LM16UU-OP	1548	2360	300
SBR 20LUU	23	24	48	96	39	10	60°	70	70	M6	12	11	LM20UU-OP	1764	2740	400
SBR 25LUU	27	30	60	130	47	11.5	50°	100	100	M6	12	14	LM25UU-OP	1960	3140	900
SBR 30LUU	33	35	70	140	56	14	50°	110	110	M8	18	15	LM30UU-OP	3140	5480	1260
SBR 40LUU	42	45	90	175	72	19	50°	180	180	M10	20	20	LM40UU-OP	4320	8040	2660

Figure 53. SBR16 Datasheet.

8.3 Appendix C.

Unit: μm

Accuracy grades		C0		C1		C2		C3		C5		C7	C8	C10
		Precision Ball Screw										Rolled Ball Screw		
Effective thread length														
Above	Or less	Representative travel distance error	Fluctuation	Representative travel distance error	Fluctuation	Representative travel distance error	Fluctuation	Representative travel distance error	Fluctuation	Representative travel distance error	Fluctuation	Travel distance error	Travel distance error	Travel distance error
—	100	3	3	3.5	5	5	7	8	8	18	18	±50/ 300mm	±100/ 300mm	±210/ 300mm
100	200	3.5	3	4.5	5	7	7	10	8	20	18			
200	315	4	3.5	6	5	8	7	12	8	23	18			
315	400	5	3.5	7	5	9	7	13	10	25	20			
400	500	6	4	8	5	10	7	15	10	27	20			
500	630	6	4	9	6	11	8	16	12	30	23			
630	800	7	5	10	7	13	9	18	13	35	25			
800	1000	8	6	11	8	15	10	21	15	40	27			
1000	1250	9	6	13	9	18	11	24	16	46	30			
1250	1600	11	7	15	10	21	13	29	18	54	35			
1600	2000	—	—	18	11	25	15	35	21	65	40			
2000	2500	—	—	22	13	30	18	41	24	77	46			
2500	3150	—	—	26	15	36	21	50	29	93	54			
3150	4000	—	—	30	18	44	25	60	35	115	65			
4000	5000	—	—	—	—	52	30	72	41	140	77			
5000	6300	—	—	—	—	65	36	90	50	170	93			
6300	8000	—	—	—	—	—	—	110	60	210	115			
8000	10000	—	—	—	—	—	—	—	—	260	140			

Note) Unit of effective thread length: mm

Fluctuation in Thread Length of 300 mm and in One Revolution (permissible value) Unit: μm

Accuracy grades	C0	C1	C2	C3	C5	C7	C8	C10
Fluctuation/300	3.5	5	7	8	18	—	—	—
Fluctuation/2π	3	4	5	6	8	—	—	—

Types and Grades

Type	Series symbol	Grade	Remarks
For positioning	Cp	1, 3, 5	ISO compliant
For transport	Ct	1, 3, 5, 7, 10	

Figure 54. Ball screw accuracy properties.

8.4 Appendix D.

GCode

Comm.	Parameters	Description	Example
G0	Axis [X/Y/Z] Position	Rapid Movement	G0 X50
G1	Axis [X/Y/Z/E] Position Feed [F]	Controlled Movement	G1 F150 X10
G4	Time in ms [P]	Dwell / Wait	G4 P500
G20	none	Set units to inch	G20
G21	none	Set units to mm	G21
G28	<Axis [X/Y/Z]>	Home	G28 X Y
G90	none	Absolute Positioning	G90
G91	none	Relative Positioning	G91
G92	Axis [X/Y/Z/E] Value	Set Position to value	G92 X5 Y10

Comm.	Parameters	Description	Example
M0	none	Stops everything after buffer is empty	M0
M17	none	Enable all stepper motors	M17
M18	none	Disable all stepper motors (move freely)	M18
M20	none	List files at the root folder of the SD Card	M20
M21	none	Initialise (mount) SD Card	M21
M22	none	Release (unmount) SD Card	M22
M23	Filename	Select File for Printing	M23 print.gco
M24	none	Start / Resume SD Card Print (see M23)	M24
M25	none	Pause SD Card Print (see M24)	M25
M26	Bytes[S]	Set SD Position in bytes	M26 S12345
M27	none	Report SD Print status	M27
M28	Filename	Write programm to SD Card	M28 print.gco
M29	Filename	Stop writing programm to SD Card	M29 print.gco
M40	none	Eject part (if possible)	M40
M41	none	Loop Programm(Stop with reset button!)	M41
M42	none	Stop if out of material (if supported)	M42
M43	none	Like M42 but leave heated bed on (if supported)	M43
M80	none	Turn on ATX Power (if neccessary)	M80
M81	none	Turn off ATX Power (if neccessary)	M81
M84	none	Stop idle hold (DO NOT use while printing!)	M84
M92	Steps_per_unit[X]	Programm set S steps per unit (resets)	M92 X123
M101	none	Set extruder 1 to forward (outdated)	M101
M102	none	Set extruder 1 to reverse (outdated)	M102
M103	none	Turn all extruders off (outdated)	M103
M104	Temperature[S]	Set extruder temperature (not waiting)	M104 S100
M105	none	Get extruder Temperature	M105
M106	<PWM Value[S 0-255]>	Set Fan Speed to S and start	M106 S123
M107	none	Turn Fan off	M107
M108	none	Set extruder speed (outdated)	M108
M109	Temperature[S]	Set extruder Temperature (waits till reached)	M109 S123
M110	Line Number[N]	Set current line number (next line number = line no. +1)	N123 M110
M111	Debug Level [S]	Set Debug Level	M111 S6
M112	none	Emergency Stop (Stop immediately)	M112
M113	<PWM [S]>	Set Extruder PWM to S (or onboard potent. If not given)	M113 S0.7
M114	none	Get Current Position	M114
M115	none	Get Firmeware Version and Capabilities	M115
M116	none	Wait for ALL temperatures	M116
M117	none	Get Zero Position in steps	M117
M119	none	Get Endstop Status	M119
M126	Time[P]	Open extruder valve (if available) and wait for P ms	M126 P500
M127	Time[P]	Close extruder valve (if available) and wait for P ms	M127 P500
M128	PWM[S]	Set internal extruder pressure S255 eq max	M128 S123
M129	Time[P]	Turn off extruder pressure and wait for P ms	M129 P500
M140	Degrees[S]	Set heated bed temperature to S (not waiting)	M140 S55
M141	Degrees[S]	Set chamber temperature to S (not waiting)	M141 S30
M142	Pressure[S]	Set holding pressure to S bar	M142 S1

M143	Degrees[S]	Set maximum hot-end temperture	M143 S275
M160	No.[S]	Set number of materials extruder can handle	M160 S4
M203	Offset[Z]	Set Z offset (stays active even after power off)	M203 Z-0.1
M226	none	Pauses printing (like pause button)	M226
M227	Steps[P/S]	Enables Automatic Reverse and Prime	M227 P1500 S1500
M228	none	Disables Automatic Reverse and Prime	M228
M229	Rotations[P/S]	Enables Automatic Reverse and Prime	M229 P1.0 S1.0
M230	[S]	Enable / Disable wait for temp.(1 = Disable 0 = Enable)	M230 S1
M240	none	Start conveyor belt motor	M240
M241	none	Stop conveyor belt motor	M241
M245	none	Start cooler fan	M245
M246	none	Stop cooler fan	M246
M300	Freq.[S] Duration[P]	Beep with S Hz for P ms	M300 S300 P1000
T	No.	Select extruder no. (starts with 0)	T1

8.5 Appendix E.

Table 10. Parts list.

Item	Quantity	Price(USD)	Total (USD)
Y-Axis table	1	160	160
Z-Axis Ball screw kit with linear guides	2	80	160
X-Axis, Ball screw	1	38	38
X-Axis, Linear Guide	2	24,5	49
PSU 350w, 36V. 2 Pcs	1	32	32
Shipping BST AUTO	1	240	240
Aluminum Profiles	1	85	85
Nema 23 425Oz-inch. 2Pcs	1	125	125
Nema 23 270Oz-inch. 2Pcs	1	98	98
CNC spindle 1.5 kW ER11, Inverter.	1	260	260
CNC milling tool. 4mm & 6mm	1	4,61	4,61
CNC Fixture clamp	1	50	50
CNC Tabletop. 20240 Aluminum	1	75	75
2.5W Laser module + Driver board	1	46	46
			0
PSU 12V	1	23,15	23,15

Controller board, Screen, Heat-bed	1	39,6	39,6
Glass plate Heat-bed. 21x20x0.3	1	9,7	9,7
Mk8 dual extruder bracket	1	3,2	3,2
Mk8 Dual extruder set	1	33,6	33,6
			0
Proximity sensor	3	4,7	14,1
Corner Bracket 3060 10 pcs	1	13,11	13,11
T Block sliding nut for 3030. M5 100 pcs	1	18,74	18,74
M5 x 10mm. 50 Pcs	1	7	7
Joint board plate corner angle 3030L7	1	5,33	5,33
Joint board plate corner angle 3030L7	1	5,36	5,36
Joint board plate corner angle 3030L7	1	5,25	5,25
Joint board plate corner angle 3030L7	1	5,46	5,46
Linear guide cover	1	25	25
Carbon fiber Vinyl sticker	1	4,6	4,6
Screw set. M3-M5	1	11	11
Assorted mounting brackets, screws etc.	1	30	30
Total sum			**1676,81**