

Abstract

The goal of this project is to design and build a prototype of recoating system for a laser cutting machine to turn it into a selective laser sintering printing machine. This prototype will be used to study new sintering materials and to design, if decided, a SLS 3D printing Machine (Selective Laser Sintering). This project has been developed in the installations and funded by *Fundació CIM*.

The project develops the mechanical design and the electronic system design. Both parts are explained on this paper, so new users can use the machine and can understand the system. With this paper, it is expected that it can be improved in a future to test other parameters and configurations.

The paper is divided in three basic blocks that are summed up here:

The first block is an introduction to the 3D printing technologies. The most used of them are explained and selective laser sintering is explained in deep. With this block the reader can understand why it is important to develop the SLS technology and what has to be done to improve the machines and the technology.

The second block is a discussion on the mechanical design of the machine. The general idea of the machine is explained so the user can understand why the machine is designed in this way. After that, each part is detailed to see how the different mechanical challenges were overcome. At the end of the block, there is a small calculations section needed on the electronic part.

The third block is an extensive explanation of the electronic system that controls and moves the machine. In that block, the different components are explained so the user can understand its basic working principles. It is also explained how the selection of the electronic components was done. Then everything is put together to see the whole electronic system.

Along with this paper, there are annexes that provide some extra information for the reader. One of these annexes refers to the mechanical part and the other one has some datasheets and coding for the electronic section.

The whole design has been done in SOLIDWORKS cad software and its electric extension ELECWORKS. The programming job was done with Arduino compiler.

Summary

ABSTRACT	1
SUMMARY	3
FIGURES SUMMARY	6
TABLE SUMMARY	12
1. INTRODUCTION	13
1.1. Project target	13
1.2. Project scope	13
2. PREFACE	15
2.1. Projects origin	15
2.2. Motivation	15
2.3. Previous requirements	16
3. STATE OF THE ART	17
3.1. 3D printing	17
3.1.1. General printing process	17
3.1.2. Fused deposition modeling (FDM)	18
3.1.3. Stereolithography (SLA)	19
3.1.4. Digital light processing (DLP)	20
3.1.5. Powder bed and inkjet head 3D printing (3DP)	20
3.1.6. Selective laser melting SLM	21
3.1.7. Selective heat sintering (SHS)	21
3.1.8. Laminated object manufacturing (LOM)	22
3.2. Selective laser sintering (SLS)	22
3.2.1. Printing process	22
3.2.2. Machine design	24
3.2.3. Sintering materials	26
3.3. Technology readiness level (TRL)	26
4. OVERALL LOOK AT THE DESIGN	29
5. RECOATER SYSTEM	32
5.1. Mechanics	33
5.1.1. Spreading system	36
5.1.1.1. Carriage selection	36
5.1.1.2. Carriage Working Principles	37

5.1.1.3. Carriage general design concepts.....	38
5.1.1.4. Part by part breakdown	40
5.1.2. Powder platforms system.....	63
5.1.2.1. Platforms selection.....	64
5.1.2.2. Platforms Working Principles.....	65
5.1.2.3. Platforms general design concepts	66
5.1.2.4. Part by part breakdown	68
5.2. Mechanical calculations	98
5.2.1. Recoating system	98
5.2.2. Platforms system	100
5.3. Electronics	103
5.3.1. Hardware	103
5.3.1.1. Stepper motors.....	103
5.3.1.2. Motor drivers	108
5.3.1.3. Endstops	110
5.3.1.3. Microcontroller.....	112
5.3.1.4. Electronic-electric circuit.....	113
5.3.2. Firmware.....	123
5.3.2.1. User interaction and working modes	123
5.3.2.2. Overall code scheme.....	124
5.3.2.3. Variable declaration.....	125
5.3.2.4. Set up and function invocation	128
5.3.2.5. Function description	129
5.3.3. Testing.....	132
5.3.3.1. Drivers, motors and Arduino testing	133
5.3.3.2. Firmware testing.....	134
5.3.3.3. Machine testing	135
6. VALIDATION AND FUTURE STEPS	136
7. ENVIRONMENTAL IMPACT	138
8. COST ANALISYS	140
9. PROJECT MASTERPLAN	142

10. CONCLUSIONS	143
11. ACKNOWLEDGMENTS	144
12. BIBLIOGRAPHY	145

Figures summary

Figure 1 FDM process illustration and BCN3D+ printer.....	18
Figure 2 SLA process schematic.....	19
Figure 3 DLP Printing process.....	20
Figure 4 3DP printing illustration.....	21
Figure 5 LOM Process schematic	22
Figure 6 Layering process.....	23
Figure 7 Part extraction	23
Figure 8 Technology readiness level.....	27
Figure 9 TRL analysis result.....	28
Figure 10 Laser cutting machine	29
Figure 11 3D CAD of the complete machine	29
Figure 12 Recoater system	32
Figure 13 Principal views	33
Figure 14 Spreading system highlighted	36
Figure 15 Spreading System principal views.....	37
Figure 16 Carriage and guides top view.....	38
Figure 17 Zero position on the left, maximum position on the right.....	38
Figure 18 Tensile elements in extreme positions.....	39
Figure 19 Highlighted parts	40
Figure 20 Cylinder.....	41
Figure 21 Principal views and Dimetric view	42
Figure 22 Cylinder's production drawing	42

Figure 23 Highlighted parts	43
Figure 23 Principal views and Dimetric view.....	43
Figure 25 Highlighted parts	44
Figure 26 Clamp view.....	44
Figure 26 Principal views and Dimetric view.....	45
Figure 28 Highlighted parts	46
Figure 28 Clips assembly	47
Figure 29 Clips view	47
Figure 31 Highlighted parts	48
Figure 31 Principal views and Dimetric view.....	48
Figure 32 Principal views and Dimetric view.....	48
Figure 34 Exploded carriage assembly	49
Figure 34 Carriage section view	49
Figure 36 Hilighted parts	50
Figure 36 Principal views and Dimetric view.....	50
Figure 38 Highlighted parts	51
Figure 38 Compacted and exploded pulley assembly.....	52
Figure 40 Highlighted parts	53
Figure 40 Tensile pulley compacted and exploded assembly.....	53
Figure 42 Highlighted parts	54
Figure 42 Principal views and Dimetric view.....	54
Figure 44 Highlighted parts	55
Figure 44 Principal views and Dimetric view.....	56

Figure 46 Highlighted parts	57
Figure 46 Compacted and exploded assembly views	58
Figure 48 Highlighted parts	59
Figure 49 Highlighted parts	60
Figure 50 Highlighted parts	61
Figure 50 Compacted and exploded assembly views	62
Figure 52 Platforms system highlighted.....	63
Figure 53 Single platform	65
Figure 54 Mechanical moving	66
Figure 55 Platforms on set up position	67
Figure 55 Full recoater assembly (left), laser machine's refference removed (right).....	68
Figure 56 From left to right: Base structure, Cubes and Platforms highlighted.....	68
Figure 58 Dimetric view	69
Figure 58 Principal views	69
Figure 60 Highlighted parts	70
Figure 60 Principal views and Dimetric view	70
Figure 62 Highlighted parts	71
Figure 62 Principal views and Dimetric view	72
Figure 64 Highlighted parts	73
Figure 64 Principal views and Dimetric view	74
Figure 66 Dimetric view.....	75
Figure 66 Principal views	75
Figure 68 Highlighted parts	76

Figure 68 Principal views and Dimetric view.....	77
Figure 70 Highlighted parts	78
Figure 70 Walls assembly	79
Figure 71 Lateral walls (edges)	79
Figure 72 Lateral Wall (middle one).....	79
Figure 74 Highlighted parts	80
Figure 74 Mounted container, principal and dimetric views	81
Figure 75 Exploded container assembly. Principal views	81
Figure 77 Highlighted parts	82
Figure 77 Principal views and Dimetric view.....	82
Figure 79 Highlighted parts	83
Figure 79 Mounted funnel assembly	84
Figure 80 Funnel joint principal views and Dimetric view.....	84
Figure 81 Exploded Funnel Assembly.....	84
Figure 82 Dimetric view	85
Figure 83 Principal views.....	85
Figure 85 Highlighted parts	86
Figure 85 Platform's sandwich assembly	87
Figure 86 Platform set exploded view.....	87
Figure 87 Platform sandwich assembly (PMMA profiles kept transparent).....	87
Figure 89 Highlighted parts	88
Figure 89 Principal views and Dimetric view.....	89
Figure 91 Highlighted parts	90

Figure 91 Principal views and Dimetric view	90
Figure 93 Highlighted parts	91
Figure 93 Part and screws	92
Figure 94 Dimetric view.....	92
Figure 95 Principal views	92
Figure 96 Highlighted parts	93
Figure 97 Principal views	94
Figure 98 Dimetric view (sectioned on the right).....	94
Figure 99 Part and screws, bearings,nuts, spring and endstop.....	94
Figure 100 Highlighted parts	95
Figure 101 Assembly view	95
Figure 102 Principal views	96
Figure 103 Dimetric view.....	96
Figure 105 Highlighted parts	97
Figure 105 Mechanical system.....	98
Figure 106 Simplified schematic.....	99
Figure 108 Threaded bar forces analysis	101
Figure 109 Stepper motor schematic	104
Figure 110 Torque – speed graph.....	107
Figure 111 Stepper motor driver waveform	108
Figure 112 Pololu DRV8825.....	109
Figure 113 Mechanical endstop	111
Figure 114 Optical endstop	111

Figure 115 Schematic 1	114
Figure 116 Schematic 2	115
Figure 117 Endstop circuit.....	117
Figure 118 Push buttons circuit.....	118
Figure 119 Pololu driver	118
Figure 120 Color code.....	119
Figure 121 Motor driver circuit.....	121
Figure 122 Stripboard.....	122
Figure 123 Gant diagram	142

Table summary

Table 1 General motor specifications	106
Table 2 Torques required	107
Table 3 Motor driver specs	109
Table 4 Arduino pins	112
Table 5 Motor driver wiring	119
Table 6 Microstepping modes	120
Table 7 Firmware variables	127
Table 8 Variables values	135
Table 9 Consumable equipment	140
Table 10 Non – expandable equipment.....	141
Table 11 Human resources	141

1. Introduction

1.1. Project target

The main target of the project is to design and build a recoater system, that can be attached to an existing laser cutting machine to turn it to a selective laser sintering (SLS) printing machine. As a secondary target and if it is possible in terms of time, some tests will be done to start the investigation on new SLS printing materials.

The machine will also have to fulfill some previous requirements that will be explained on future sections. These requirements are set as a result of the collaboration with *Fundació CIM*.

In personal terms, the target of the project is also to learn more about 3D printing, production of finished parts, cost analysis, mechanics and electronics. All this fields will be needed in this project so a big step forward on this knowledge should be achieved.

1.2. Project scope

The project scope can be divided in two kind of benefiteres depending on when are they are being benefited:

While developing the project:

BCN3D Technologies technologies and its related makers community will be benefited while the project is being developed. The *BCN3D Technologies* 3D printing technologies will be tested in their installations while manufacturing the different parts. This will result in an exchange of information between both teams.

However, the most important knowledge exchange will appear when testing the machine as it will result in some important specifications to build a future SLS machine.

After the project is done:

Once the project is developed, other users will benefit of it. The basic idea is that building this prototype will allow engineers to investigate with new sintering materials and techniques that will lower the price and the size of the SLS printing machines. The people who will be benefited will be:

- Engineers: As it was explained, they will have a new tool to develop a future low cost SLS machine.
- Fablab: Fabrication establishments will be able to acquire a SLS printer that is now too

expensive to buy and maintain. This will allow the people to build pieces with a high precision technology.

- Makers: This community is growing more and more every year. With cheap SLS technology they could experiment or even create an open source platform like RepRap fused filament printers. This would also make the technology to evolve faster.
- Home production: The reduced cost and size of a new SLS machine could make them to turn into smaller desktop versions. That would result in being able to have a SLS machine at home or at educational institutions.
- R&D companies: Companies that have a R&D department could build its prototypes with one of the fastest 3D printing technology with a reduced price per part.
- Small and medium-sized enterprises (SMEs): Small companies could afford a small and cheap SLS machine what would allow them to make a step forward on their designs and technology development.

As it has been seen, the scope of this project is really wide and with a huge variety of people involved.

2. Preface

2.1. Projects origin

When we were looking for a final year project topic we had in mind a project that allow us to create something physical as a result of the work done during the project. After spending some of our university years on competition teams that build a final product, we knew the huge motivation of creating something useful that could solve a real problem.

After some weeks thinking how we could do so, we contacted *Fundació CIM* to ask if they had any short term project. The answer was really positive and three projects were proposed to us. One related to stereolithography 3D printing, another about building an improvement for a laser engraving machine, and the last one about creating a prototype for testing different SLS 3D printing materials. The SLS project was finally chosen because it was the most feasible and appropriate for a final year project.

The research group had already done some tests with a handmade prototype that was attached to the same laser machine that is going to be used for this prototype. However, this prototype was moved by hand and it was not very precise. To solve this, our prototype had to be numerically controlled to allow testing the different materials in deep.

2.2. Motivation

There are two basic motivations when developing SLS printing. The first one is related with the 3D printing technologies and its advantages while the second one is more related with SLS technology itself.

3D rapid prototyping technologies are one of the best ways to have a real scale prototype of a part to check dimensional fit or design. Sometimes it is also the only way to build some parts, which have a difficult geometry, for a reasonable price. This is why 3D technologies are growing fast even at domestic level.

However, some of the technologies create parts that are not mechanically functional or dimensionally accurate. Between the technologies that provide a good dimensional precision and parts that can be mechanically functional, SLS is one of the most flexibles in terms of part dimension and material adaptability. Although its big advantages, the printing process needs some conditions that are difficult to achieve in small machines such as high temperature or inert atmosphere.

Because of this printing conditions, SLS machines are expensive and big, what makes them

impossible to be designed as a desktop machine. But now, some materials are being designed in a new way that will allow room temperature printing even without the existence of an inert atmosphere.

Designing a machine that can test this materials and provide information to the user is the main goal and motivation of this project. With this results, future engineers would be able to develop an optimized SLS machine that would see its price and size reduced.

2.3. Previous requirements

There are some requirements that the machine has to fulfill to make it cheap to build and to fit the existing equipment. This requirements are a consequence of the collaboration with *Fundació CIM* and have been an extra of difficulty when designing the machine. In general terms, though, this collaboration has helped us with the manufacturing of the machine by providing us with the last 3D printing technologies and components from other printers.

The requirements are:

- **Existing laser cutting machine:** The design of the machine have to fit the existing laser cutting machine that can be slightly modified.
- **Feeding material:** The feeding material was provided at the beginning of the project and cannot be modified.
- **Stock components usage:** To lower the price of building the prototype, 3D printed parts and components from other printers will be used.
- **Low cost production methods:** To reduce the cost of the project, manufacturing techniques have to be as easy as possible. For example, 3D printed parts, laser cutting or easy machining techniques such as milling or drilling.
- **Flexibility:** The machine has to be able to change some of the printing parameters to be able to test different printing configurations.

3. State of the art

After setting the objective of the project it is really useful to look at how the 3D printing technologies are being developed and what can be improved. Even though the project is a research project and the machine is a simple prototype, it is also a chance to test new methods, new architectures and new ways to overtake the problems of 3D printing. To do so, the existing 3D technologies have to be analyzed focusing on SLS printing.

3.1. 3D printing

3D printing (also known as additive manufacturing AM) is a process that allows the user to synthesize a 3D object. A lot of engineers and historians think that 3D printing along with rapid prototyping techniques are beginning the 3rd industrial revolution. 3D printing allows to create almost any geometry that can be designed, however depending on the technique used by the printer some considerations have to be done.

3.1.1. General printing process

To understand the different methods to generate 3D parts, it is important to understand the general process that all the methods follow. This process contains 5 steps: modeling, slicing, coding, printing and post processing.

Modeling

The part to be printed has to be modeled with a 3D cad software or scanned from a real object. The first one is the most common used way to create virtual 3D parts and it is also the most reliable. It allows to adjust the geometry to fit the printing process and it has more flexibility. In fact, scanned parts are usually processed with a 3D cad software to eliminate scanning errors and to obtain a printable part.

Slicing

Once the part has been designed or scanned, a slicing software divides the part in slices. This process is really important as the slice thickness will determine the finish of the part. This process is entirely automatic.

Coding

After slicing the part, a program must be used to transform the slices files into a single file that can be delivered to the printer. This software will also seek the manifold errors that would turn into impossible printing and may even solve them. In this case, each process has a different

coding resulting in different types of files. The coding determines the part finish and the printing time.

One of the most common code for 3D printing is the G-code. It is used on SLS, FDM, SHS and LOW printing among others. This code is a text file with the orders to move the machine to print the part. It is called G code because it uses G orders (G + number) to specify what the machine has to do.

Printing

With the compiled code, the printer can begin the printing process. This process usually lasts for hours if the part is medium sized and depends on what type of printer is being used.

Post processing

It is really difficult to obtain completely finished parts for high precision applications. When dimensional precision is required, the part is oversized and printed to then remove material by milling or other material removing process.

As some printers cannot physically print cantilevers it is normal to add supports to print this parts. After the printing is finished, this supports must be removed by milling, drilling or diluting in water if the supports are soluble.

This general process is followed by all the printing techniques with some slightly differences. During the following sections, the different printing methods will be seen.

3.1.2. Fused deposition modeling (FDM)

Also known as fused filament fabrication (FFF) is the cheapest and most used 3D printing manufacturing method. The FDM machines use a nozzle to heat up a plastic filament melting it and depositing it to create the 3D geometry.

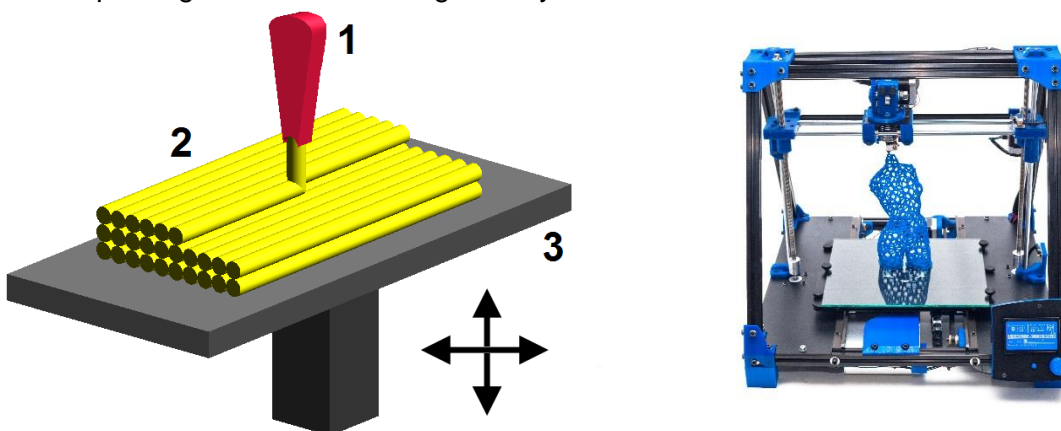


Figure 1 FDM process illustration and BCN3D+ printer

Like most of the 3D printing technologies, was invented on the 80's decade and it was commercialized in the 1990. However, the machine was as expensive as other SLS or stereolithography printing machines (that were much more precise). Because of this factors, the machine was neither a revolution nor a sale success.

However, with the end of the patent on this technology and the cheapening of the components, this printer succeed as the cheapest 3D printing machine. It was the first machine to be available for home printing at a relative low price and it can even be built at home. Even though the basic technology has not changed since then, the RepRap open source project and the development of freeware firmware such as marlin, has helped to develop this printers improving the printing parts and the cost.

One of the advantages of this kind of printers is that they can print with a lot of different materials. In fact, any material that can be heated and converted to a paste can be used as printing material (PLA, ABS, mortar, chocolate...).

However, this printer has some problems that limit its uses. The dimensional precision is not very good and it depends on a lot of factors. In addition, it cannot print cantilevers needing supports to do so that will waste material, rise the printing and post-processing time.

3.1.3. Stereolithography (SLA)

This process first appeared during the 1970's decade but was commercialized in 1986. It is a more complex physical process than adding plastic like FDM. However, it uses the same printing sequence (slice printing) but works by focusing an ultraviolet (UV) laser on to a vat of photopolymer resin which turns the resin into a loid polymer instead of adding fused plastic.

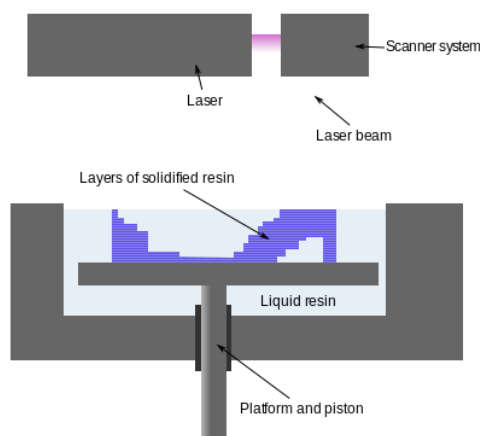


Figure 2 SLA process schematic

Although the physical principle is different, the process is the same but substituting the plastic nozzle by a laser and the plastic material by a resin. This fact implies some of the problems of FDM printing such as not being able to print cantilevers or needing supports to do so. However, speed and printing size availability are improved as well as dimensional precision.

This kind of printers are used in industrial process in the automotive sector. However, the high cost of the machine and the resin has been a burden to its application on the industry and at home.

3.1.4. Digital light processing (DLP)

Digital light processing, also known as DLP, printing machines use the same physical principle as stereolithography machines. However, the process has been optimized by substituting the laser by a DLP projector what allows to polymerize the whole slice in seconds. Doing this the printing time is reduced and there is a gain in terms of precision. To understand the process, is like if every slice was a picture that is projected on the resin. The finish of the piece is as good as the resolution of the projector.



Figure 3 DLP Printing process

With a precise projector and good slicing, this system is one of the most precise and allows to print the smallest pieces. The basic problems with DLP printing is the small printing volume which makes it only available for printing small parts. The price is also high due to the cost of the DLP projector and the resin. In addition, the resin cannot be stored for a long time as it can polymerize with the light.

3.1.5. Powder bed and inkjet head 3D printing (3DP)

The 3DP printing technique is one of the powder bed techniques. As described by its name, powder bed techniques use powder to print the parts. A mechanism spreads a layer of powder which is agglutinated using heat or a binding material. This way of printing parts is also used

on SLS printing which is the printing technique used on this project. In this case the binding material is deposited by an inkjet head to the selected places to create the slice. After that, the system spreads another layer of powder which will turn into the next slice.

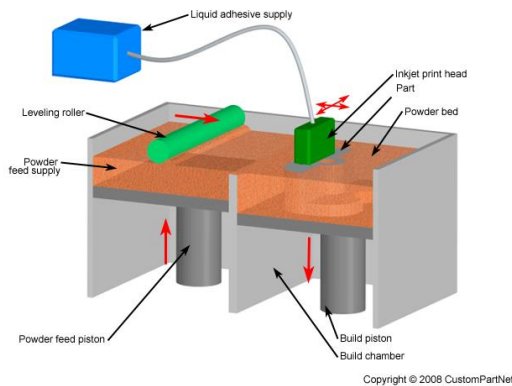


Figure 4 3DP printing illustration

This technique uses a really well known technique like inkjet printing that is common in 2D printing. This turns into a really reliable printing system that can fit in a relatively small machine. The price of the machine is relatively low compared to other powder bed printing machines, and the fact of working at the room temperature avoids the problems derived from dilatation.

The printing speed is as fast as the inkjet moves along the surface, which with 2D printing can be really fast. In any case, is faster than most of the other powder bed techniques.

However, the parts printed with this technique cannot be structural and will have an undetermined behavior when taking mechanical efforts. This converts the 3DP printing in a useful tool to print cheap and fast prototypes with a good dimensional precision but not mechanically functional.

3.1.6. Selective laser melting SLM

Selective laser melting (SLM) and selective laser sintering (SLS) uses the same working principle. The only difference is that SLM melts the powder and SLS only sinters it. SLS printing machine will be widely explained in following sections as it is the technique used on this project.

3.1.7. Selective heat sintering (SHS)

This printer technology works exactly with the same idea than SLS printing but the laser is substituted by a hot printhead. This makes the machine less expensive and reduces its size so it can be used in desktop versions.

The main disadvantage is the longer time to print and that the parts printed using this technique

are softer.

3.1.8. Laminated object manufacturing (LOM)

Laminated object manufacturing is a process where the different slices of the pieces are obtained by cutting the surface with a laser from a sheet and applying heat to unite them. The heat is applied by a roller that is also used to add some pressure to the sheets.



Figure 5 LOM Process schematic

This process is not very well known by most of the people but is really cheap for metal parts in relation with other process, and bigger parts can be made. However, it is less precise than stereolithography or SLS printing.

3.2. Selective laser sintering (SLS)

As mentioned before selective laser sintering is one of the printing techniques that uses a powder bed. In that case, heat is applied to the required parts of the powder to sinter the powder creating a solid part. On this section, the SLS printing technique will be deeply analyzed to see the main advantages, disadvantages and what can be improved from existing machines.

3.2.1. Printing process

In order to understand the printer parts it is needed to understand the printing process. The SLS printing process follows a sequence that is repeated several times to make the slices that conform the final printed part. This sequence is:

1. Lowering the printing zone
2. Rising the powder feeding platform
3. Powder layering
4. Laser sintering
5. Repeat until the part is done

The Figure 6 exemplifies the powder layering process with the most commonly used architecture. However at the machine analysis section other architectures will be explained.

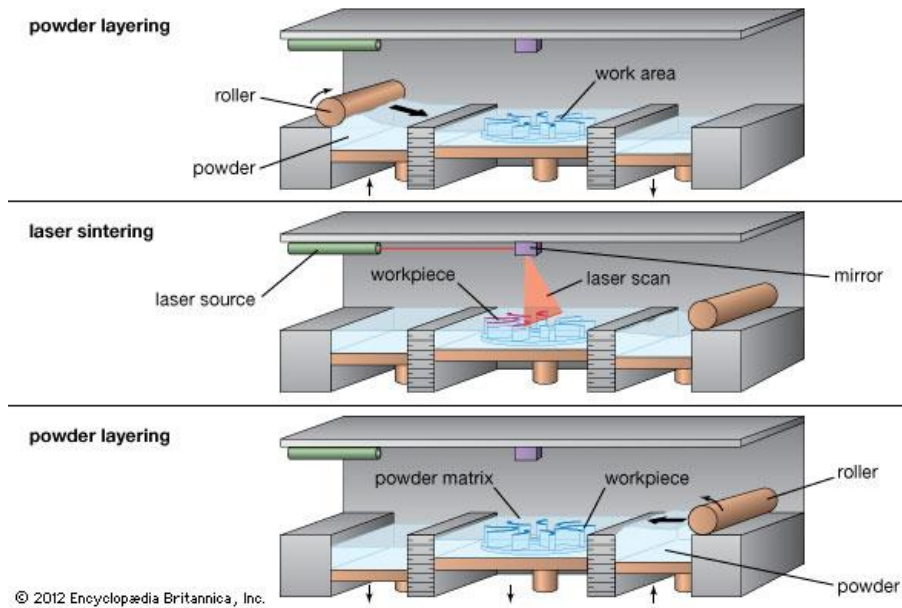


Figure 6 Layering process

After finishing the part, it must be extracted from the printzone and cleaned from the powder waste that is generated during the printing process (Figure 7)



Figure 7 Part extraction

Finally, the powder that has not been used must be extracted from the powder feeding platform and recycled. This powder has to be mixed with new powder and the powder removed from the part as it has lost some of its original properties.

3.2.2. Machine design

SLS printing machines are a fusion of two different machines: laser and recoating system. The laser system is the part that will heat the required area of the powder bed to create the solid part. The recoating system will then spread a new layer of powder and lower the part that is being printed to add a new slice.

While the laser system is more or less the same in all the machines, the only variations are in terms of power and precision, the recoating system can have some architecture differences.

The basic actions that need to be done when spreading a new layer are:

- Lowering the printzone platform
- Feed the system with new powder
- Spread the new powder to create a uniform layer

The first part of the process is the same in all the cases because the printzone must be always a square platform able to move in the vertical direction. What can be discussed on terms of design is the best way to feed the system with new powder.

Powder feeding

The most common way to do so is with two independent platforms located next to the printzone. The fact of having two independent platforms saves time as the spreading system has to travel only to one side of the machine to spread the powder but does not need to return to the previous position. However, this is not the best system in terms of space as it requires doubling the printing area. This will make the machine quite big for printing medium parts.

Another option is to have only one feeding platform. This solution is simpler but the system spends more time adding a new layer of powder because the layering system must return to the original position.

The last option that is used in a few new machines is to locate the powder cartridge above the printing zone. This system is more complex because it is difficult to ensure a good powder spreading but saves a lot of space. This machines can be as big as the printing zone taking advantage of the space above the machine that otherwise remains unused.

Layering

Layering the powder that has been fed is an operation that will determine some of the part's final properties such as density, mechanical properties or finish of the part. There are two basic options to spread and layering the powder from the powder feeding platforms to the printzone:

- **Straight recoater:** The straight recoater is the most used option on commercial machines. Even though it is not the best option, it is simple and provides a good layering. The main problem with straight recoater is that when there is a powder imperfection it can be dragged through the powder bed causing a porosity inside the final part. In addition, it is difficult to compress the powder and therefore the density of the printed part.
- **Cylindrical recoater:** Cylindrical recoaters are also widely used on commercial SLS machines. The problems that appeared with straight recoaters are solved with the cylindrical recoaters, but a new variable appears. How does the cylinder have to move? There are three options to answer this question. However, fixed cylinder that does not rotate is not a valid answer as it turns into a straight recoater with a cylindrical geometry. If the cylinder rotates “on the direction” of the movement, the powder can be compressed with a high degree of control. If the cylinder rotates “in opposition of the movement direction”, the surface will be smoother but the compression of the powder bed cannot be done.

Another factor that will determine the density of the powder bed is the layering speed. It has empirically been proved that higher speeds mean higher density.

Printing Chamber

For what has been seen until now, SLS machines do not seem to be very complicated and the only expensive system is the laser system. So why are SLS machines so expensive, big and complicated to have as desktop version? The answer to this question is the printing chamber conditions.

Like in laser cutting machines, there are some toxic gases that are produced when heating the powder. In addition, to avoid burning the powder an inert atmosphere must be created so the powder cannot set on fire. To complicate it a little bit more and to avoid problems with dilatation, the whole system must be at a temperature near to the powder sintering. That is also the reason why powder has to be recycled and not directly used again.

All of this extra requirements are really expensive both, money and space, and are the reason that SLS machines cannot be reduced to a desktop version.

3.2.3. Sintering materials

There are a lot of sintering materials available on the market. However, the laser power and the machine characteristics will determine which materials can be sintered. Sintering materials can be classified in two great groups: one component materials and two components materials.

- One component materials: One component materials are not a common option in selective laser sintering because it is difficult to properly control the sintering of the grains. The material is a fine powder usually manufactured by milling balls.
- Two component materials: Two component materials are the chosen option for almost all the sintering operations. The two materials can be combined in two different ways. They can form a mixed powder of two separate materials forming a composite. In this case, both materials can sinter or not depending on the final properties needed for the printed part. The two materials can be combined also combined on a coated grain powder. The grains are covered by a second material which will sinter to create the printed part.

Almost all the materials that can be sintered can be arranged in one or two component powders. The most used materials in selective laser sintering are divided in polymeric and metallic materials:

- Polymeric: Nylon, ABS, PLA, polystyrene amongst others
- Metallic: Steel, aluminum and titan alloys. The most used is aluminum.

3.3. Technology readiness level (TRL)

Technology readiness level is a very useful way to analyze in which stage is the technology that is being developed. It is used by several organizations and companies in the world by performing a technology readiness assessment (TRA). The following Figure 8 illustrates the different stages of the technology development level.

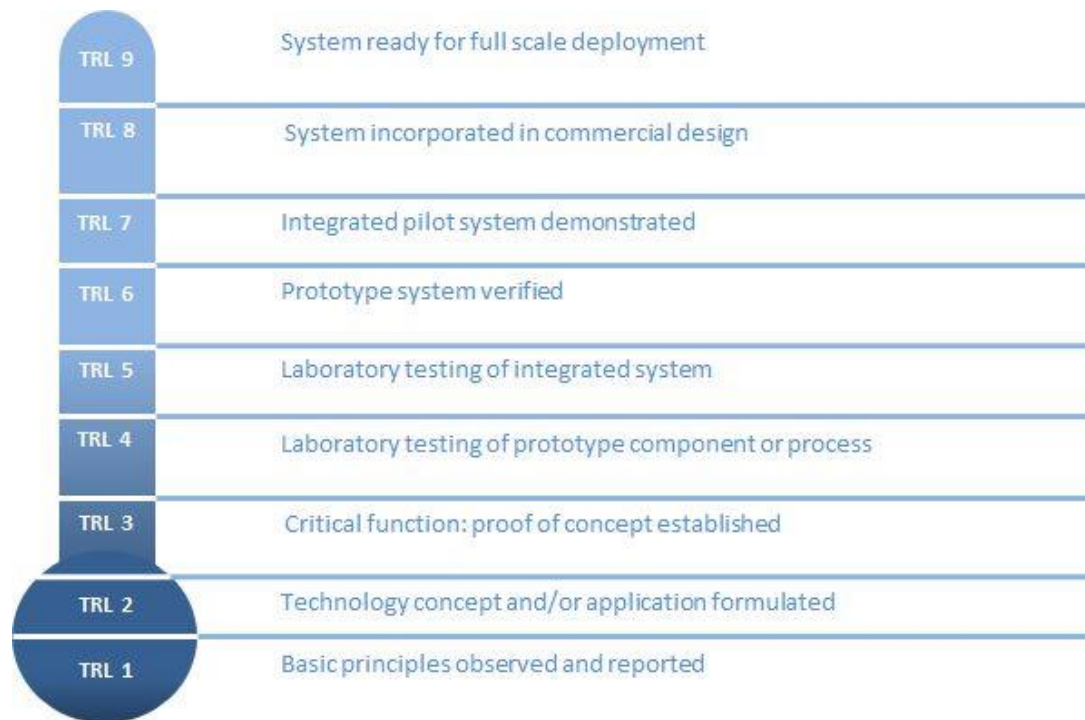


Figure 8 Technology readiness level

The TRL analysis is useful to know what to do next. It is a way to evaluate what has already been done, avoiding doing again that work, and what has to be done. It is also a helping tool to ensure that all the steps to create a new product are done. If the TRL plan is followed until the end, it will probably avoid troubles during the designing period and will ensure the full utility and taking advantage of the technology that is being developed.

There are a lot of ways to determine the technology readiness level of a technology depending on what is being analyzed. Some of the methods are an exhaustive look to the risks and benefits, while others are more concerned about timing of the project. To know the technology readiness level of a project, a TIR calculator provided by the NASA and accepted as the world most accurate description will be used.

This calculator uses sets of questions that need to be answered about the project development. To adapt the calculator to the project that is being developed, some of the questions have been omitted.

The full analysis of the TRL can be found on the [appendix xxx](#). The summary of the TRL calculation is on the Figure 9:

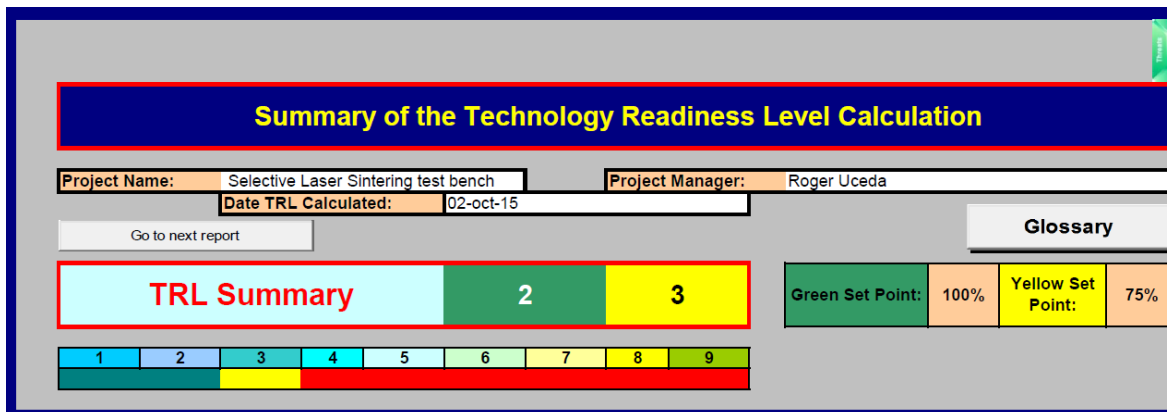


Figure 9 TRL analysis result

As it was expected, level three is partially completed (94,11%) and level four is far from being completed (25%). This result is interesting as it reflects the reality of the project. The technology and its application has been fully developed, but there are some critical functions of the powder that is going to be tested have not been proved. The fourth level has to be completed which means to test the technology on a lab environment. To do so the prototype will be built.

4. Overall look at the design

First of all, it is necessary to take a look to the whole assembly. Its conformed by two main parts: the *Laser cutting machine* (see appendix XX, machine image in Figure 10) and our recoater system. The recoater system must fit into the *Laser cutting machine*. To do so, on the CAD files, available space is modelled by a blue surface, as it is seen in Figure 11.



Figure 10 Laser cutting machine

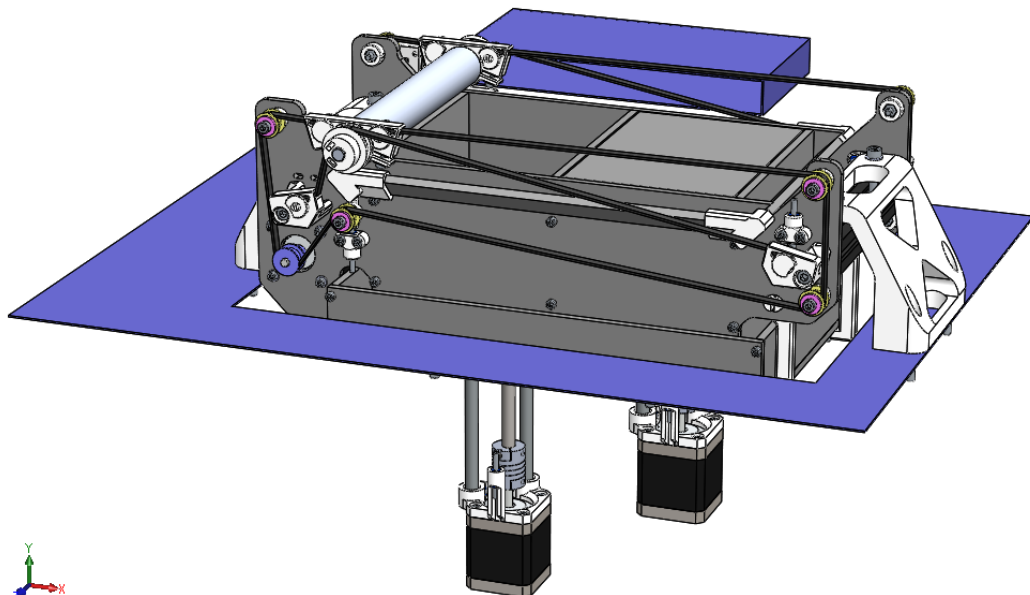


Figure 11 3D CAD of the complete machine

During the design explanation, this blue surface will be kept hidden to simplify the assembly.

The laser cutting machine can move a focused laser point over X and Y axis. That is, over a flat surface. Laser power, movement speed and acceleration, and the path to follow is CNC controlled. This allows you to cut/engrave different materials, all flat. However, we need a machine which builds 3D pieces so it is needed to print different layers, one above the other. It can be accomplished by adding a Z axis and that's essentially what the self designed recoater system brings to the assembly.

The recoater system has been designed to solve different basic functions:

Store the feeding material: A container in which feeding material is stored, the container can move to feed the printing zone with more material when needed.

Define the printing zone: Depending on the recoater system size, the printing zone varies.

Set the desired layer heights: This parameter must vary in steps of minimum 0,01mm. So the Z height adjustment system have to allow this precision.

Feed material between layers: A rotatory cylinder spreads the feeding material from the storage container to the printing zone, after every layer.

Recover residual material: During all the process, its usual to see material excessing the delimited surfaces. Due to this, a specific funnel and container have been designed to recycle this surplus material.

In addition, the design fulfills some other concepts which make it the best solution for its purpose:

Accessibility: Make it as accessible as it can be, when building the assembly and when using the assembly to test printing materials.

Easy mounting and replacing: Make it easy to build and reduce the amount of tooling. All nuts have its own housing, allowing the user to build the whole assembly with just hexagonal keys (different sizes depending on bolt's metric).

Adaptability: Make all the things as much adjustable as they can be to correct possible production defects and unexpected problems which can appear during testing.

Electronic precision: Let the final user electronically control all the different variables during testing process in order to get high precision movements and solid repeatability.

Simplicity: Keep all things as much simplified as it can be making it easy to repair, solve

problems and evolve the design if necessary.

Cost efficient: Reduce the final budget of the prototype using material from other BCN3D Technologies machines, laser cut profiles and 3D printed parts.

Space efficient: Fit perfectly inside the laser cutting machine and ensure the widest print zone possible. Having this in mind during design allows to print bigger testing pieces which can be mechanically tested.

Reliability: Mechanical and electronic design must allow precise repeatability tests, so keeping all things simple and using the less parts possible to do all the functions make a more solid machine. Also, reducing the amount of unnecessary wiring and keeping electronic PCBs in one place assures a robust design. Not less important, a simplified firmware allows the user to know exactly what the machine is doing and how to solve any problem, if that's the case.

Whole assembly CAD file and parts' CAD can be found in the attached CD.

Having these general design concepts in mind, we can proceed to go deeper into both parts: mechanics and electronics of our self designed recoater system.

5. Recoater System

Focusing on this part of the whole machine, it is what manages feeding material and makes it possible to melt powder in different layers. In this section it is explained in high detail how mechanics work and have been designed to guarantee the best result during testing, and then how electronics have been selected, programmed and set up to make everything work as expected.

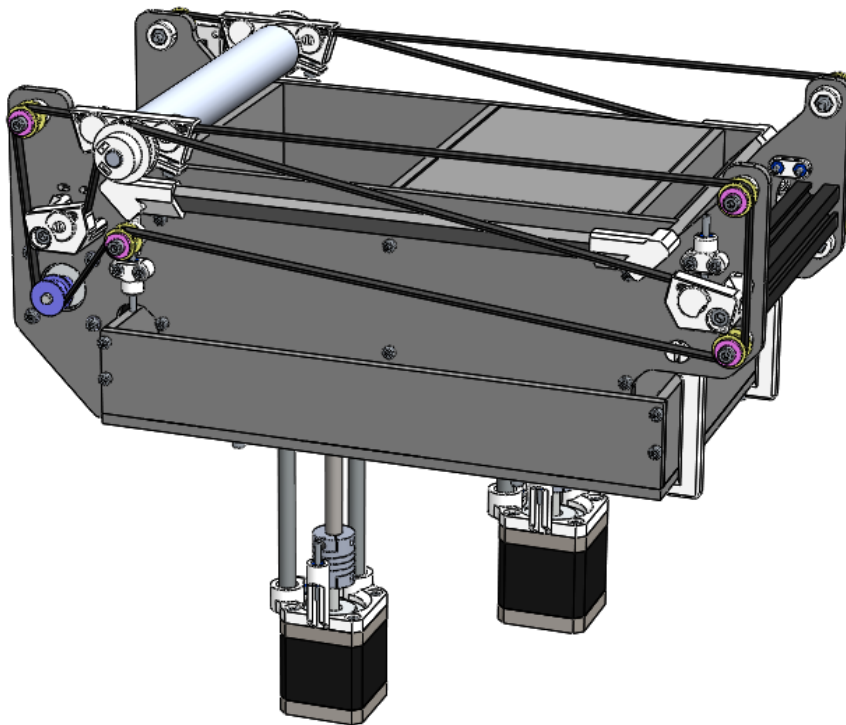


Figure 12 Recoater system

5.1. Mechanics

Mechanical parts are all these which do not involve electrical components, in exception of the motors (steppers) and endstop sensors, which are a mechanical part electronically controlled.

Steppers will be considered in 6.1 to explain mechanical configurations, and in 6.2 to explain its own working principles and how to electronically control them. Datasheet is attached in appendix.

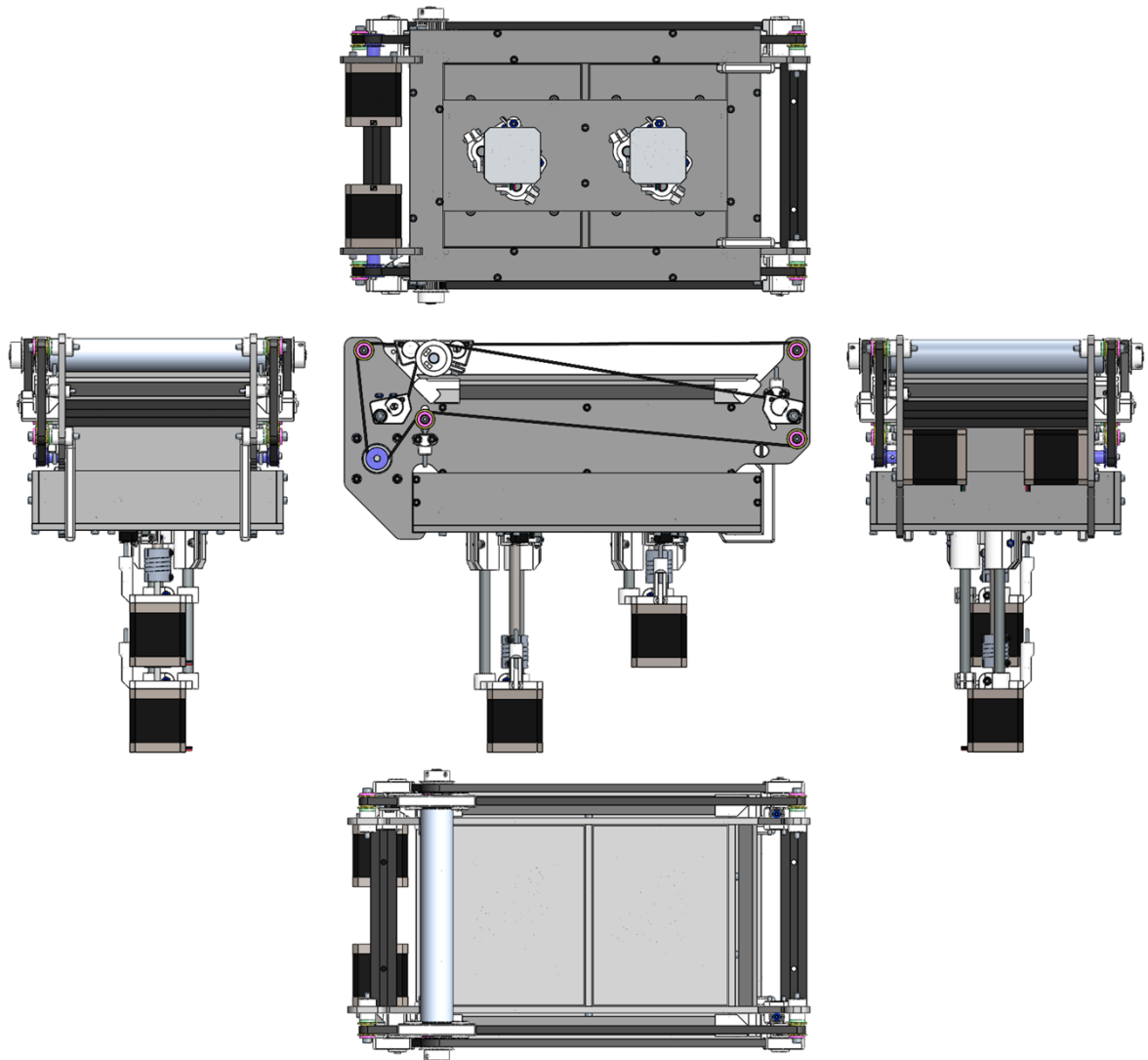


Figure 13 Principal views

So, mechanically speaking, it is seen we have different parts self developed involving methacrylate (PMMA, Poly(Methyl Methacrylate) laser cut profiles, 3D printed parts and a machined cylinder, and then other mechanical commercial components involving screws, nuts, bearings, springs, rod and threaded bars, couplings, belts, pulleys and so on. All of them

detailed in the bill of materials (BOM) which can be found in appendix and also in the CAD files in the attached CD.

To explain all this mechanical assembly, we will separate it in two main sets: the spreading system which is capable of moving feeding material from the powder container to the printing zone, and the platform system which brings the ability to change Z height to work in different layers.

In these two sections, the structure is the same:

1. at first we analyze different basic solutions and choose the best one
2. then the working principles of the chosen solution are explained
3. after that we go deeper into general design concepts of the assembly
4. finally, we get in a part-by-part breakdown, justifying self-designed parts and commercial parts used.

NOTE: Different 3D printed PLA parts must guarantee some mechanical properties. To make sure of this before producing the final part, FEA (Finite Elements Analysis) comes to mind.

However, it is worth mentioning FEA on PLA is highly difficult because of its nature: it is a linear elastic orthomorphous material. Adding to this, if the material is 3D printed using Fused Deposition Modelling process, its properties are being altered constantly when the material is fused and solidified again. This issues must be added to the fact that the piece is printed in layers, where each layer is built at different temperatures, as well as the room temperature changes during printing. Different other parameters which differs on every printing, like layer height, infill pattern. etc also affect the final part's properties. It is impossible to avoid other complexities inherent to the printed part shape itself.

Even knowing all this factors, FEA can be done to our printed models¹. After all, it is really hard to come up with standardized numbers, so PLA 3D printed parts used have been designed by live testing process, which has been the most reliable one. Live testing process is not a budget problem when producing cost is as low as it is for PLA parts (about 0,02€/g).

¹ <http://my3dmatter.com/influence-infill-layer-height-pattern/>

5.1.1. Spreading system

This mechanical set has one main function: move feeding material from the powder container to the printing zone creating a homogeny layer of powder of the desired height (electronically defined by the user), sequentially in order to get the 3D printed part built. To get this a carriage moves transversally spreading the powder from the feeding container to the printing zone.

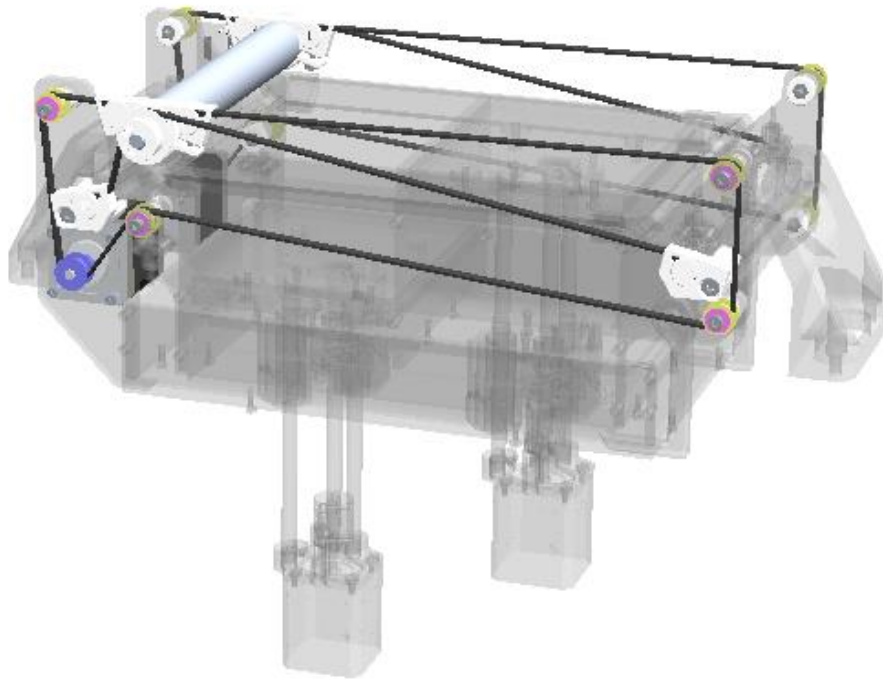


Figure 14 Spreading system highlighted

5.1.1.1. Carriage selection

In order to spread the powder, different systems come in mind.

On one hand, a straight recoater (consisting in a solid fixed bar) is the most used option on commercial machines. Even though it is not the best option, it is simple and provides a good layering. The main problem with straight recoater comes up when there is a powder imperfection, then it may be dragged through the powder bed causing a porosity inside the final part. In addition, it is difficult to compress the powder and therefore the density of the printed part.

On the other hand, cylindrical recoaters are found. These ones are also widely used on commercial SLS machines. The problems that appeared with straight recoaters are solved with the cylindrical recoaters, but a new variable appears: cylinder movement. It can be fixed, which turns the cylinder into a straight recoater with a cylindrical geometry; it can rotate “on the

direction” of the movement, then the powder can be compressed with a high degree of control; and finally the cylinder can rotate “in opposition of the movement direction” (reverse rotatory cylinder since now), which leads to a smoother surface as it repels powder imperfections but also delivers lower compression of the powder. Powder compression (that is, its density) can also be altered by the layering speed. It has empirically been proved that higher speeds mean higher density.

Due to these facts, the reverse rotatory cylinder has been chosen, as its seen in Figure 15.

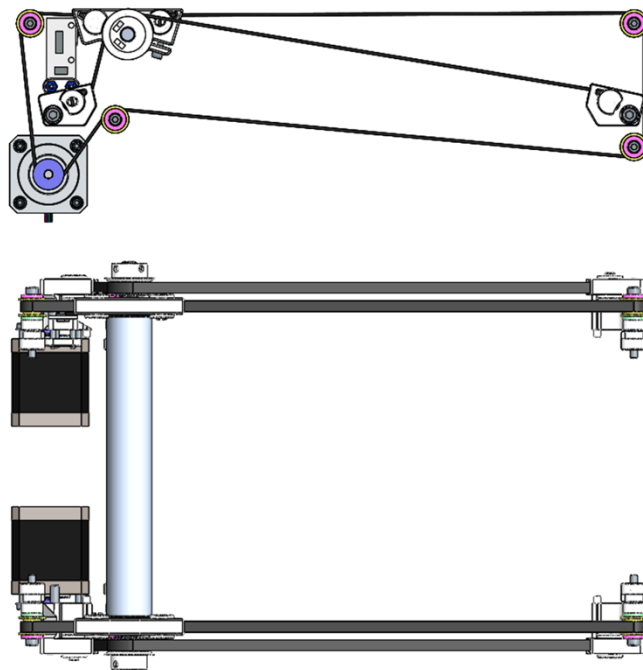


Figure 15 Spreading System principal views

5.1.1.2. Carriage Working Principles

To make this work, the cylinder moves above two guides (laser cut profile, which are also main walls and structural support of the whole recoater system). Two symmetric belts actioned by two respective steppers bring transversal movement to the cylinder along the guides, and two symmetric fixed belts makes contact with two pulleys fixed to the cylinder, this brings the reversed rotatory movement as the cylinder moves through. See Figure 16.

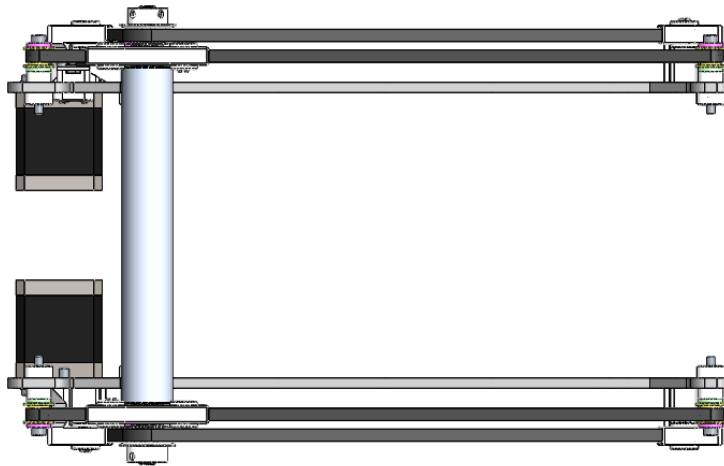


Figure 16 Carriage and guides top view

The carriage moves from zero position to its maximum position and comes back between layers, spreading the powder (Figure 17).

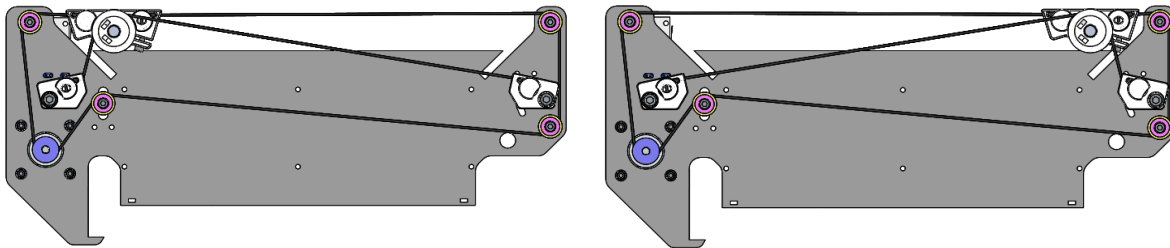


Figure 17 Zero position on the left, maximum position on the right

5.1.1.3. Carriage general design concepts

Now it is known why the recoater uses a cylinder carriage and how it works. To design the spreading system though, some other concepts have been kept on mind and in this section we are going into it. Carriage travel distance and speed, cylinder rotation speed, maximum and minimum configurations.

Carriage travel speed is defined by steppers' movement and its pulley gear ratio which formulation is explained on the electronic section. Being it electronically adjustable by the user.

Carriage travel distance has been set to 240mm, 10mm longer than both platforms in order to

over travel 5mm on each end. This over travel let possible exceeding powder to go to the residual container and also put the carriage in a non obstructive position when the laser moves around X and Y axis.

The carriage zero position (Figure 17) is set by an electronic endstop pushed by the carriage when moving to zero position. This endstop can be moved along two slots, letting the user set different 'zero' positions depending on its requirements. Max position (Figure 17) is electronically set by motor steps, Calculations are done on firmware-level and are explained in electronics section of this report.

Cylinder reverse rotatory speed is defined by the gear ratio of cylinder's pulley, which is more or less twice the travel speed (detailed calculation on the electronic section) for the first tests. This fixed value allows the user to change spreading velocity modifying just one value (travel speed). But also brings the possibility to change the pulley and adapt to other gear ratios if necessary. In fact, the pulley is 3D printed.

Motor belts are designed to cover all the travel horizontally, adding no vertical pressure to the carriage and limiting its swinging movement. A mobile pulley allows the user to add more tension if needed. Belt travel is highly conditioned by space and steppers position.

Fixed belts add extra pressure between the carriage and the guides. That assures the powder is correctly spread and the cylinder makes its function and is not just rolling over the powder. Belt tension can be easily adjusted moving one of the fixed supports.

Both belt's tensile elements have been studied in all their working positions to make sure belt angles are acceptable and no elements collide on extreme cases (Figure 18).

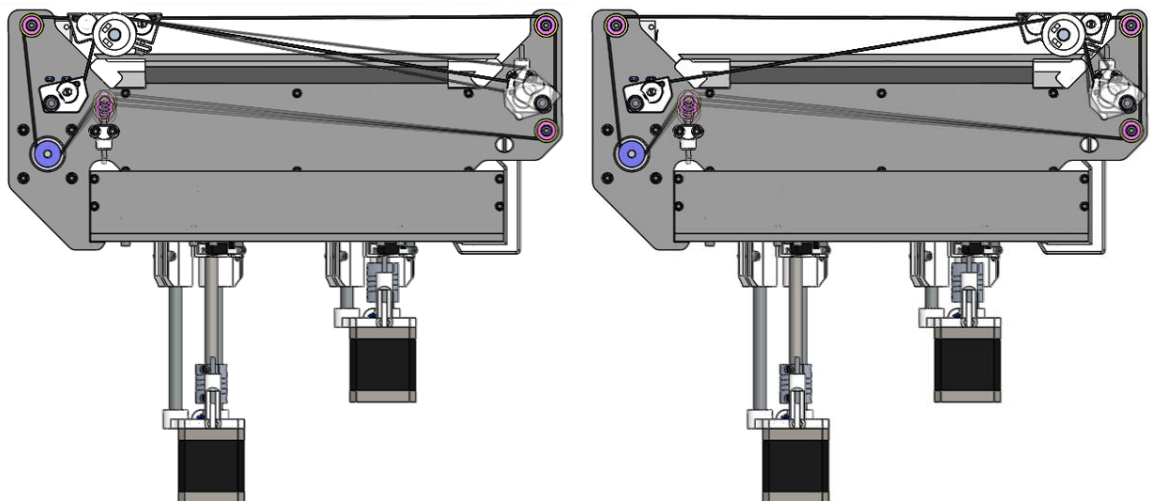


Figure 18 Tensile elements in extreme positions.

Carriage on Zero (Left) and max (Right) position

Carriage height and width has been set to the maximum that laser machine can handle, that gave us a max height of 30mm and max width of 225mm.

5.1.1.4. Part by part breakdown

Knowing these general design concepts, we can explain in detail how different parts have been designed (for self-designed ones) or selected (for commercial ones). All the elements explained are highlighted in Figure 19.

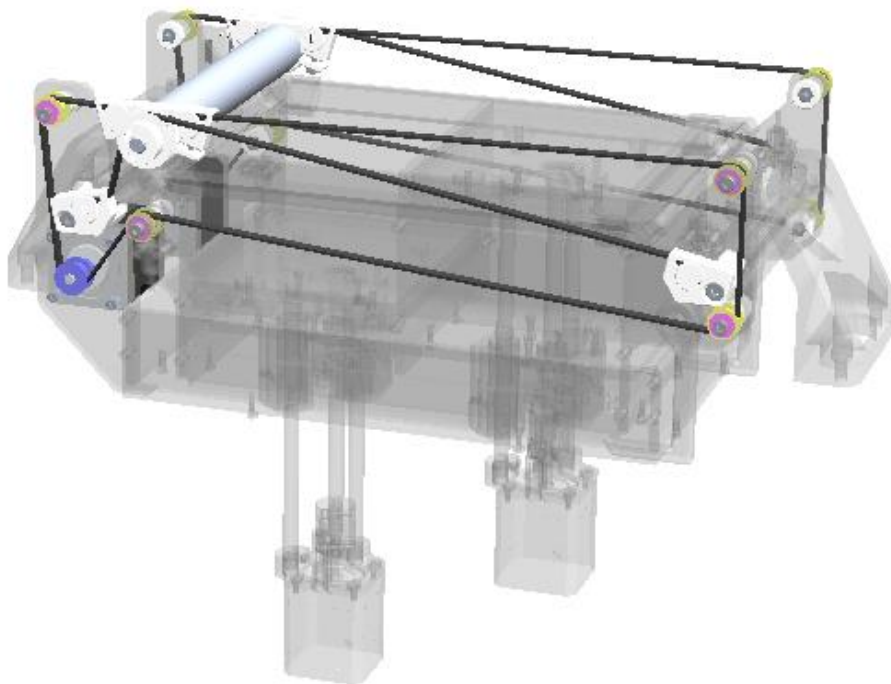


Figure 19 Highlighted parts

Each part has its own descriptive name (**bold**) and CAD name (*italic*). Part code names for the CAD files follow the next rules to assure a clean file structure:

Example: **REC-A001-001** (*Cylinder*)

REC: depending on the subsystem. REC for recoater and PLA for platforms.

A001: means the part belongs to assembly 001 inside the recoater subsystem.

001: is the part 001 from the assembly A001.

(Cylinder): descriptive name to make the file structure reading more accessible.

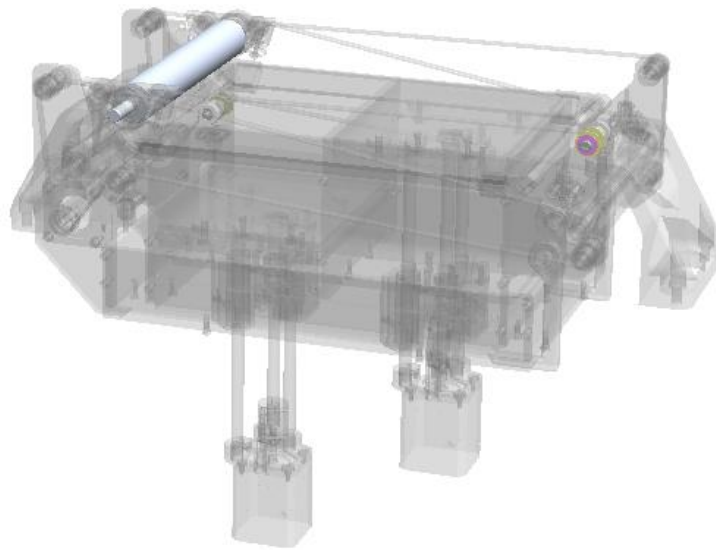
Cylinder - REC-A001-001 (Cylinder)

Figure 20 Cylinder

Main design concept:

- Material has to be solid, smooth and not sticky to spread the powder uniformly.
- A cylinder which covers all the depth of feeding/printing surface, to roll along its width.
- Needs supports to induce the roll movement.

Assembly limitations:

- Cylinder radius must be limited to a maximum 15mm due to the available height between printing surface and the laser's mirror.
- Total depth is conditioned to laser machine available housing (in order to bring the maximum printable area).

Final design:

- Aluminum machined cylinder. Production drawing with tolerances in Figure 22. 7075 aluminum bar has been used. *BCN3D TECHNOLOGIES* already had in stock, this reduces prototype's final budget.
- Radius is limited to 12,5mm. This feature brings 5mm available to adjust the laser focal distance.
- Two M8 supports at both ends fit inside M8 radial bearings (*608ZZ Radial bearing*), which transmits the translation movement from fixed clamps to rolling cylinder. In

order to get the desired hole-axis adjustment and assuming bearing's hole is produced guaranteeing H7 tolerance, M8 supports (axis) are h6 designed. That means a diameter of $8_{-0,009}^{+0}$ mm which enables hand positioning.

- A fixed pulley is also attached on each support, to get the reversed rotation movement.
- Total depth is set to 225mm.

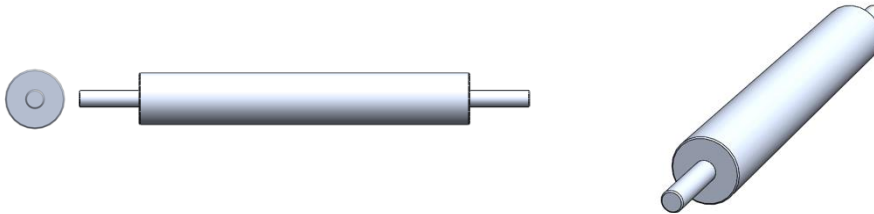


Figure 21 Principal views and Dimetric view

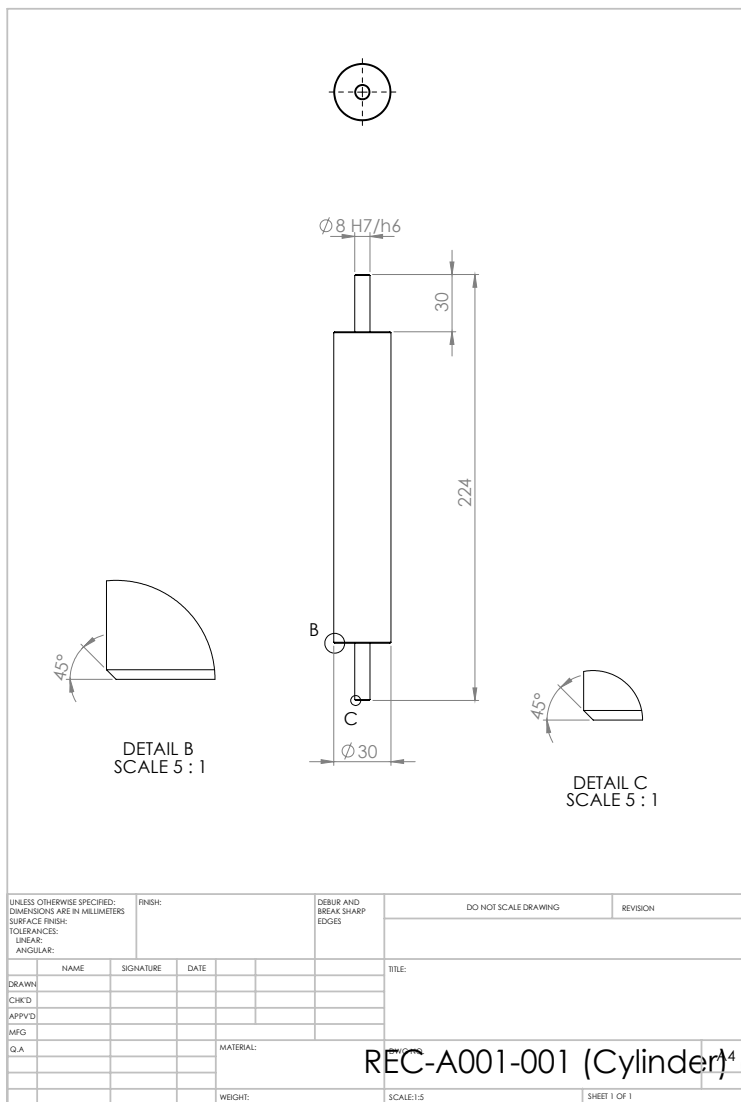


Figure 22 Cylinder's production drawing

Cylinder fixed pulley - REC-A001-002 (Pulley)

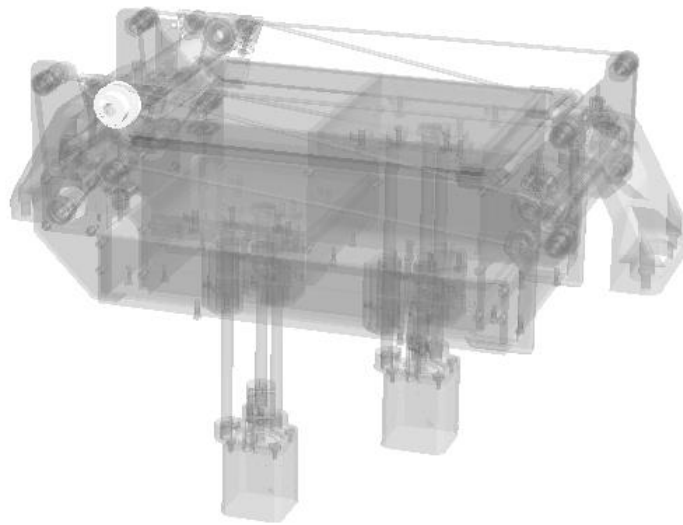


Figure 23 Highlighted parts

Main design concept:

- We need different pulleys if we want to change the reversed rotation speed, changing the gear ratio.
- Pulley has to be fixed to the cylinder.

Assembly limitations:

- Maximum pulley diameter must no exceed the clamp highest point, as it is what sets the maximum height of the carriage.
- Gear must fit belt's tooth pitch.

Final design:

- 3D Printed PLA pulley, this allows easily change between different gear ratios just adapting the CAD file and printing new ones.
- Two bolts in a 90 degree separation fix the pulley on the support.

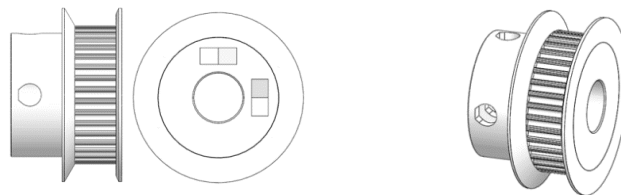


Figure 24 Principal views and Dimetric view

Clamp - REC-A001-003 (Clamp)

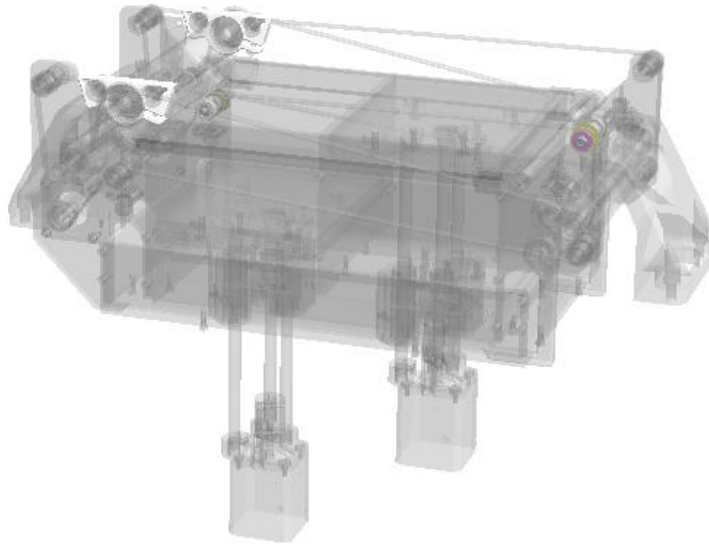


Figure 25 Highlighted parts

Main design concept:

- Clamp must be fixed to the radial bearing.
- Clamp acts as support for the motor belt.
- It will press the endstop when finding zero position.

Assembly limitations:

- This clamp is also what defines carriage's maximum height.

Final design:

- 3D Printed PLA clamps, brings possibility for a cheap complex design.

Fixture method for the radial bearing consists in an open circular loop, pressed by one M3 bolt. Special design for the motor belt support allows the user not to use extra tooling. Belt edges loop into a circular housing on the clamp, getting the belt fit with its own tooth. A clip prevents loop squeezing (

- Figure 26).

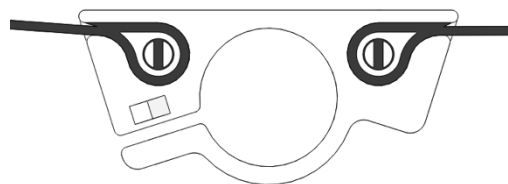


Figure 26 Clamp view

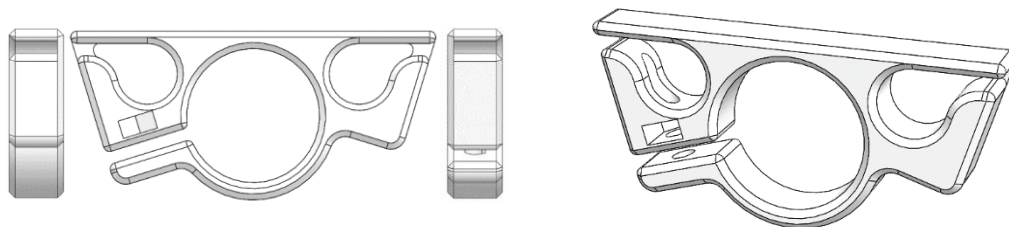


Figure 27 Principal views and Dimetric view

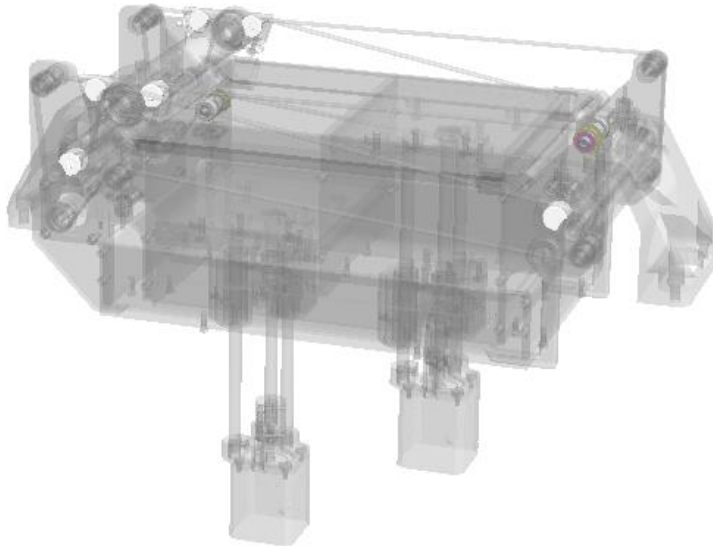
Clip - REC-A005 (Clip)

Figure 28 Highlighted parts

Main design concept:

- Cylindrical element to pass through the clamp's belt loop, preventing loop squeezing.
- Easy to mount and remove, without extra tooling.

Assembly limitations:

- Loop size limits cylinder radius.

Final design:

- 3D printed PLA tubular clip which fits inside belt's loop. Main part is in contact with the belt (*REC-A001-004 (Clip A)*), secondary part prevents main part to become detached (*REC-A001-006 (Clip B)*).
- Loop diameter is fixed by clamp size, which is limited by carriage height. That defines clip size. Main part cylinder's wall is 1 mm thick, this brings 5 mm diameter housing for the secondary part to fit in. Secondary part has two legs which click into main part when the travel ends (Figure 29)
- In order to avoid aluminum cylinder's or fixed pulley's collision, head reduction has been done into clip heads.

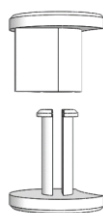


Figure 29 Clips assembly

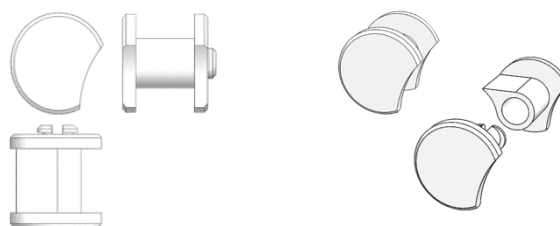


Figure 30 Clips view

Bearing and spacers - 608ZZ Radial bearing, DIN125 M8

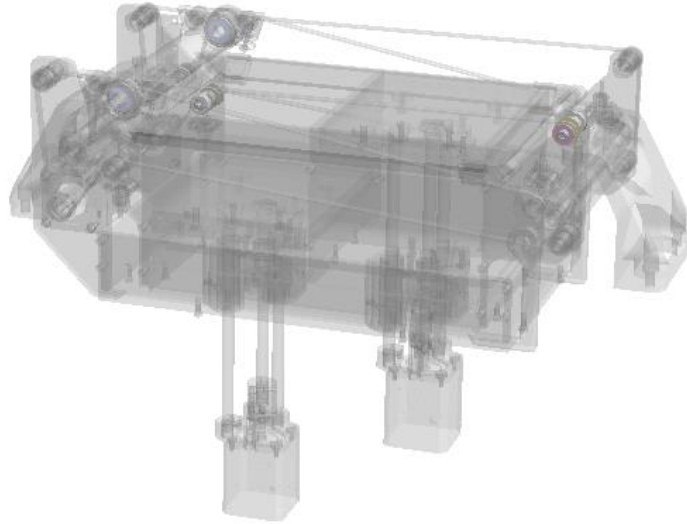


Figure 31 Highlighted parts

Main design concept:

- Bearing to transmit translation movement from the motor belt, allowing the cylinder to rotate freely.

Assembly limitations:

- Aluminum cylinder edges have a limited length.
- This part must avoid clamp, pulley and cylinder collision. (Figure 34 and Figure 35)

Final design:

- Commercial M8 radial bearing is used to transmit movements (Figure 33).
- DIN125 M8 washers are used as spacers to avoid collision between elements (Figure 32).

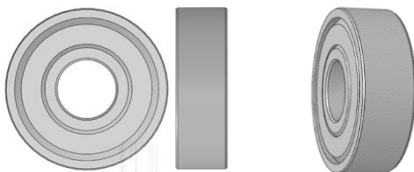


Figure 33 Principal views and Dimetric view

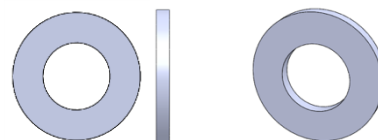


Figure 32 Principal views and Dimetric view

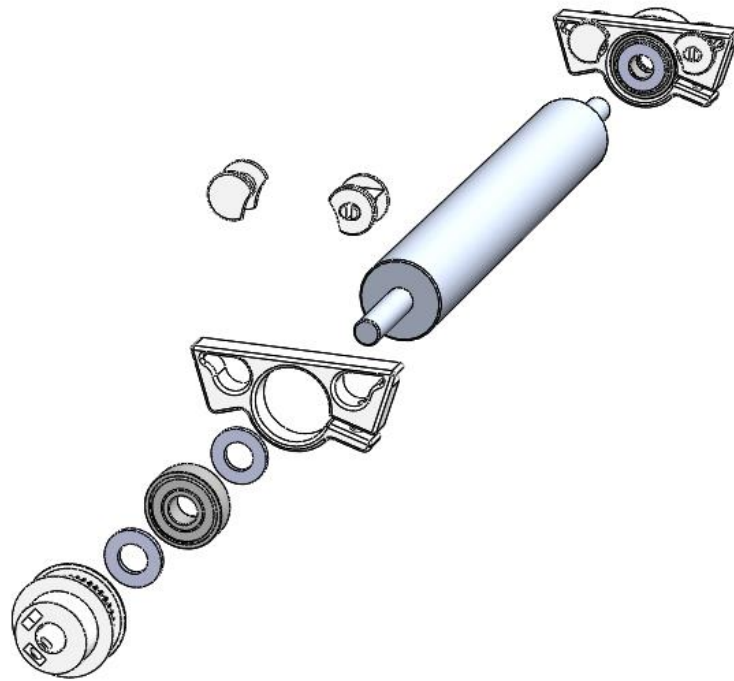


Figure 34 Exploded carriage assembly



Figure 35 Carriage section view

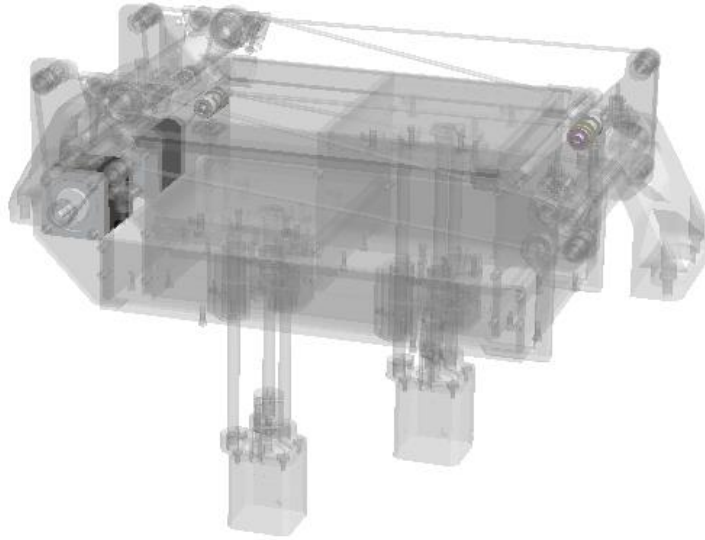
Motors - SY42STH47-1684A_Real Colors (cut)

Figure 36 Highlighted parts

Main design concept:

- Steppers electronically controllable.
- Defined torque amount.

Assembly limitations:

- More related to budget limitations, we will use commercial steppers already used in other machines like *BCN3D+*.

Final design:

- Steppers selected are explained in more detail in electronics section.

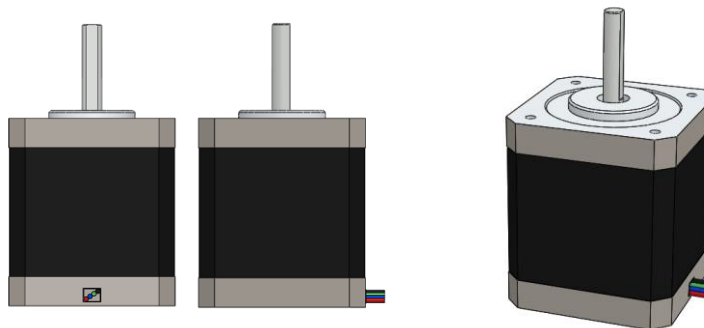


Figure 37 Principal views and Dimetric view

Pulley assembly - REC-A002 (Pulley)

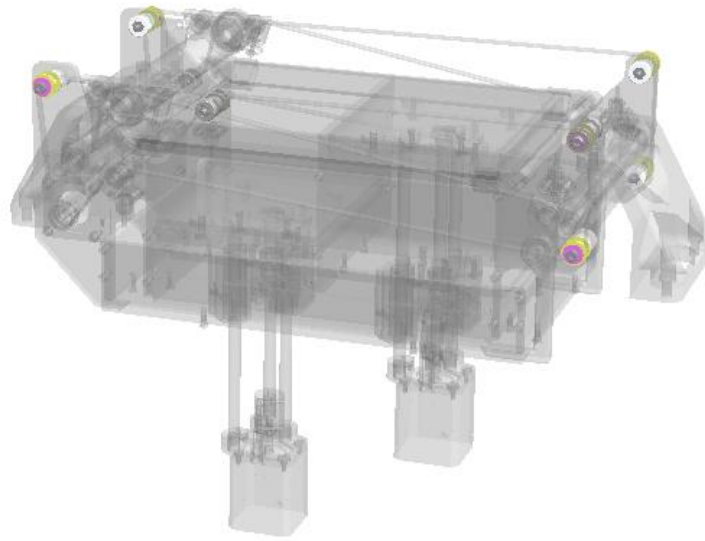


Figure 38 Highlighted parts

Main design concept:

- Easy to mount pulley to guide motor belt tracing.
- No need of gears, just smooth rolling.

Assembly limitations:

- Specific space between frame mount (cube main wall) and pulley itself.

Final design:

- An assembly which includes an M4 Bolt, which supports two fixed bushings (*Selfoil 4-8-12-2-10*, *Selfoil 4-8-12-2-4*) and two mobile bushings where the belt makes contact (*IGUS JFM-0810-038*, *IGUS JFM-0810-06*), a 3D printed PLA spacer (*REC-A002-001 (Pulley Spacer)*) to position the bushings on the belt plane, and all this fixed by a nut, held by a 3D printed nut holder (*REC-A002-002 (Pulley Nut Holder)*).

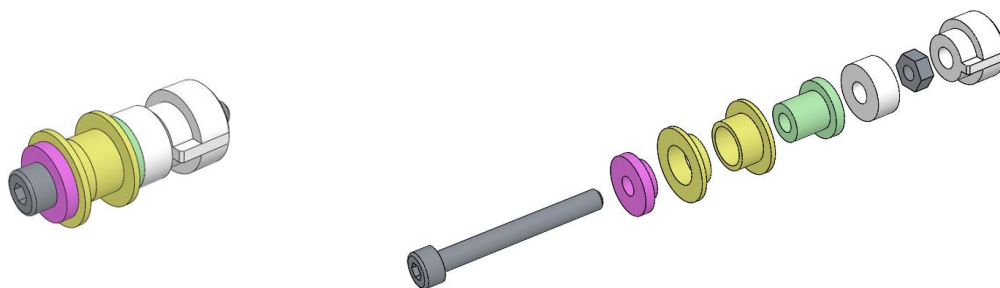


Figure 39 Compacted and exploded pulley assembly.

In exploded, from left to right: M4 Bolt, IGUS JFM-0810-06, Selfoil 4-8-12-2-4, Selfoil 4-8-12-2-10, IGUS JFM-0810-038, spacer, nut, nut holder.

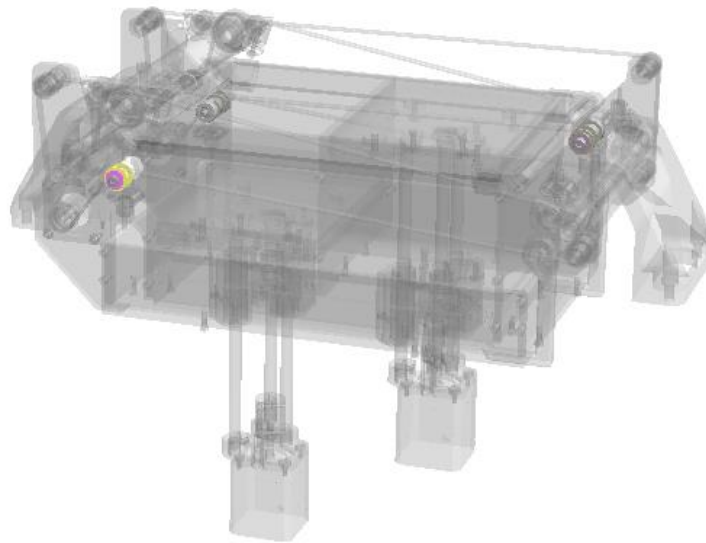
Tensile pulley - REC-A003 (Tensile Pulley)

Figure 40 Highlighted parts

Main design concept:

- As similar as Pulley assembly, just needs to modify the nut holder to fit on a slot. This allows the tensile function as it moves vertically through the slot.

Assembly limitations:

- Slot size to make the part solid and reliable.

Final design:

- Basically the same assembly as pulley assembly but changing the nut holder by one (REC-A003-001 (Tensile Pulley Nut Holder)) which fits into a slotted housing.

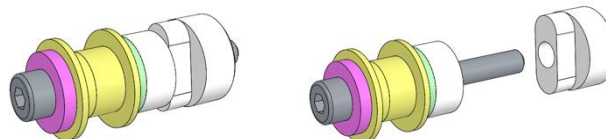


Figure 41 Tensile pulley compacted and exploded assembly.

Special nut holder isolated in exploded one.

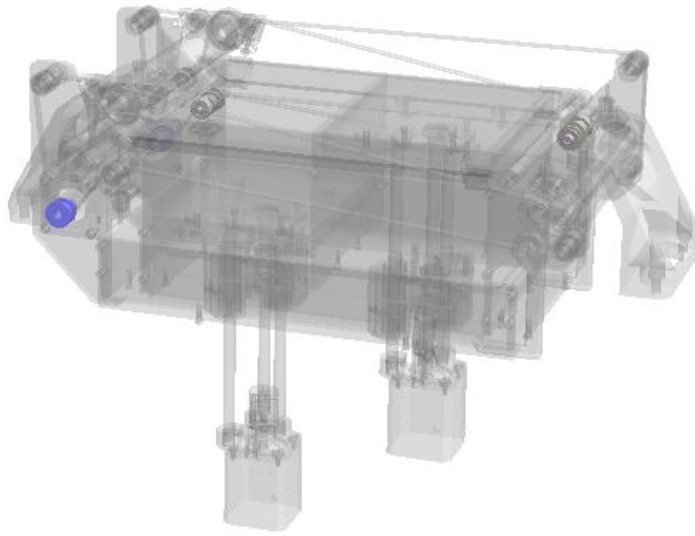
Motor pulley - Belt pulley

Figure 42 Highlighted parts

Main design concept:

- Pulley to transmit movement from stepper axis to the belt.

Assembly limitations:

- Space limitations

Final design:

- We use a commercial pulley already used in other machines like *BCN3D+*.

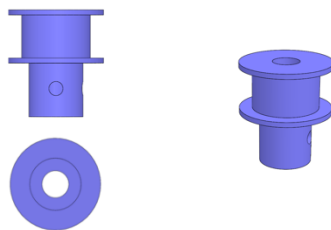


Figure 43 Principal views and
Dimetric view

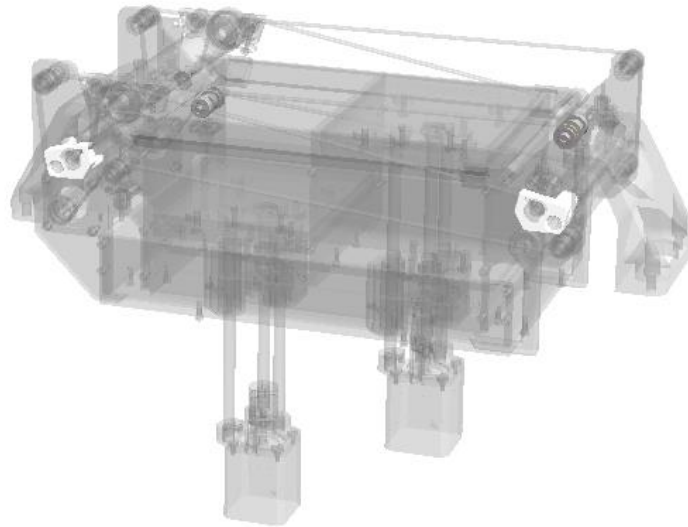
Fixed belt support - REC-A001-009 (*Fixed Belt Support*)

Figure 44 Highlighted parts

Main design concept:

- Solid support to fix fixed belt ends.
- Must allow the user to tighten the belt.
- Preferable to use the same belt fixture solution as the carriage clamps.
- When fixing belt ends, belt plane is considerably separated (23 mm) from the mounting point. The support has to solve this issue.

Assembly limitations:

- To design this part, some elements collide because of the position needed. This supports must be attached to a lower point than the carriage travel plane, to apply belt pressure onto the cylinder fixed pulley.

Final design:

- 3D printed PLA complex part, designed to be printed properly.
- Uses the same belt end fixture as the carriage clamps (and the same clip concept).
- Solves the spacing problem to reach the belt plane.
- In order to reduce the amount of screws but maintaining the solid fixture property required, a pin protrudes and fits into the main frame. The other edge has a M5 bolt which screws directly to the main frame (aluminum extruded profiles), avoiding the use of an extra nut.

- To allow the tensile function, one support stands at each end of the belt. One is completely fixed to the frame, while the other can pivot around the M5 bolt, letting the user get the belt tightened if desired.
- The part has been designed to not collide in any position (Figure 18). Including slots for belts and wiring (for the one near the endstop (*REC-A001-011 (Fixed Belt Support Slotted)*)).

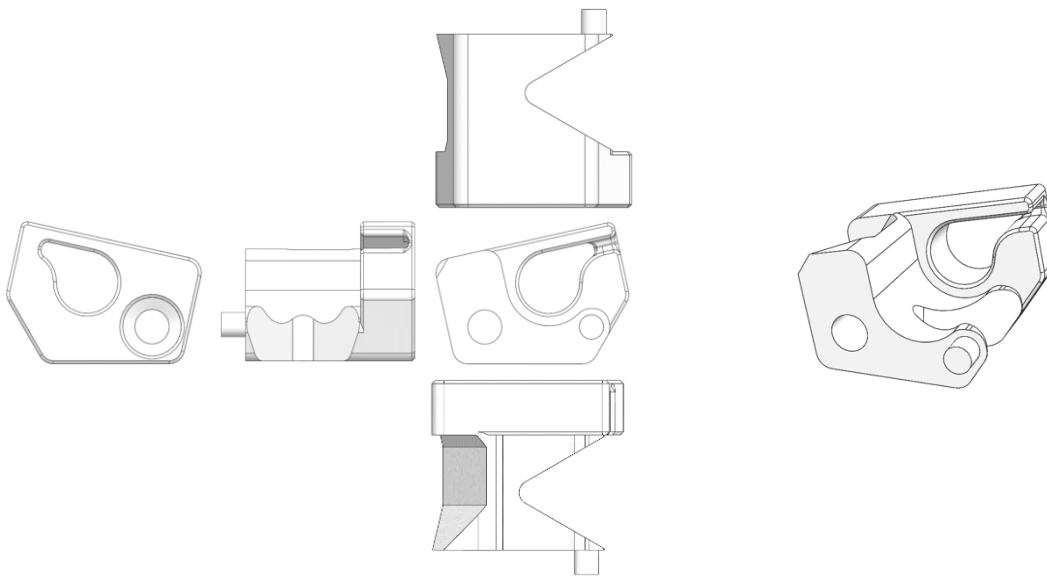


Figure 45 Principal views and Dimetric view

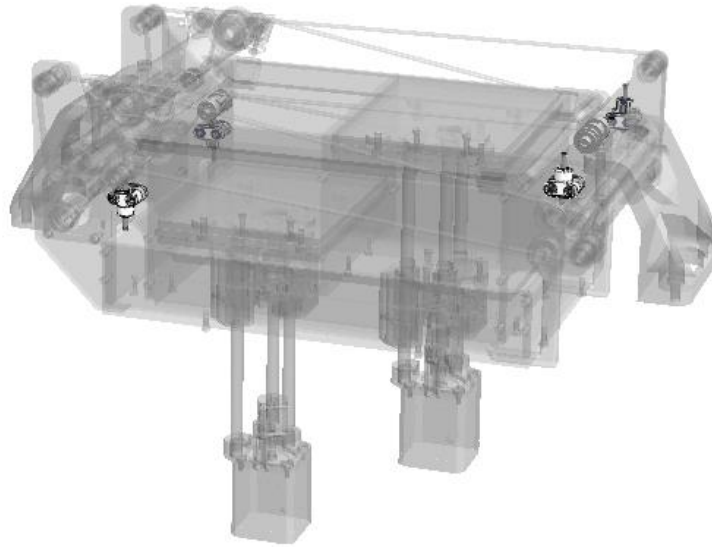
Screw and support for tensile elements - REC-A004 (Tensile Screw), REC-A004-001 (Bolt Support)

Figure 46 Highlighted parts

Main design concept:

- Support for a long bolt, which act as a stop screw.
- Solid and precise adjustability.
- This tensile element must be able to act over both Tensile pulley and the pivoting Fixed belt support.

Assembly limitations:

- Assembly must be compact to avoid interferences with other recoater elements.

Final design:

- The assembly is attached to the frame by two bolts (both nuts held by a 3D printed nut holder (REC-A001-014 (Endstop Nut Holder))).
- The stop screw passes through, being fixed by two nuts pressed with a spring.

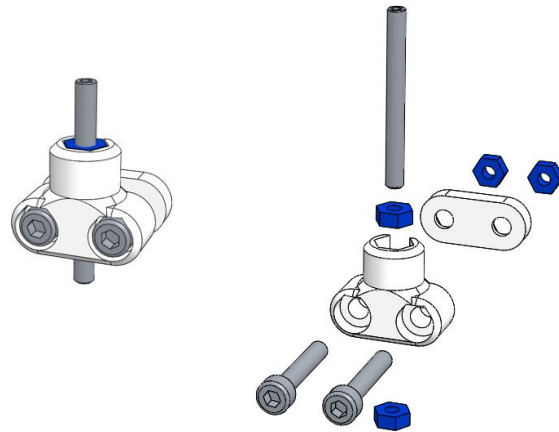


Figure 47 Compacted and exploded assembly views

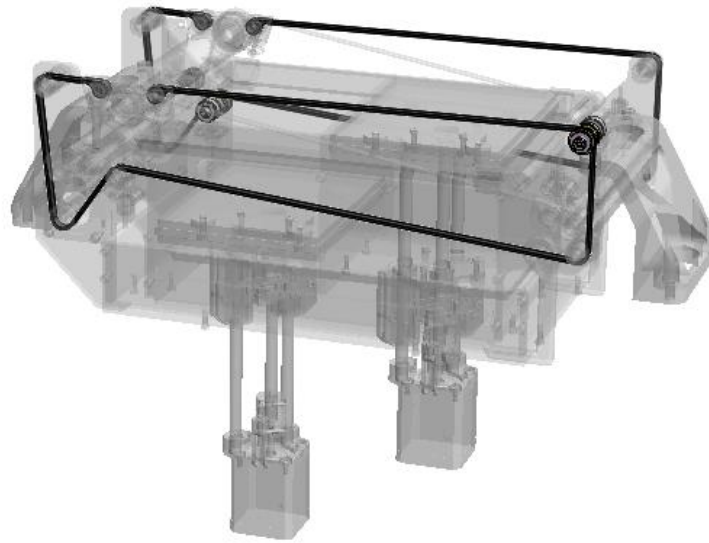
Motor belt - REC-A001-013 (Motor belt)

Figure 48 Highlighted parts

Main design concept:

- Stepper must transmit perfectly power and movement into it.
- Trace must be as short as possible in order to reduce unnecessary material.
- Avoid extremely closed trace angles to reduce fatigue on testing.
- On the carriage plane, belt trace must be horizontal and not to induce extra pressure to the aluminum cylinder.

Assembly limitations:

- Space limitations which highly defined belt's trace.

Final design:

- Commercial belt GT2 6mm wide.
- Belt satisfies all the main design concepts as its seen.

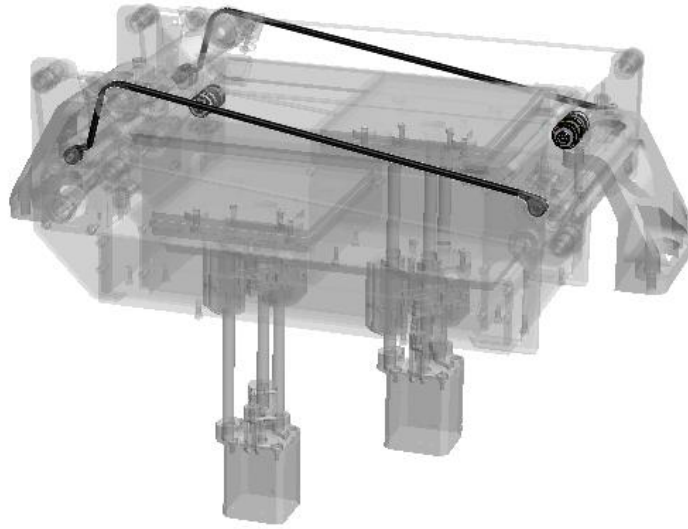
Fixed Belt - REC-A001-012 (Fixed belt)

Figure 49 Highlighted parts

Main design concept:

- This belt must induce pressure to aluminum cylinder's fixed pulley. On one hand to transmit reverse rotation movement, on the other to assure cylinder's contact to the printing zone.

Assembly limitations:

- Space limitations which highly defined belt's trace.

Final design:

- Commercial belt GT2 6mm wide.
- Belt's final position satisfies main design concepts; extreme configurations can be seen in Figure 18.

Endstop set – Endstop, REC-A001-013 (Endstop Spacer), REC-A001-014 (Endstop Nut Holder)

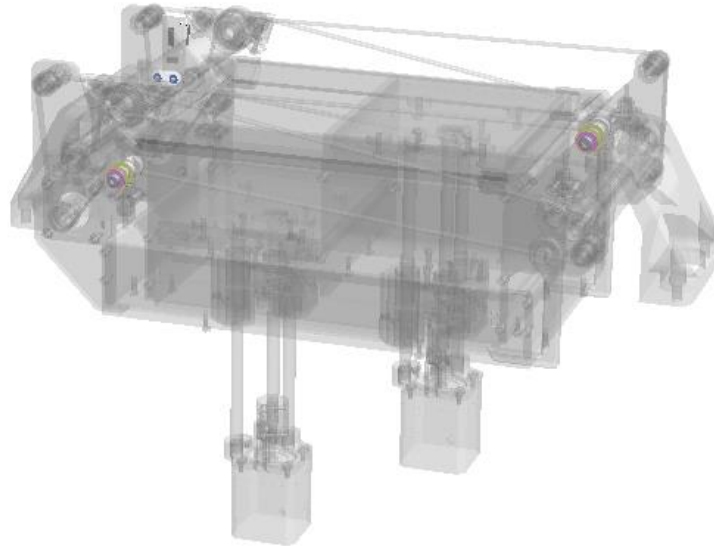


Figure 50 Highlighted parts

Main design concept:

- Electronic element to get zero carriage position.
- Mechanical movement to allow the user to calibrate manually this position.

Assembly limitations:

- Endstop position must get in contact with clamp (endstop's activator element).

Final design:

- Commercial mechanical endstop mounted into a pcb board. Detailed information into electronics section.
- To guarantee proper contact with clamp, a 3D printed PLA spacer (REC-A001-013 (Endstop Spacer)) has been designed. This set is screwed to main frame using two M3 bolts and two nuts held by the same element used earlier: (REC-A001-014 (Endstop Nut Holder)).

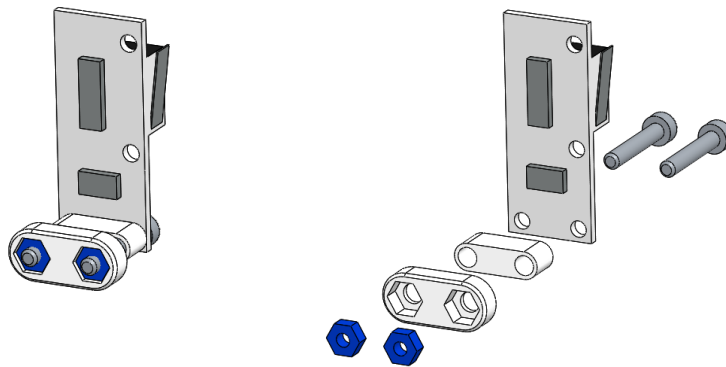


Figure 51 Compacted and exploded assembly views

5.1.2. Powder platforms system

The platforms system consists of a powder feeding platform and a printing zone platform. When the spreading system makes a new layer, the powder feeding platform moves up a specific distance as the printing zone platform moves down as much as the specified layer height.

The platforms system also includes a funnel and a container. The funnel directs exceeding material to the container allowing the user to recycle the overflowing powder.

Another thing which is considered in this assembly is the main union between the Laser machine and the recoater system.

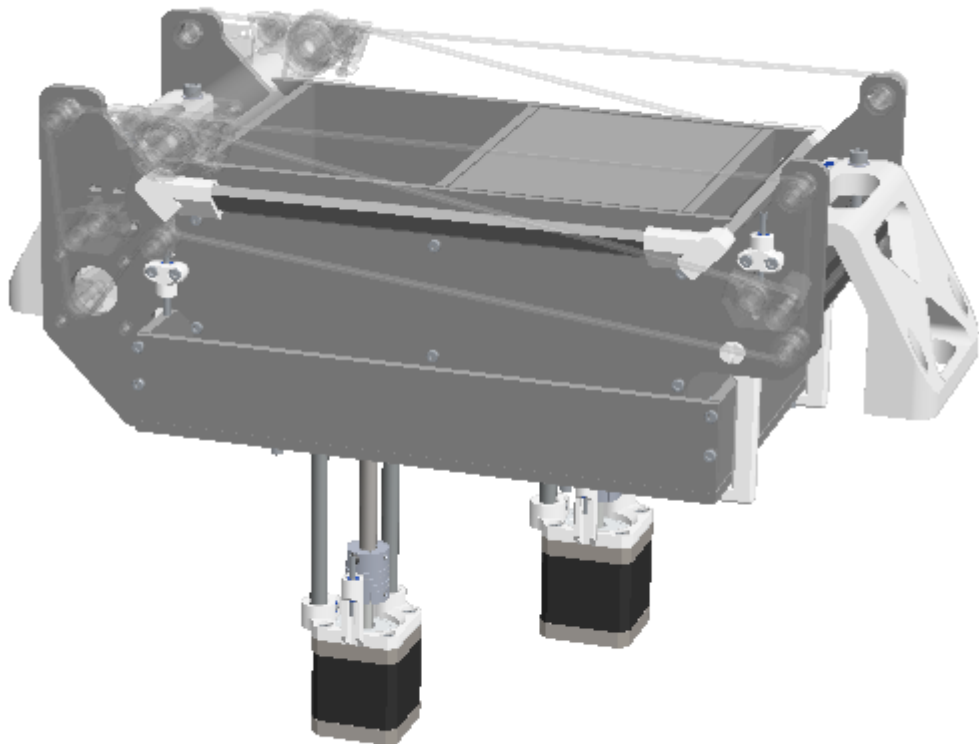


Figure 52 Platforms system highlighted

5.1.2.1. Platforms selection

In order to accomplish the main function, which is feed and layer powder, some configurations come in mind. The most efficient: Independent feeding container, three cubes side by side, two cubes side by side.

Independent feeding container means the user can benefit from wider printing zone. So the whole recoater system's area can be used to move the laser around and fuse the powder. Unfortunately, the laser machine has a reduced height of 40mm between the laser lower part, and the printing zone. That makes nearly impossible to properly design an independent feeding system. Adding material manually opening laser machine's cover is not a desirable solution due to slowness of the process and weak repeatability.

The next interesting option is to have three cubes side by side. Feeding, printing, Feeding. This method used by other SLS producers as seen in the State Of The art section benefits from some advantages: at first, the amount of material which goes to the container reduces because it ends up mainly on a feeding platform; next, the carriage movement reduces to a half because it only has to move to one side per one layer, and to the other side when doing the next layer; finally this process makes the printing process a bit more constant, as the cylinder turns on different directions alternating between layers. This solution has also one big disadvantage: space useful for printing is reduced 1/3 of the main area. That make us look into the third concept: Two cubes.

Pretty similar to the three cubes solution, we choose the two cubes only. One storing feeding material and the other storing the printed layers. This design brings the possibility of electronically controlling how the feeding platform turns up and the amount of material delivered per layer; also maintains an acceptable height between printing surface and laser (which allows the carriage to move from one side to the other and come back without interfering any element); feed the printing zone automatically, without opening the cover and easily refill the feeding cube, as it is only one. All this maintaining the printable area ratio to 1/2 and using only two independent platform assemblies reducing the final budget. That means a printing area of 105x140 mm and a maximum height of 65 mm.

5.1.2.2. Platforms Working Principles

To explain how all this work, we will pick one single platform as seen in Figure 53.

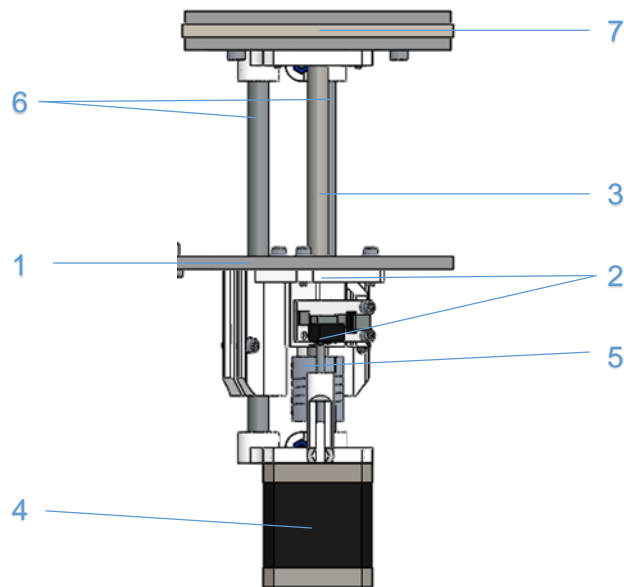


Figure 53 Single platform

So middle surface (1) is fixed to the main structure and M8 nuts (2), held by PLA 3D printed motion idler, as well. When the threaded bar (3) turns, it goes up or down depending on the rotation direction. To move this threaded bar, a stepper (4) is axially attached by an elastic coupling (5) and its rotation is locked by two smooth guides (6). So all the assembly goes up an down moving the platforms (7), the threaded bar also rotates over Z axis and middle surface rests locked.

Rotating both steppers in different directions makes the feeding material platform to deliver powder and the printing platform to make house for the new layer (Figure 54). Then the carriage moves to spread the powder into the printing zone.

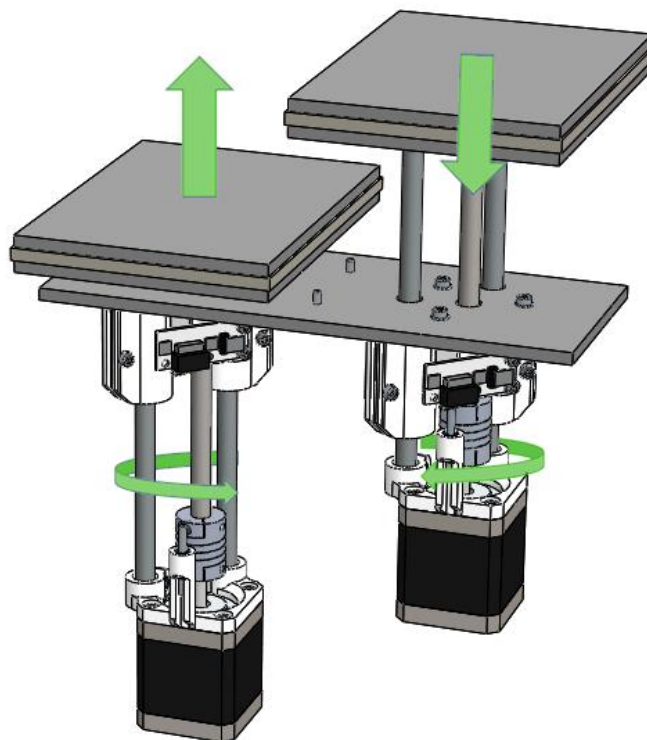


Figure 54 Mechanical moving

5.1.2.3. Platforms general design concepts

Designing this assembly, some general concepts have been considered in order to make it accomplish different purposes. Some of them are pure functionality issues, mentioned earlier like the powder recycling system or the Laser machine joint, others involve production or building facilities. All of them expanded in the following lines.

Giving independent movement to both platforms allows the user to correct the density factor between containers (usually the powder is more compressed when printing) and have different presets to refill the feeding container or remove a printed part.

When the printing process begins, both platforms stay on a set up configuration (Figure 55), explained on the electronics section. To get that, both platforms move down to the endstop and then the printing one moves up to the surface (electronically specified).

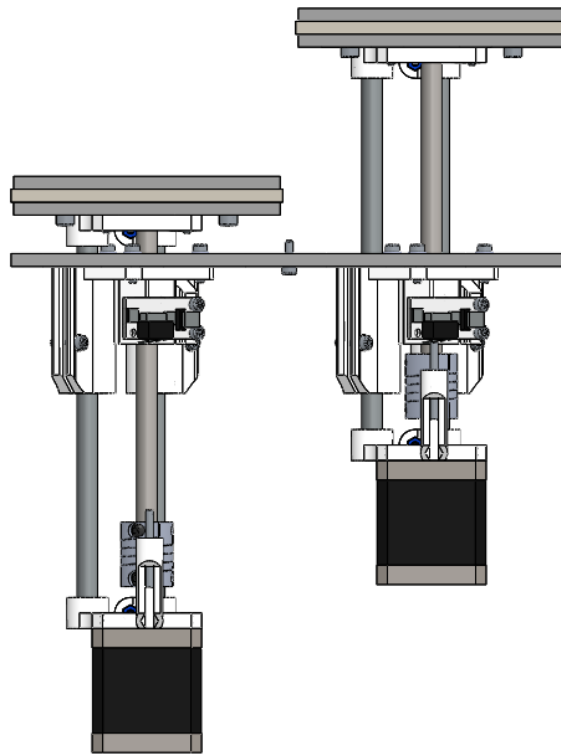


Figure 55 Platforms on set up position

Platforms movement speed is directly related to the threaded bar screw ratio and motor maximum speed (both more detailed in electronics section). Unless this is not critical when printing, it becomes important when setting up machine zero.

To recover the exceeding material, a robust funnel has been designed to throw it to an easy to remove container. This two parts are explained in more detail on the next section but the general concept for both was to make a easy to put and remove system, non obstructive for the rest of the elements.

In order to make the full design the most compact solution, frontal walls act as a whole frame to support all different recoater elements as well as used as walls for the cubes and the main joint with the laser machine. Lateral cube walls are also attached to this frontal walls, and middle surface for the platforms (the fixed one) has been reduced to a single piece. That brings a very robust set which allows a highly reliable testing.

5.1.2.4. Part by part breakdown

With these general design concepts in mind, it is time to explain in detail how different parts have been selected (for commercial ones) or designed (for self-designed ones). All the elements explained are highlighted in Figure 52. The full assembly also includes a blue reference took from the laser machine. However, it has been removed to simplify the images, as its seen in Figure 56.

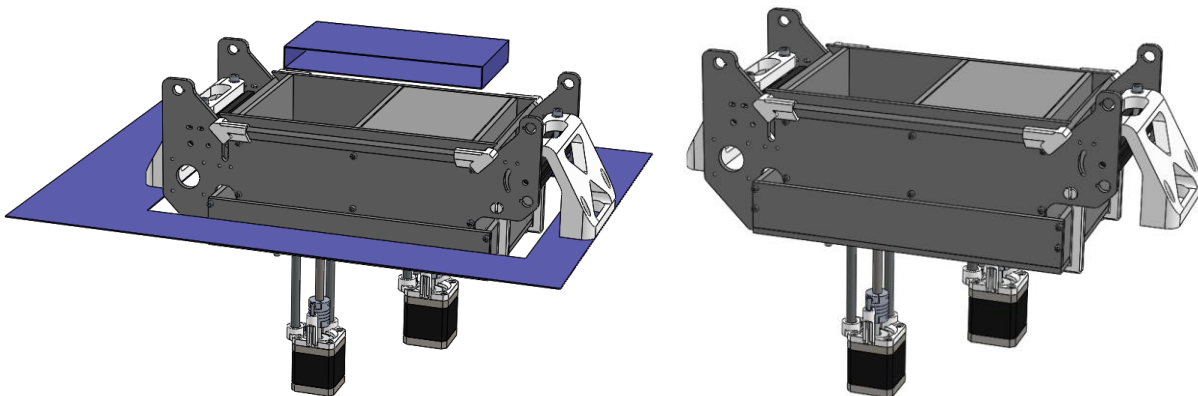


Figure 56 Full recoater assembly (left), laser machine's reference removed (right)

To make this assembly easier to work with, we will break it down in three subassemblies, named: Base structure, Cubes and Platforms as seen in Figure 57.

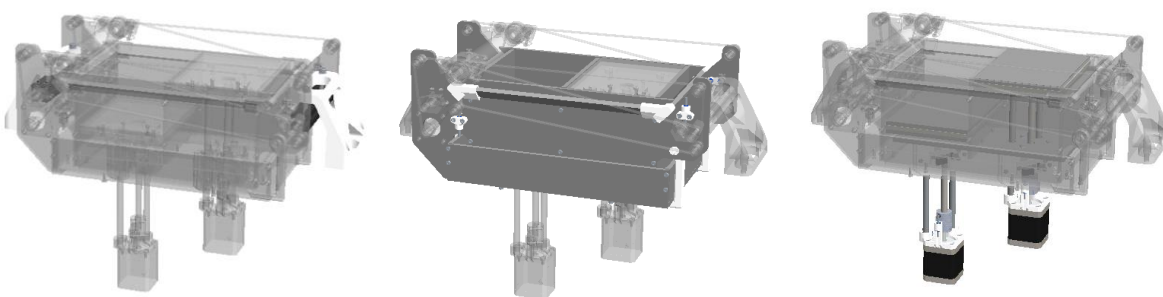


Figure 57 From left to right: Base structure, Cubes and Platforms highlighted

Each part has its own descriptive name (**bold**) and CAD name (*italic*). CAD names follow the rules explained in page 39.

Base Structure

Main junction between *Laser cutting machine* and Recoater System's main frame.

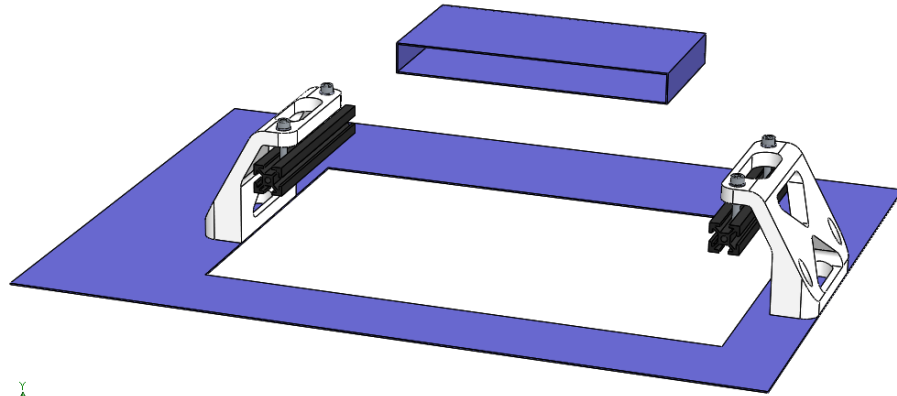


Figure 58 Dimetric view

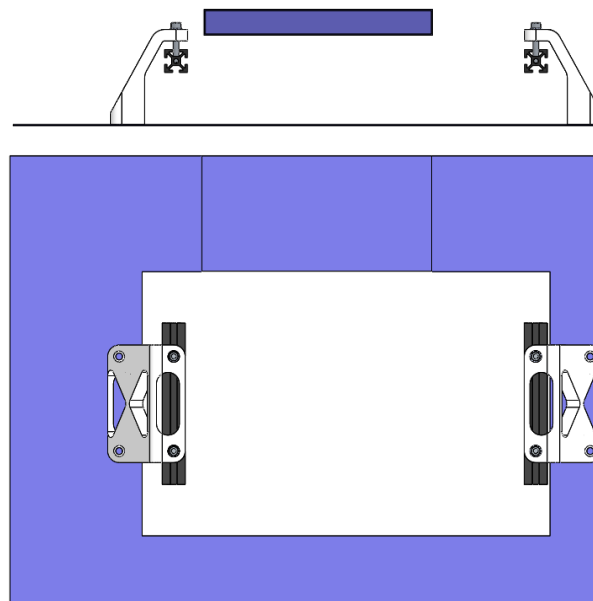


Figure 59 Principal views

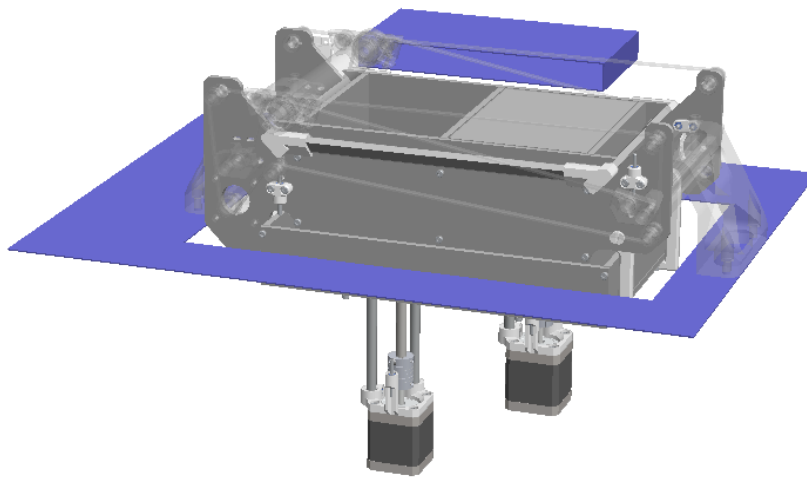
Laser machine base - PLA-A002-002 (Aluminum Sheet)

Figure 60 Highlighted parts

Main design concept:

- A laser machine's simplified CAD. This model makes it easier to work with when designing other recoater elements.

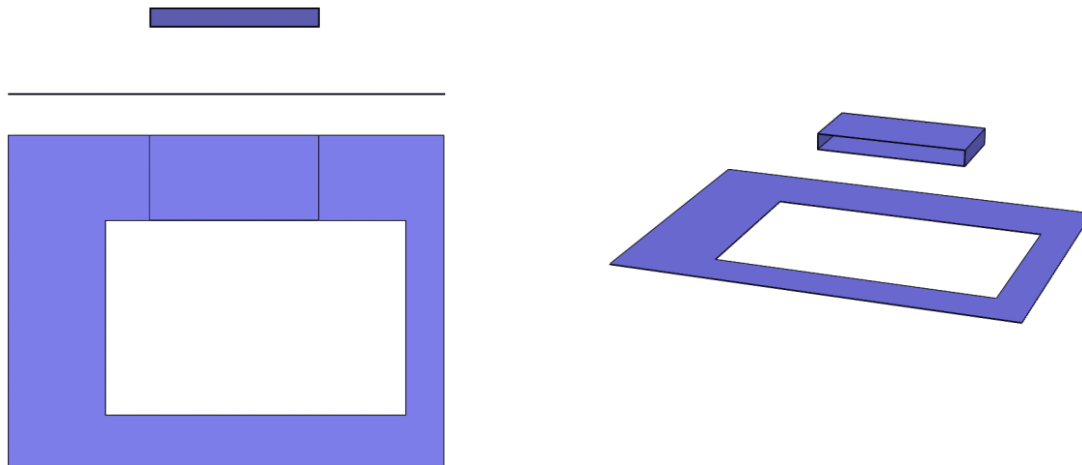


Figure 61 Principal views and Dimetric view

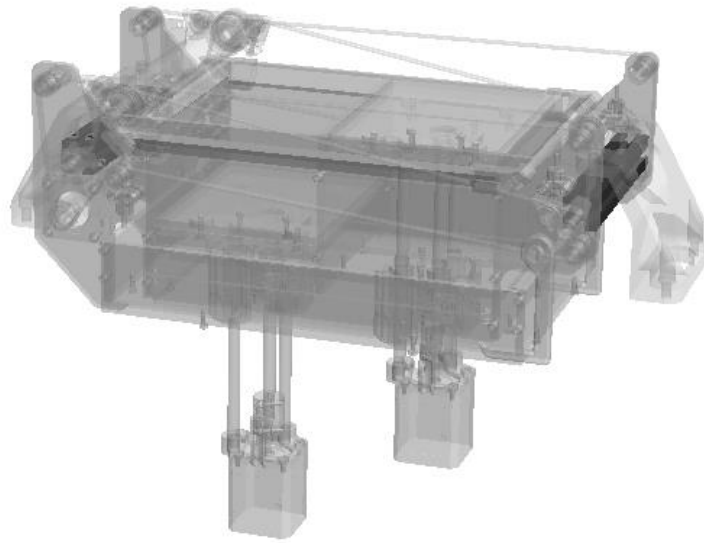
Aluminum profile - PLA-A002-001 (Side Profile)

Figure 62 Highlighted parts

Main design concept:

- Solid joint point between recoater and laser machine.
- Stiffener for main frame PMMA walls, which may deflect when tightening belts.

Assembly limitations:

- Avoid interferences.
- Central section point match with M4 of Fixed belt supports, so that defines belt angles.

Final design:

- Commercial extruded aluminum profiles, also used as main structure for other machines like *BCN3D+*.
- Fixed belt support's M4 bolt makes the joint between extruded profile and main frame PMMA laser cut profile.
- Two vertical threaded holes conform the joint with base support, allowing the user to set proper recoater height and adjust laser's focal distance.

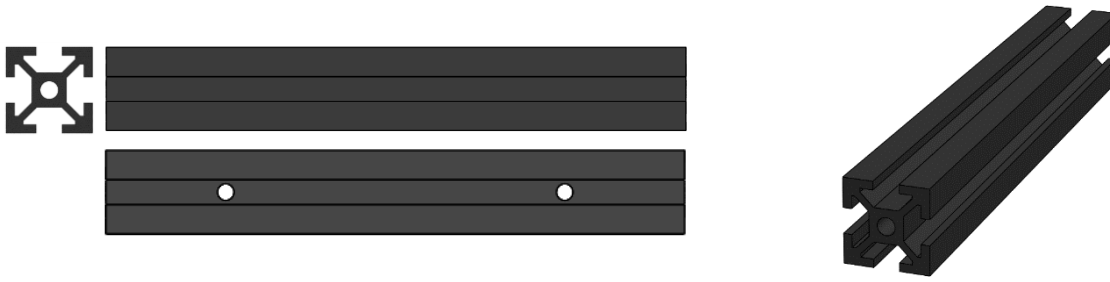


Figure 63 Principal views and Dimetric view

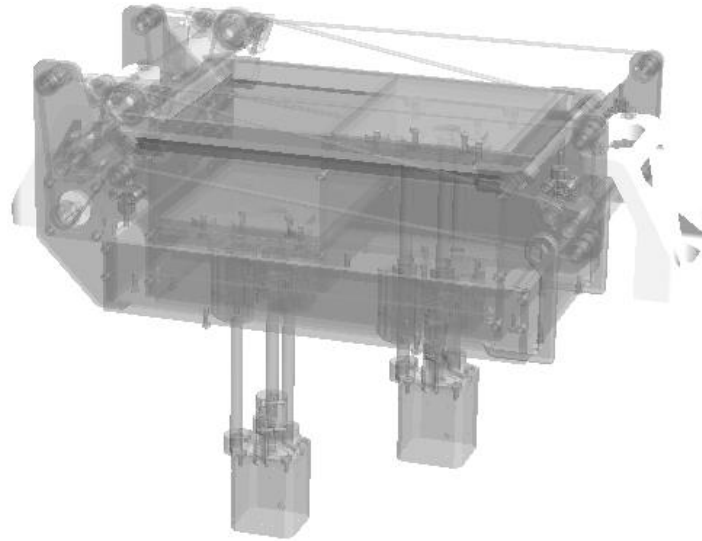
Base support - PLA-A002-003 (Large Support)

Figure 64 Highlighted parts

Main design concept:

- Solid support from laser machine's base to aluminum profiles from the recoater. This support holds the whole recoater assembly.
- 3D printed part to reduce costs.

Assembly limitations:

- Space is extremely limited.

Final design:

- 3D printed support designed to be printed. Material reduction has been done in order to reduce printing time.
- Two M5 bolts fix the support to laser machine base.
- Two M5 bolts fix the support to aluminum profiles. Depending on screwed distance, user can adjust recoater height.

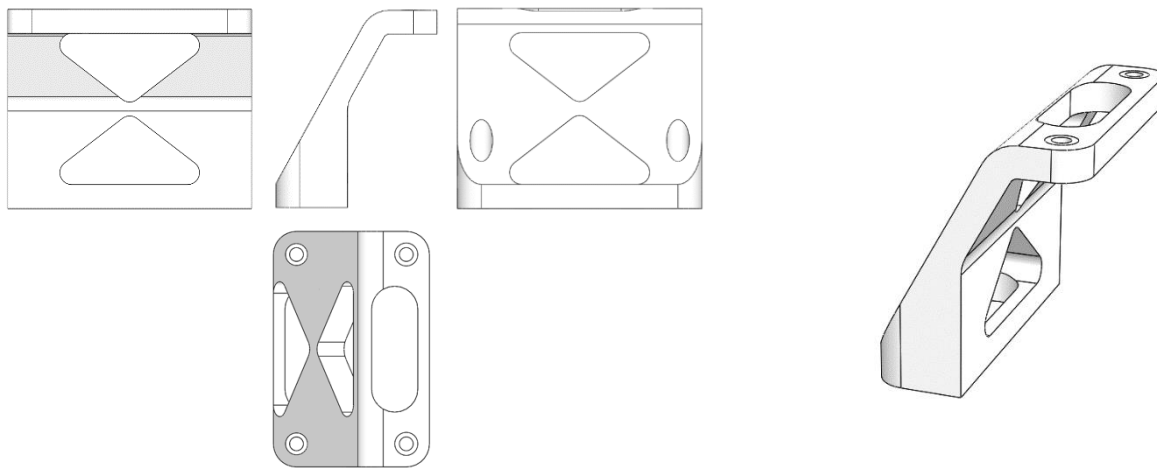


Figure 65 Principal views and Dimetric view

Cubes

Recoater System's main frame. Includes the funnel and the container to manage the exceeding powder.

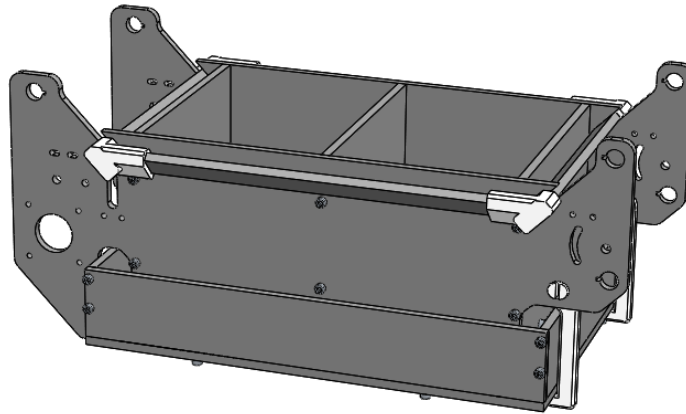


Figure 66 Dimetric view

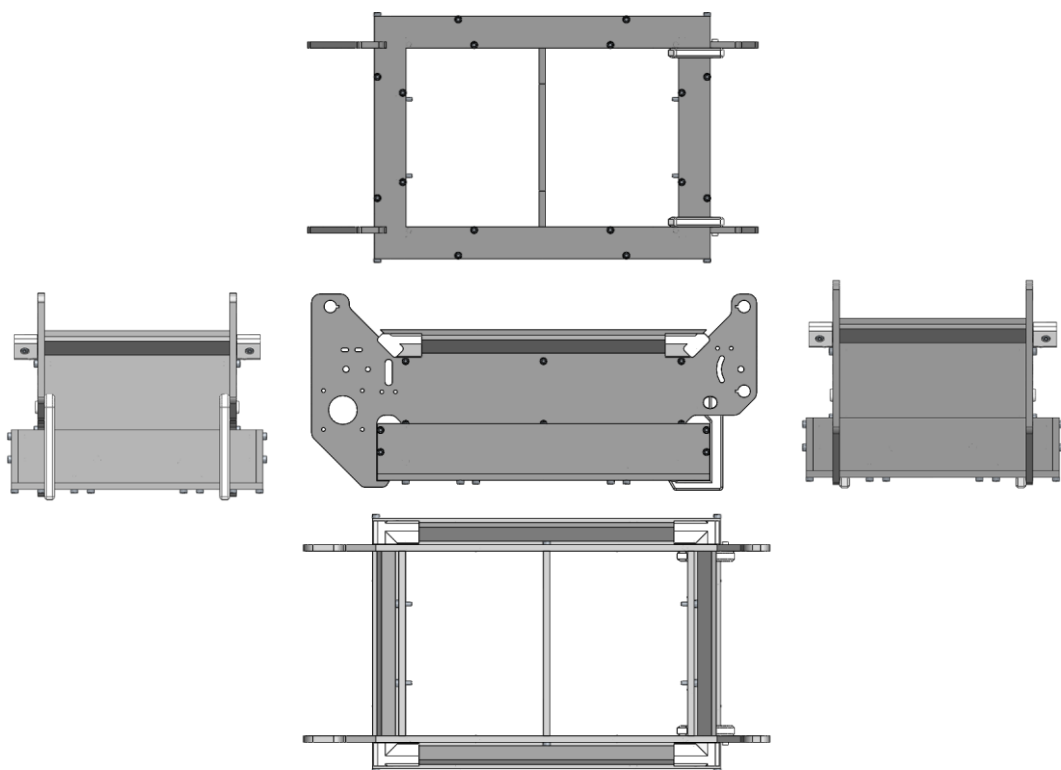


Figure 67 Principal views

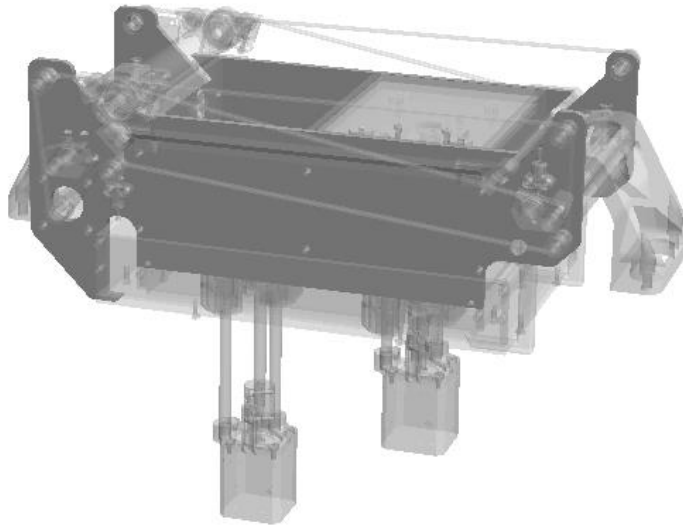
Main front walls - PLA-A003-001 (Wall A)

Figure 68 Highlighted parts

Main design concept:

- Early referred to it as 'Main Frame', its first function is to act as support for almost all recoater elements, including steppers, pulleys, lateral walls, belt supports, exceeding material container, funnel, etc.
- Also act as lateral wall for feeding material container and printing zone cubes.
- Serve as guide to the rolling carriage.

Assembly limitations:

- Space limitations from laser machine's available housing.

Final design:

- 5mm PMMA laser cut profile.
- Includes all holes and slots, taking advantage of laser cut precision, to act as support for almost all recoater elements.

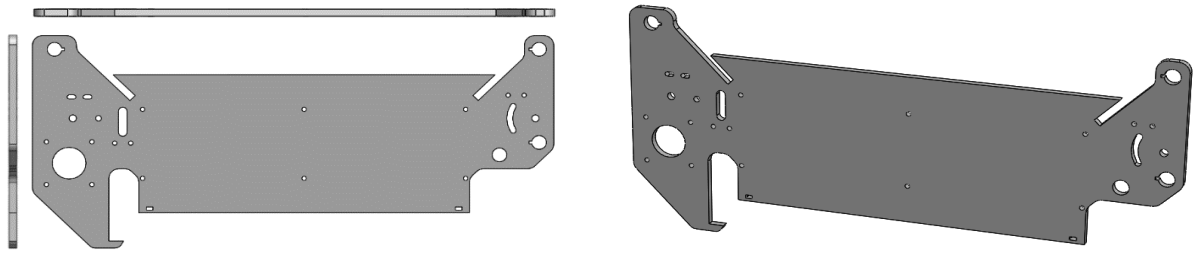


Figure 69 Principal views and Dimetric view

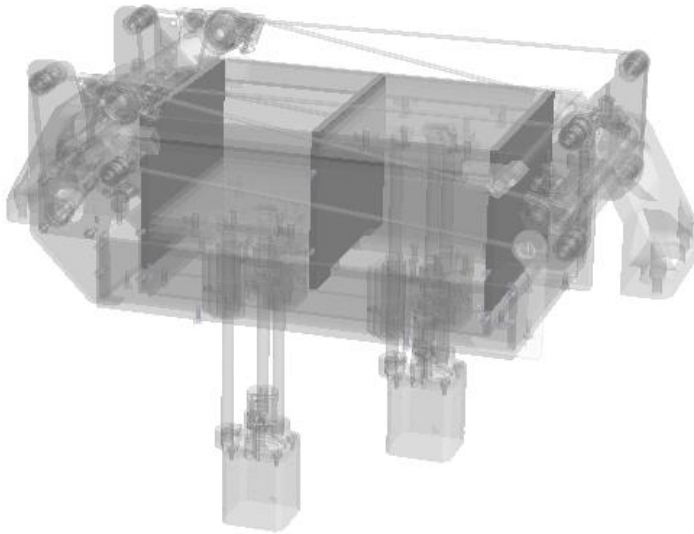
Lateral walls - PLA-A003-002 (Wall B), PLA-A003-002 (Wall B Middle)

Figure 70 Highlighted parts

Main design concept:

- Three lateral walls define printing area and feeding material container boundaries.
- Solid and precise structure to let the platforms move smoothly up and down.

Assembly limitations:

- Middle wall is slotted to fit middle base surface.

Final design:

- 5mm PMMA laser cut profile.
- Includes all holes for screws taking advantage of laser cut precision.
- Two laterals are the same (Figure 72), the one in the middle (Figure 73) includes a slot for middle surface housing. Positioned lateral walls are showed with and without middle surface in Figure 71.

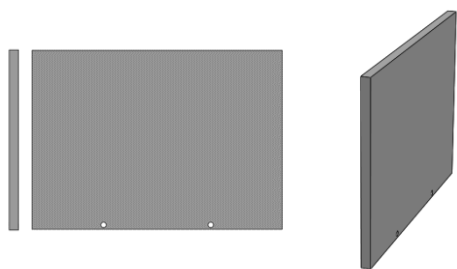


Figure 72 Lateral walls (edges)



Figure 73 Lateral Wall (middle one)

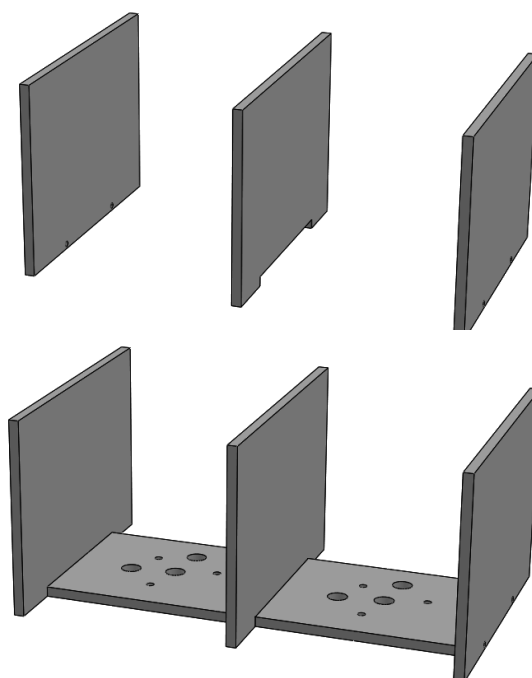


Figure 71 Walls assembly

Container - *PLA-A003-003 (Container Wall A), PLA-A003-004 (Container Wall B), PLA-A003-005 (Container Floor), PLA-A003-006 (Container Wall A ext), PLA-A003-007 (Container Wall B ext), Magnet, PLA-A003-010 (Container Holder)*

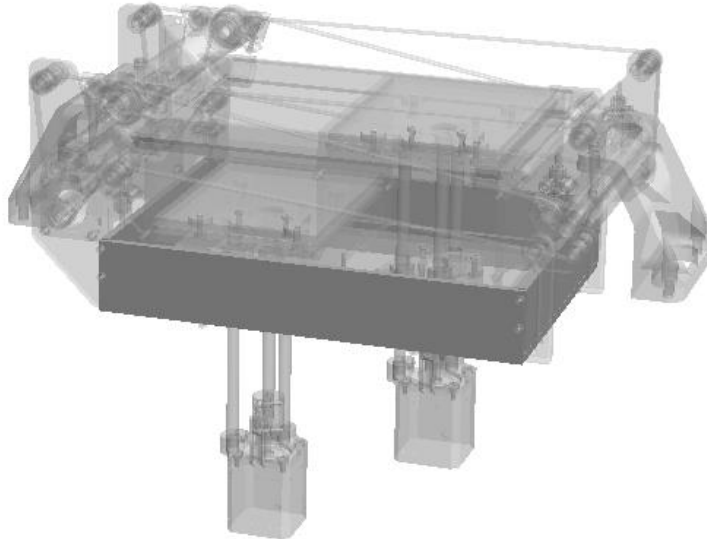


Figure 74 Highlighted parts

Main design concept:

- Specific container to keep exceeding powder during printing.
- Easy to mount, dismount and empty.
- Keep Z steppers away from powder as much as possible

Assembly limitations:

- A container at the lowest point of Z axis would void the third condition, making Z axis elements below the platforms highly susceptible to get powder soaked. So the container must be as near to the exceeding surface as its possible, keeping it simple.

Final design:

- Assembly made of 5mm PMMA laser cut profiles joint by screws.
- Container wraps the cubes walls, giving free and clean space to Z axis elements.
- Magnet-assisted positioning to make it easier to mount after emptying.
- Solid fixture using 3D printed PLA clamps (*PLA-A003-010 (Container Holder)*).

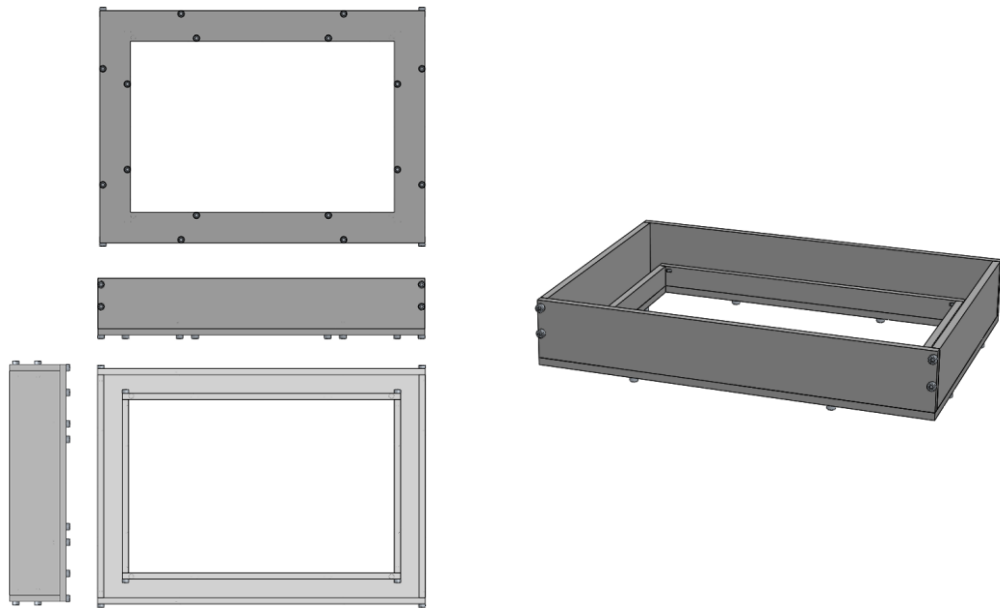


Figure 75 Mounted container, principal and dimetric views

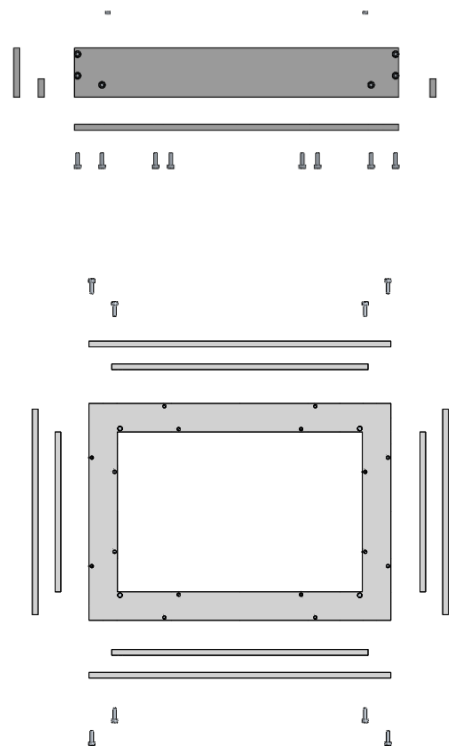


Figure 76 Exploded container assembly. Principal views

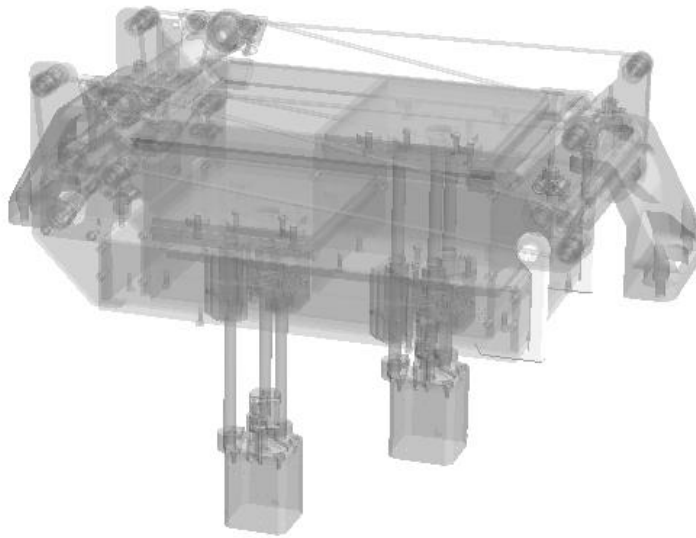
Container Holder - PLA-A003-010 (Container Holder)

Figure 77 Highlighted parts

Main design concept:

- Easy to mount clamp to solidly fix the exceeding material container.

Final design:

- 3D printed clamps.
- Using clip solution, it is the easiest way to mount the clamps to the main frame.
- Clamps pivot freely when positioning the container and rest fixed when it is mounted.

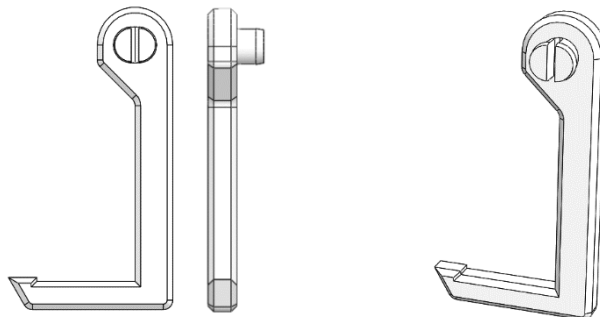


Figure 78 Principal views and Dimetric view

Funnel - PLA-A003-010 (Funnel Wall A), PLA-A003-008 (Funnel Wall B), PLA-A003-009 (Funnel Joint)

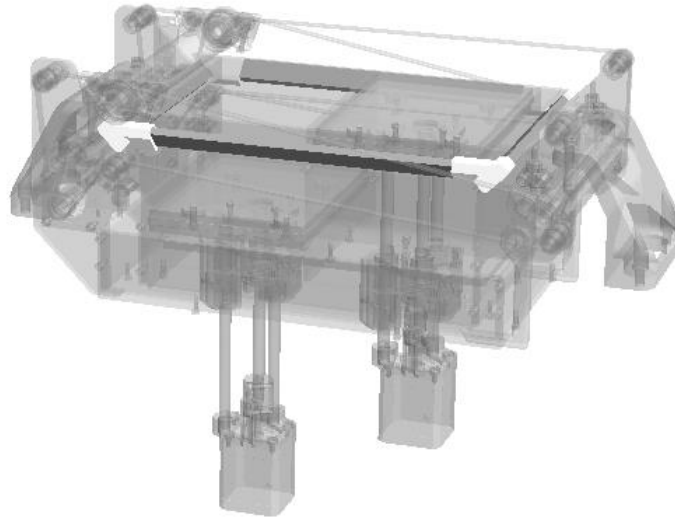


Figure 79 Highlighted parts

Main design concept:

- Specific funnel to redirect exceeding material to the container.
- Must fit into main frame.
- Easy to mount/dismount.
- Solid design.

Assembly limitations:

- Space limitations due to its position.

Final design:

- Assembly made of 5mm PMMA laser cut profiles joint by screws to 3D printed PLA joints, which give the desired 45-degree angle to funnel walls.
- PLA 3D printed joints (Figure 81) position the walls at a desired 45-degree angle, and hold them firmly.
- Bolts are screwed directly on PMMA profiles and make pressure to PLA joints, fixing the assembly but making it easy too to remove if needed (Figure 82).

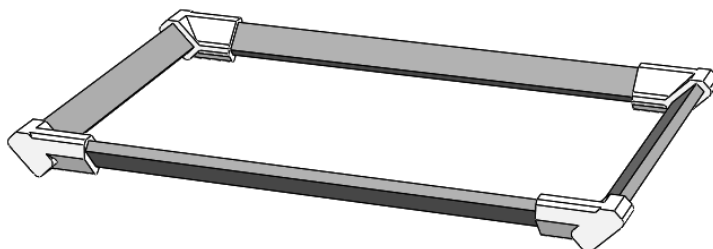


Figure 80 Mounted funnel assembly

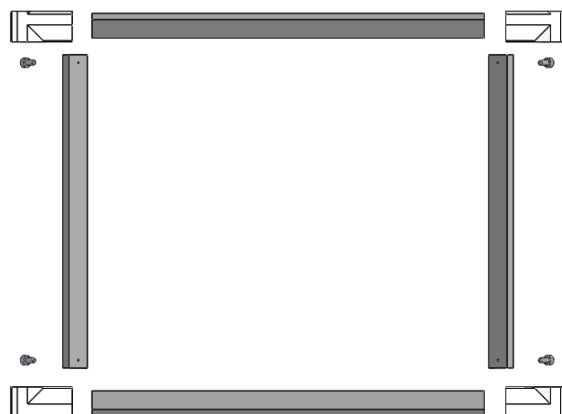


Figure 82 Exploded Funnel Assembly

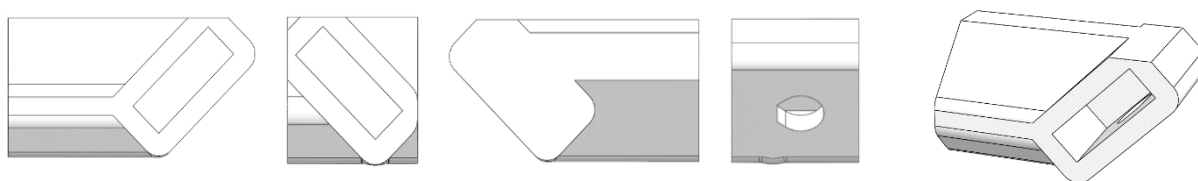


Figure 81 Funnel joint principal views and Dimetric view

Plaforms

Mobile Platforms system.

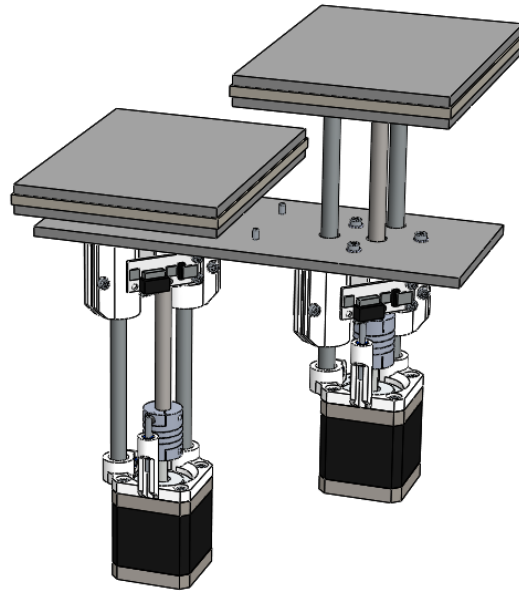


Figure 83 Dimetric view

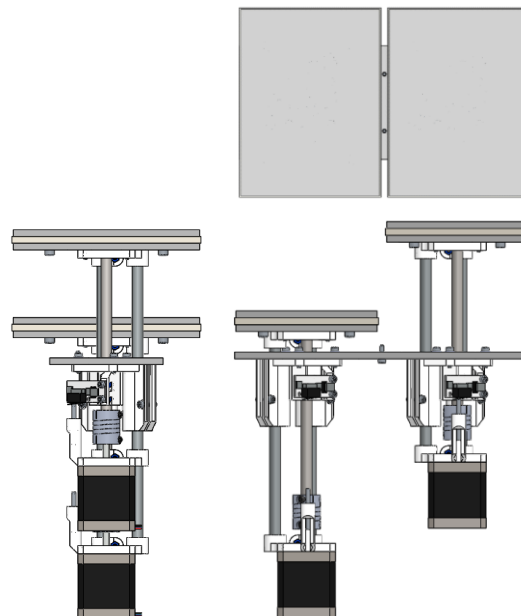


Figure 84 Principal views

Platforms - PLA-A004-001 (Bottom Surface), PLA-A004-002 (Foam), PLA-A004-003 (Top Surface), PLA-A004-011 (Platform Spacer)

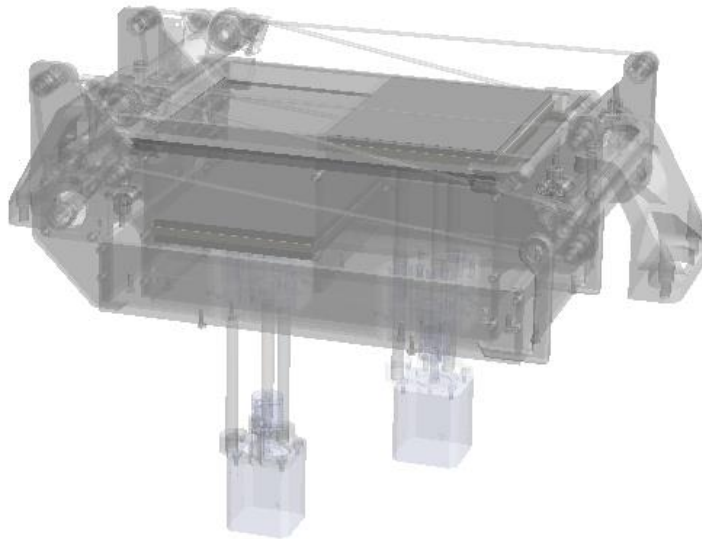


Figure 85 Highlighted parts

Main design concept:

- Solid platform system to move up and down precisely the powder on both cubes.

Assembly limitations:

- Deal with possible building imperfections which lead to a non perfectly vertical cube walls.
- Friction between PMMA pieces can be higher than expected if walls verticality varies.

Final design:

- A set of three layers allow the platform to move smoothly: two 5mm PMMA laser cut profiles and one foam layer sandwiched in between (Figure 86).
- Bottom PMMA layer includes laser cut holes for screws.
- PMMA profiles are 1mm shorter per each side, to prevent stranding or excessive friction induced by verticality wall issues.
- The foam layer also includes four 3D printed PLA spacers in order to maintain parallelism between platform elements.
- Foam allows platforms to move with lower friction than if its done directly with PMMA profiles, as foam adapts to possible surface variations.

- Top PMMA surface includes blind threaded holes, where bolts through spacers are screwed, to make sure the platform set acts like a single block. In Figure 88 it is seen how the set looks when mounted, as PMMA profiles have been kept in transparent look.

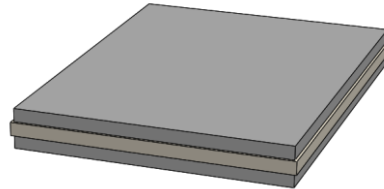


Figure 86 Platform's sandwich assembly

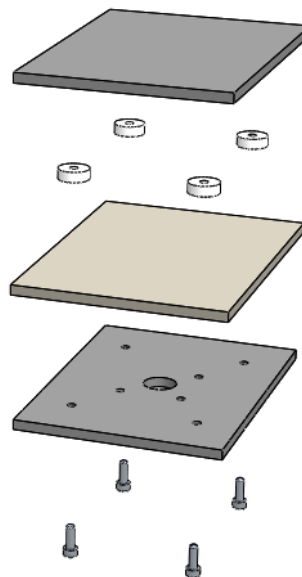


Figure 87 Platform set exploded view

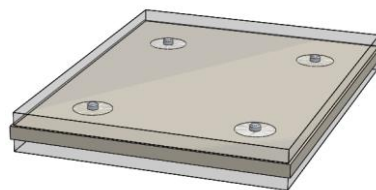


Figure 88 Platform sandwich assembly (PMMA profiles kept transparent)

Bars - *PLA-A004-004 (Rod Bar M8), PLA-A004-005 (Smooth Bar)*

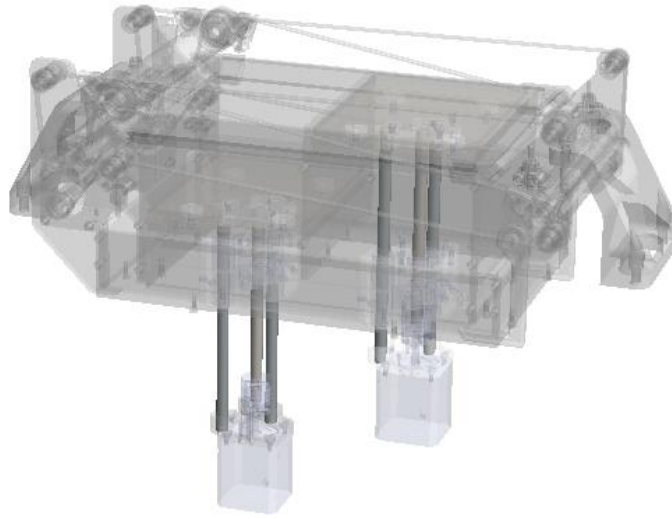


Figure 89 Highlighted parts

Main design concept:

- Smooth bars to guide whole platform set.
- Threaded bar to move vertically whole platform set.

Assembly limitations:

- In order to use same bars as other machines like *BCN3D+*, M8 bars would be preferable.

Final design:

- M8 bars used in *BCN3D+* printer provides a smooth movement.
- Smooth bar (*PLA-A004-005 (Smooth Bar)*) 160 mm long and threaded bar (*PLA-A004-004 (Rod Bar M8)*) 136 mm long let the assembly use the full printing volume height when printing.



Figure 90 Principal views and Dimetric view

Middle base surface - PLA-A004-006 (Mid Surface)

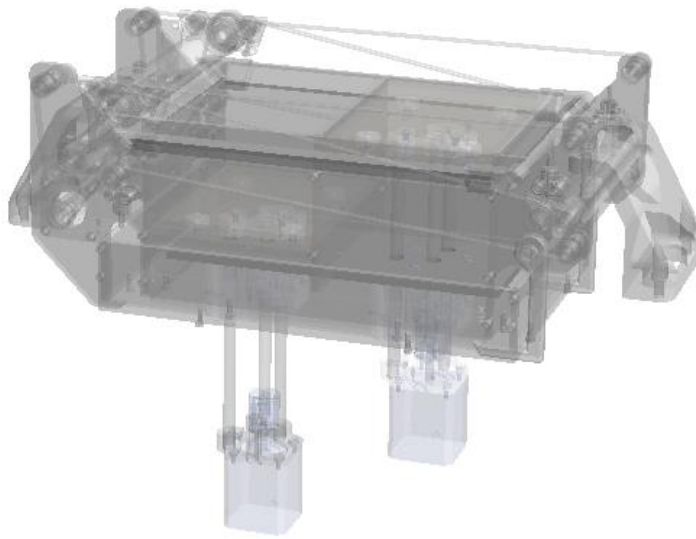


Figure 91 Highlighted parts

Main design concept:

- Solid surface in which both platform systems are held.

Assembly limitations:

- Must allow the user mount the platform assembly.

Final design:

- One single 5mm PMMA laser cut profile which includes holes for screws and bars.
- Solidly screwed to cubes structure.
- Keeping free zones to use tooling on mounting.

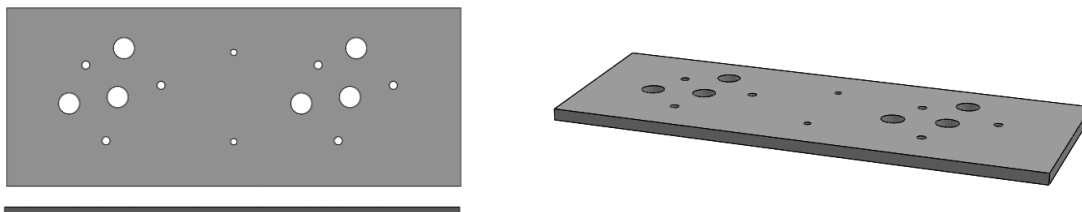


Figure 92 Principal views and Dimetric view

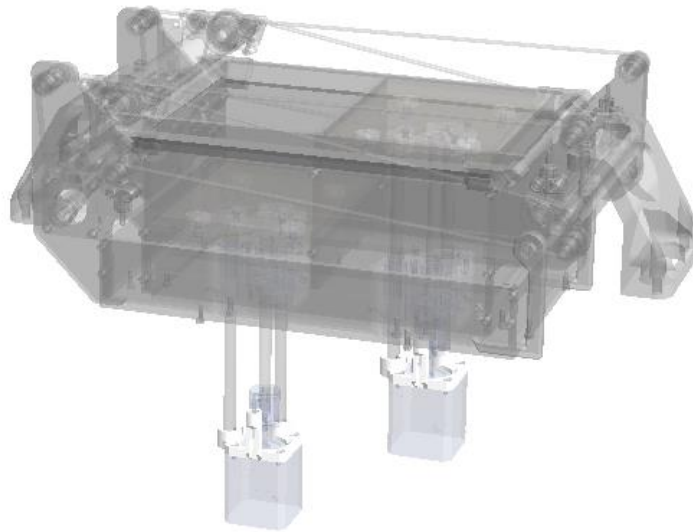
Z motor holder - PLA-A004-007 (Z Lower Clamp)

Figure 93 Highlighted parts

Main design concept:

- Block stepper's degrees of freedom allowing it to go only up and down.
- Hold Z-endstop bolt, to adjust manually the Zero configuration.

Assembly limitations:

- Space limitations.

Final design:

- 3D printed PLA part.
- Fixed to stepper on 3 points.
- Clamps both smooth bars with a clamping bolt
- Turret comes up to hold the endstop M3 bolt, this one gets fixed by two nuts pressed with a spring, as seen in the section view in Figure 94. This M3 bolt allows the user to set properly Z axis' zero position.

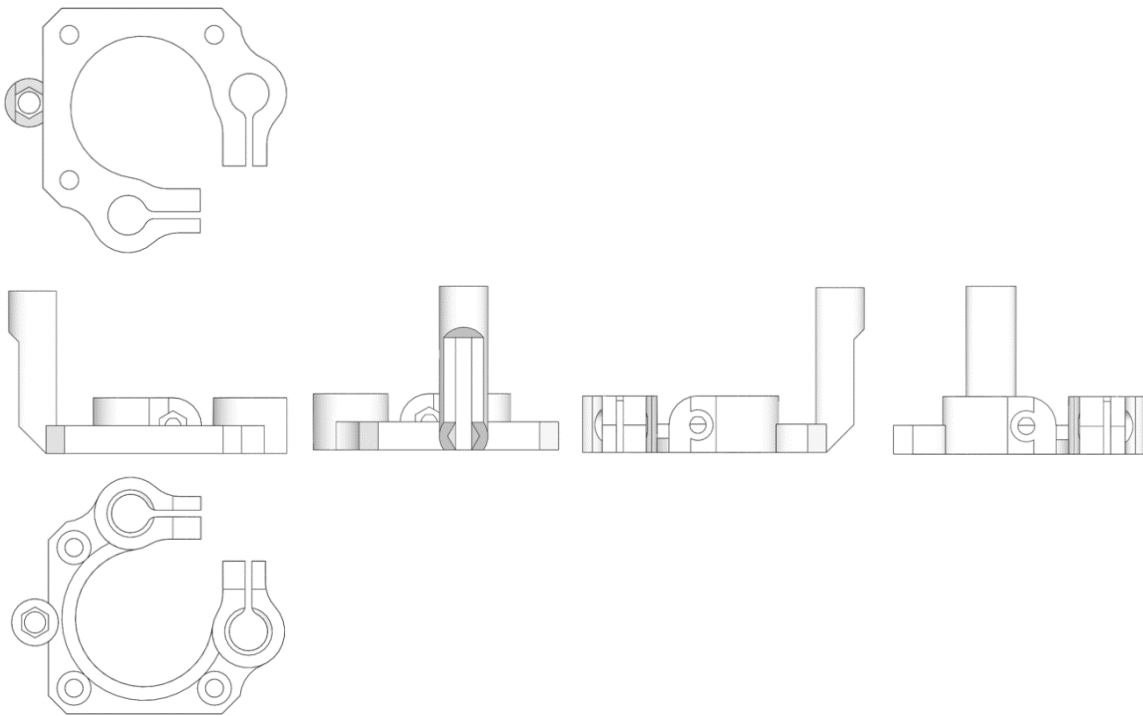


Figure 96 Principal views

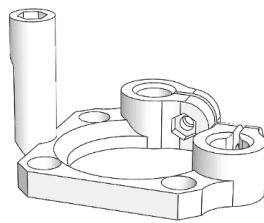


Figure 95 Dimetric view

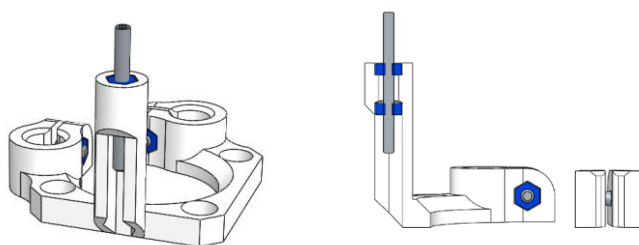


Figure 94 Part and screws

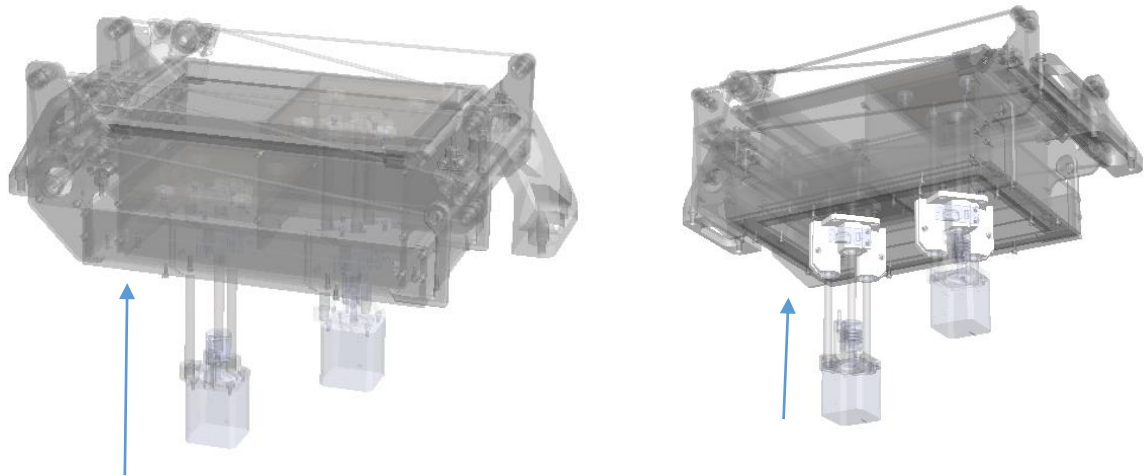
Z mid surface holder (fixed) - PLA-A004-008 (Z Motion Idler)

Figure 97 Highlighted parts

Main design concept:

- Guide both bars vertically.
- Support for Z-endstop.
- Housing for threaded M8 bar nuts.

Assembly limitations:

- This part and the middle base surface are the only ones which rest fixed on the platform system assembly.

Final design:

- 3D printed PLA part.
- Fixed to middle base surface on 3 points.
- 4 linear bearings (*LM8 Linear bearing*) are used to make contact with smooth bars, 2 for each one (Figure 100).
- Clamps both linear bearings with a clamping bolt.
- A proper housing gives the desired angle and position to the Endstop PCB.
- Threaded M8 bar nuts are held in pressure by a internal spring.



Figure 98 Principal views

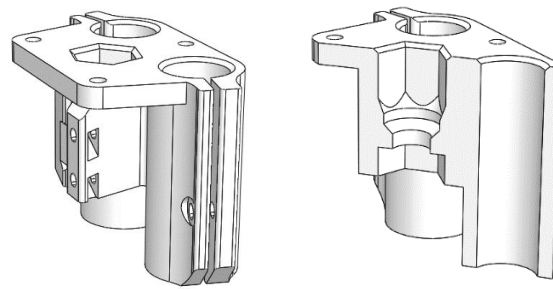


Figure 99 Dimetric view (sectioned on the right)

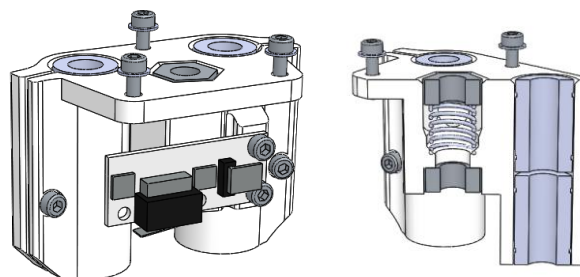


Figure 100 Part and screws, bearings, nuts, spring and endstop

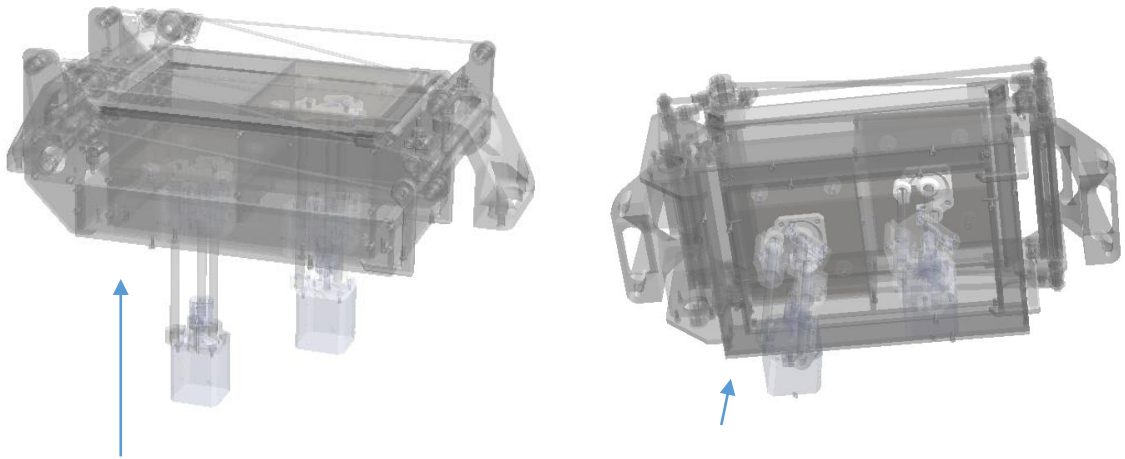
Z platform holder - PLA-A004-009 (Z Upper Clamp)

Figure 101 Highlighted parts

Main design concept:

- Block platform degrees of freedom allowing it to go only up and down.

Assembly limitations:

- Difficult are to work when mounting the assembly.

Final design:

- 3D printed PLA part.
- Fixed to platform on 3 points.
- Clamps both smooth bars with a clamping bolt
- A hole in the middle holds a bushing (*Selfoil 4-8-12-2-10*) to allow the threaded bar to rotate smoothly (Figure 102).

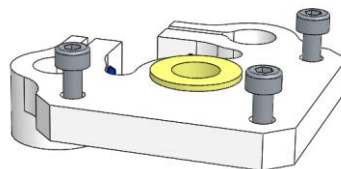


Figure 102 Assembly view

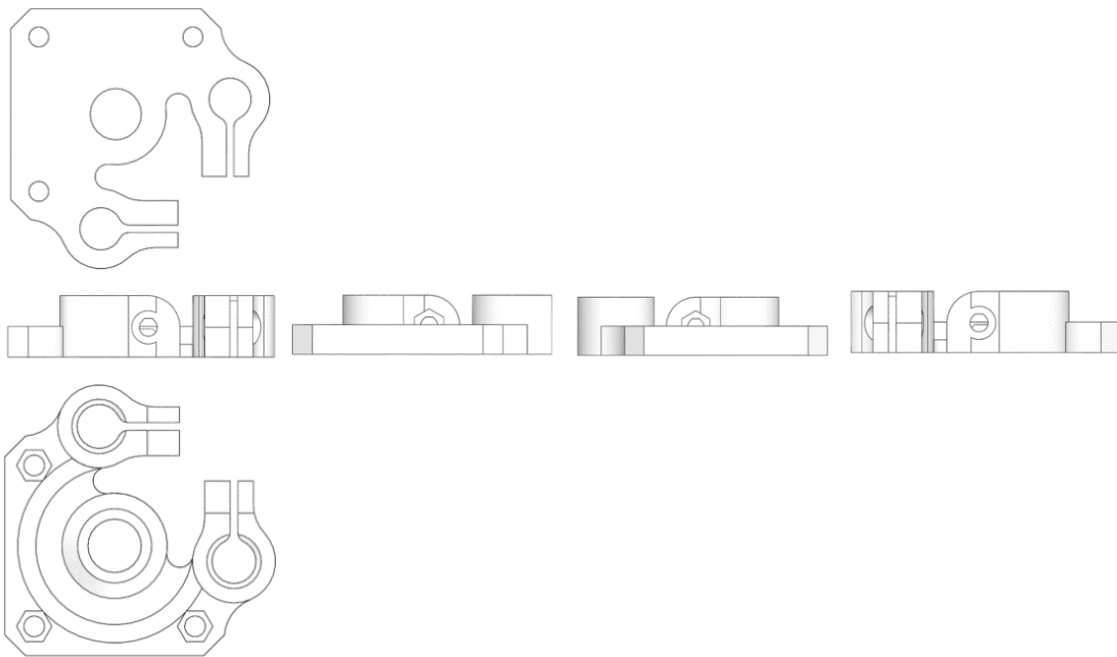


Figure 103 Principal views

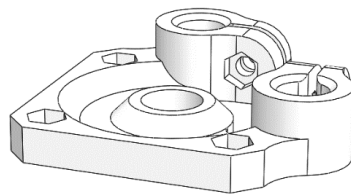


Figure 104 Dimetric view

Endstop and Motors - Endstop, SY42STH47-1684A_Real Colors (cut)

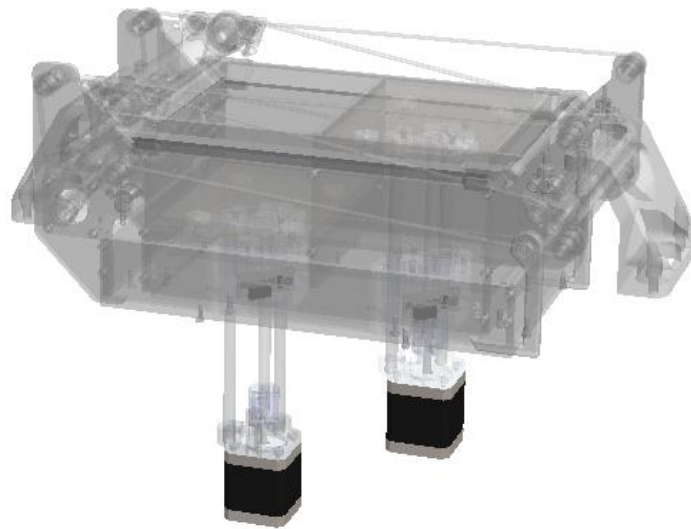


Figure 105 Highlighted parts

Both elements are the same used on the spreading system.

5.2. Mechanical calculations

To choose the electronic components that will move the system, some mechanical calculations need to be done to see how much torque will be need to move the system. With this values, the electronic will be chosen from the stock in *Fundació CIM*.

There are basically three systems that have to be calculated and tested: stepper motors, controller and power supply. All of them are located on the recoating system as the laser machine has its own electronic system.

5.2.1. Recoating system

Constant speed

In the Figure 106 a schematic view of the recoating system is represented to understand how the system works. The motor generates a torque that is transmitted to the cylinder through the belt. The cylinder is supported directly on the methacrylate box creating a friction force.

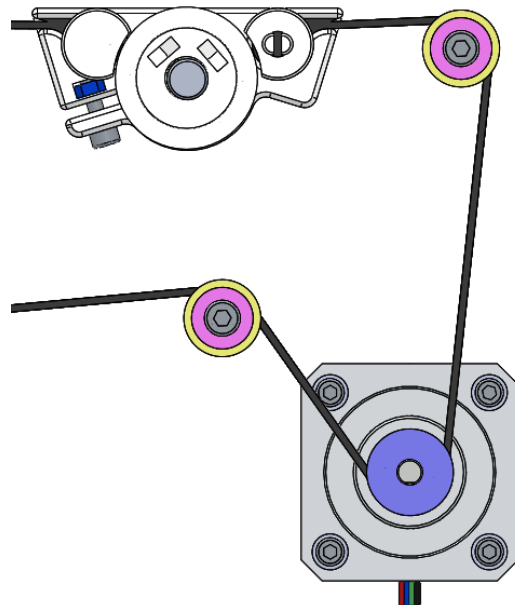


Figure 106 Mechanical system

On the Figure 107, a simplified schematic of the system allows to draw the force diagram where the forces in red are related to the cylinder or to pieces directly attached to it and the green F is the force on the motor shaft that is intended to be found.

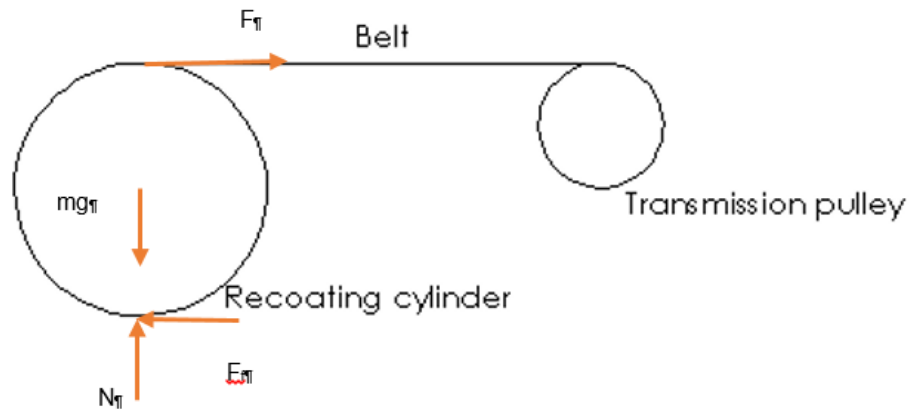


Figure 107 Simplified schematic

From the force diagram and the equilibrium constraint the following equations can be set:

$$N * \mu = F$$

$$mg + F_p = N$$

Clearing F from this system:

$$F = \frac{\mu * (mg + F_p)}{1 - \mu}$$

The motor pulley has a radius of 6,1 mm. The static friction coefficient μ for the aluminum and Methacrylate is $\mu = 0,1$. The mass of the system is $m = 0,319$ Kg.

So the value of the F force is:

$$F = \frac{0,1 * (0,319 * 9,81 + 1,31)}{1 - 0,1} = 0,493 \text{ N}$$

So the torque required to the motor is:

$$\tau = F * r_{pulley} = 0,493 * 6,1 = 3 \text{ N} * \text{mm} = 0,03 \text{ Kg} * \text{cm}$$

Acceleration

To calculate the torque required to begin the movement the acceleration is set to zero to perform a static analysis. As static analysis does not take in account acceleration, the motor should have some extra torque power to add some acceleration. The analysis is done on that way because is simpler and high acceleration will be never set to the machine. The force diagram is the same and the only change is the value of the friction coefficient. In this case, as it is a static case $\mu = 0,2$.

Calculating again the force F and the torque:

$$F = \frac{0,2 * (0,319 * 9,81 + 1,31)}{1 - 0,2} = 0,986 \text{ N}$$

$$\tau = F * r_{pulley} = 0,986 * 6,1 = 6,017 \text{ N} * \text{mm} = 0,063 \text{ Kg} * \text{cm}$$

So the torque is maximum at the beginning of the movement.

5.2.2. Platforms system

As it has been told before, the platforms system consists of the powder feeding platform and the printing zone platform. This two platforms, are moved by a stepper motor that turns a power screw to turn the rotatory movement into lineal controlled movement.

To see if the stepper motors provided by *Fundació Cim* are suitable for this application the calculation of the torque required to lift the platforms must be done. Basically, the stepper motors must be able to lift the platforms full of powder.

The power screw is basically an inclined plane rolled around an axis. So the diagram of the

forces that actuates on the system are shown in the Figure 108.

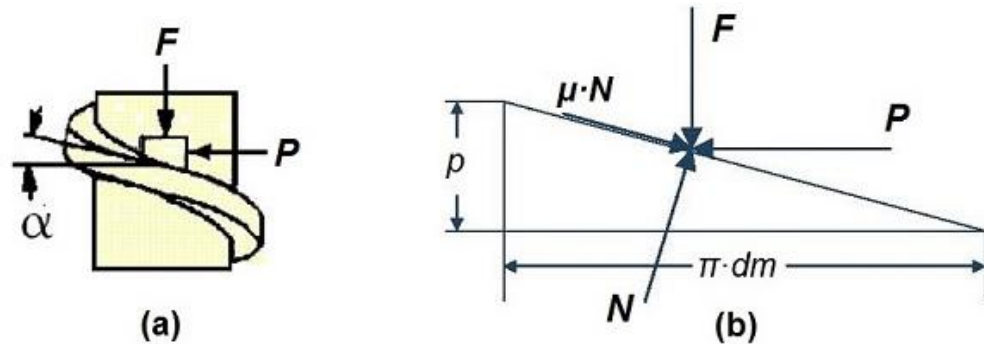


Figure 108 Threaded bar forces analysis

Where:

F : Force to be lifted by the platform

N : Normal force to the screw plane

P : Force to be determined

F_f : Friction force

Another factor has to be taken into account on the studied case as there is a spring inside the idler (as it has been described on previous pages). As the spring force is an inner piece force it does not affect the overall diagram, but because of the force applied to the faces of the screw the friction force gets bigger.

To calculate the required torque to lift the platforms up, acceleration is set to 0. So what is being calculated is the amount of torque needed to start moving the platforms. The formula to calculate the torque T of the motor is:

$$T = \frac{D_s}{2} P$$

So the force P has to be determined applying the equilibrium of forces equation:

$$F_f \cdot \cos(\alpha) - P + N \sin(\alpha) = 0$$

$$N \cdot \cos(\alpha) - F_f \sin(\alpha) - F = 0$$

Where the F_f takes in account not only the normal force N but also the pressure provided by

the spring:

$$F_f = \mu(N + k\Delta x \cos(\alpha))$$

Clearing P from the equations:

$$P = \mu(N + k\Delta x \cos(\alpha)) \cos(\alpha) + N \sin(\alpha)$$

Where normal force N:

$$N = \frac{F + \mu k \Delta x \cos(\alpha) \sin(\alpha)}{\cos(\alpha) - \mu \sin(\alpha)}$$

Even though it could seem that force N depends on the spring characteristics (what would mean that the assumption of this force being an inner force is false) the $k\Delta x$ term is the force made by the spring which is constant. That means that the spring does not affect the equilibrium of the forces.

F force and α angle have to be calculated. The force F corresponds to the weight of the powder at the platforms maximum capacity plus the weight of the platform itself. With the values $\rho=1\text{g/cm}^3$, $V=1396,5\text{ cm}^3$, $g=9,81\text{ m/s}^2$, $D_s=8\text{mm}$, $\text{coarse}=1,25\text{ mm}$.

$$F = \rho * V * g = \frac{1 * 1396,5}{1000} * 9,81 = 13,7\text{ N}$$

$$\alpha = \arctan\left(\frac{\text{coarse}}{\pi D_s}\right) = \arctan\left(\frac{1,25}{\pi * 8}\right) = 2,84^\circ$$

With this results, the N force and the P unknown force taking $k=80$

$$N = \frac{13,7 + 0,2 * 80 * 10^3 * 3 * 10^{-3} * \cos(2,84^\circ) * \sin(2,84^\circ)}{\cos(2,84^\circ) - 0,2 * \sin(2,84^\circ)} = 16,25\text{ N}$$

$$P = 0,2 * [16,25 + 80 * 10^3 * 3 * 10^{-3} * \cos(2,84^\circ)] * \cos(2,84^\circ) + 16,25 * \sin(2,84^\circ) \\ = 51,93\text{ N}$$

So the final torque T:

$$T = \frac{D_s}{2} P = \frac{8 * 10^{-3}}{2} * 51,93 = 0,207\text{ Nm}$$

5.3. Electronics

The electronic system that controls and moves all the recoating system has three principal elements: Stepper motors, sensors and microcontrollers. All of these elements are taken from other existing plastic extrusion machines that are manufactured in *Fundació Cim*. This was one of the previous requirements to make the prototype as it would save a lot of money by taking the pieces from large stocks or already contracted providers.

With this handicap, the system will not be as optimized as it could be with full freedom on choosing the different elements. However, it also has some advantages such as reliability (everything has already been tested) and stock disposal.

Electronics can be analyzed in two different parts that are linked between them through the microcontroller: hardware and software. On the hardware analysis, the suitability of the different systems will be analyzed (motors, motor-driver, endstops, controller) while in the software part the firmware will be analyzed.

5.3.1. Hardware

On this first part of the hardware analysis the different components will be analyzed to see how they work and if they are suitable for our application. After doing so, everything will be put together along with the electric-electronic circuit.

The movement of the mechanism is provided by four stepper motors that are powered through three motor drivers and a power supply. These motor drivers are controlled with a microcontroller that has also three endstop sensors connected to set the home position of the machine. The interface to interact with the user will be six push-buttons that will select the action to be done by the system. This part will be widely explained on the firmware part.

On the following chapters, each of these systems will be deeply analyzed.

5.3.1.1. Stepper motors

Nowadays stepper motors are the widest chosen option to move small mechanisms with a good performance on precision. Basically a stepper motor is a brushless DC electric motor that divides a full rotation into a number of equal steps. The motor's position can then be commanded to move and hold at one of these steps without any feedback sensor (an open-loop controller).

Electrical analysis

Like all the electrical motors, stepper motors need to be controlled to ensure the torque and the speed required for its application. This gives you a really wide set of current-voltage combinations as it happens with other electrical motors. However, stepper motors never runs on steady state because of its architecture and its operation mode. To achieve the stepped movement, steppers motors have slotted magnets on the rotor and the stator. Rearranging the alignment of this slots the motors turns a single step.

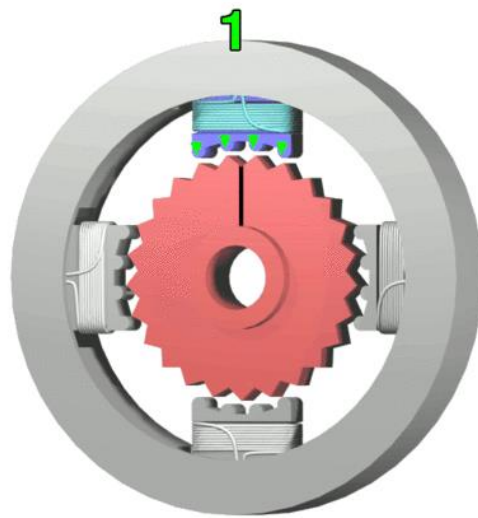


Figure 109 Stepper motor schematic

When turning a single step the motor actually go through a transient state to the target position. This would not be a problem when moving one step, but the stepper motor turns at a certain speed by moving a certain number of steps per second. This means transient states in a small amount of time (milliseconds). This leads to resonance and other important troubles that should be analyzed by simulating each stepper motor. As this is not the objective of this project, the basic behavior when changing the voltage applied to the coils of the stepper motor has been extracted from other studies and are summarized as:

More voltage:

Pros:

- Less rising time
- More power
- More Speed

Cons:

- More heating
- More rigidity (vibrations)

Another problem when applying more voltage is the current. The motor will take as much current as required to turn at a certain speed or apply a high torque to the load. If the motor driver does not limit this current it can damage the motor.

Mechanical analysis

When choosing a stepper motor there are some important mechanical specifications that have to be taken into account to make sure that the chosen motor will be able to move the mechanism and stop it.

Pull-in-torque: The maximum torque load at which a step motor will start and run in synchronism with a fixed frequency pulse train without losing step positions

Pull-out-torque: The maximum torque load that can be applied to a motor running at a fixed stepping rate while maintaining synchronism. Any additional load torque will cause the motor to stall or miss steps.

Holding torque: The maximum restoring torque that is developed by the energized motor when the shaft is slowly rotated by external means. The windings are on but not being switched.

Detent torque: The maximum torque required to slowly rotate a step motor shaft with no power applied to the windings. This applies only to permanent magnet or hybrid motors. The leads are separated from each other.

The most important specifications in the studied mechanism are the pull-in-torque and the pull-out-torque. The holding torque is not important as the only part of the mechanism that could have some problems in terms of holding a load are the platforms, which have a power screw that makes sure they do not move in state of rest.

As it was seen on the mechanical calculations, the motors have to be able to provide at least these torques to move the mechanism:

The stepper motors that are provided by the *Fundació Cim* are the SY42STH47-1684a Nema 17 hybrid bipolar stepper motor series. The datasheet of this stepper motor can be found on the annex. The basic properties that have to be taken in account are summarized on the Table 1.

Table 1 General motor specifications

General specifications	
Holding torque (Kg*cm)	4,4
Detent torque (g*cm)	200
Step angle (°)	1,8
Steps	200
Number of phase	2

With this data the precision of the motor can be discussed. It will not be done in deep because it has already been proved for the plastic extrusion 3D printers that use the same motor. The application is the same, lifting down the printing platform by a threaded bar. However, it can easily be seen that with steps of $1,8^\circ$ plus the reduction introduced by the threaded bar is enough to ensure the precision of the movement. In fact, even if the motors were not as precise as intended, they could be managed in half, quarter or even eighth step mode. This would allow to divide each step in multiple micro steps. The formulas to calculate the relation between linear and rotatory movement will be explained on the firmware paragraph, as it is needed to run the motors.

After this brief introduction on stepper motors and seeing that they have enough precision to run the platforms, it is needed to know whether they can move the platforms and the recoater in terms of enough torque. The problem here is a little more complex than the precision. Firstly, the forces are different than the ones applied to the motors in the already existing 3D printers. Secondly, the pull out torque follows an empirical curve that depends on the fixed voltage and the current. For each pair of voltage and current there is a curve that relates the rotor speed in rpm with the pull-out torque.

In the datasheet of the motor there is a curve of this relation when the motor runs at 24V and $1,68^a$ (Figure 110). This curve can be used to determine if the motor will have enough torque to move the system, but it will be an approximation. To know it for sure the system would have to be simulated in Simulink or another mathematical simulation platform which is not the goal of this project. So basically, it is going to be checked that the motor has enough power to widely

move the system and to change the parameters empirically.

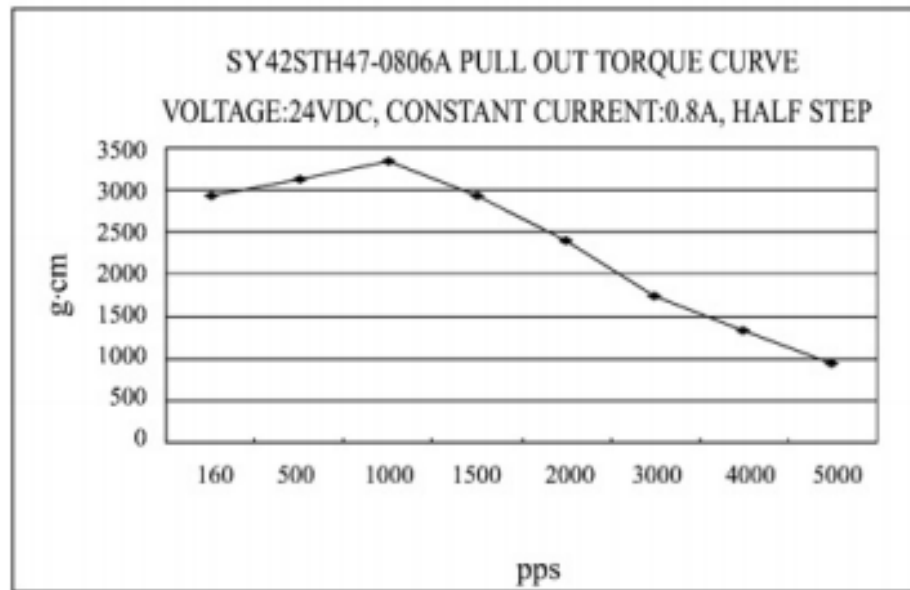


Figure 110 Torque – speed graph

The unit PPS (pulses per second) can be easily converted to RPM (revolutions per minute) by the relation: 1 PPS = 0,3 RPM

This relation is different if the step angle changes from 1,8° to another angle. The maximum torques that the motor needs to supply are summarised on the Table 2:

Table 2 Torques required

Recoater acceleration	428 g*cm
Recoater constant speed	208 g*cm
Platform motor	2110 g*cm

So the calculation shows that there is no torque problem with the recoater motors. In fact, they could be way smaller to optimize the system. The platform motor would perfectly run in low speeds but not t high speeds. Luckily, the platforms will move at a very sow speed. In addition, this is the worst case, in which the platform is loaded with a full charge of powder (which will not be the case when printing small testing parts.

As a conclusion, the motors that are provided by *Fundació CIM* will be able to move the system

and it will even be possible to adapt its parameters to make them run smoothly.

5.3.1.2. Motor drivers

Choosing the motor driver is as important as choosing the stepper motor. The motor driver is the brain of the stepper motor and can dramatically change its properties (torque, speed...). The stepper motor is one of the most complex motors that can be found nowadays, but mechanically is relatively equal to other electric motors. However, what makes the difference is how the motor is controlled. The motor is controlled by sending step signals to the different phases. This signals are provided by the motor driver that acts as a nexus between low voltage and power controlling electronics.

This is an example of the wave form that needs to be given on the coils of the stepper motor (Figure 111). In that case the stepper motor runs in full step mode (otherwise the waves would be much more complicated). So the stepper motor without the motor driver is a bunch of coils and magnets.

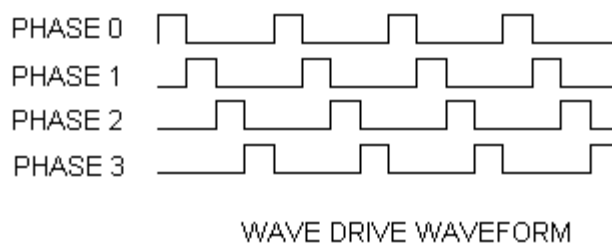


Figure 111 Stepper motor driver waveform

Like in the previous paragraph about the stepper motor, *Fundació Cim* is already using a motor driver for its 3D printers. Once again, this motor driver will be analyzed to decide if it is suitable for the recoating mechanism.

The motor driver provided by *Fundació CIM* is the DRV8825 high current breakout carrier for the texas instruments DRV8825 microchip. The datasheet for both the breakout carrier and the microchip can be found on the annex. Some of the most important data to analyze the motor driver and some electrical data for the stepper motor are written on the Table 3:

Table 3 Motor driver specs

Minimum operating voltage:	8,2 V
Maximum operating voltage:	45 V
Continuous current per phase:	1,5 A
Maximum current per phase:	2,2 A
Minimum logic voltage:	2,5 V
Maximum logic voltage:	5,25
Microstep resolutions:	Full, 1/2, 1/4, 1/8, 1/16, and 1/32

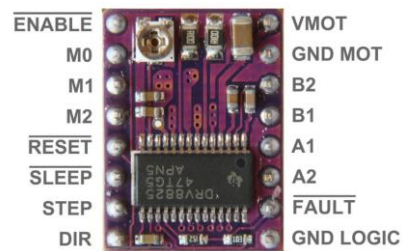


Figure 112 Pololu DRV8825

- Operating voltage:** As it can be observed in the specifications, the voltage that can be delivered by the motor driver, is wide enough for the stepper used on the mechanism. In fact, it allows to choose any kind of power supply between this to values. This will have to be taken in account when finding a suitable power supply for the motors.
- Logic voltage:** As it was said before, the motor driver is a nexus between power and logic electronics. To control the motors, logic signals must be rated between 2,5V and 5,25V. This will be critic when choosing the microcontroller.
- Current per phase:** The current per phase limits the current that the driver can manage before getting in trouble to evacuate the heat. It is rated at 1,5A of continuous current which is less than what the motor can accept (1,68A). This means that the motor will not be able to run at the maximum current rate. Working under the maximum

current rate is a problem as you cannot achieve maximum torque, but it will avoid damaging the motor.

- **Microstep resolutions:** This is one of the best things about DRV8825 breakout done by *POLOLU*. Simply changing the state of the digital pins M0, M1 and M2 you can choose the step resolution. This means that several tests can be done to set the perfect microstepping resolution to get a smooth movement.

Microstepping divides each step into 2, 4, 8, 16 or 32 steps multiplying the steps per turn. This allows the motor to run smoother but decreases torque and maximum speed. It also stabilize the motor as the steps are shorter and is more difficult to have resonance and increases resolution but not accuracy. Even though it would be a good option, it will have to be tested when the machine is build.

Limiting the current:

Another feature that makes *POLOLU* DRV8825 a great stepper controller is that allow the user to limit the current that goes through the driver and consequently through the motor. This is going to be very useful in order to test the electronic system without damaging the motors nor the motor drivers.

Setting the current limit is a really easy action to do with the driver set up. There is a potentiometer screw located at the corner of the driver that regulates the V_{ref} voltage. V_{ref} voltage can be measured on the potentiometer screw or next to M2 pin. The formula used to set the current limit is:

$$I_{max} = V_{ref} * 2$$

So by setting the V_{ref} value to 0,5 V the I_{max} will be 1 A. This is the starting value that will be set to test the system because it allows to move the motors above the minimum power required and it is low enough to o burn out the motors or the drivers. If more power is required, the maximum intensity will be raised to higher power. However it is expected that the system has enough power with lower current values which would allow to reduce the intensity optimizing the system.

6.2.1.3 Endstops

Endstops are common elements in numerically controlled machines as they allow to set the home position in an easy and reliable way. There are different types of endstops depending on how they detect the proximity of the object to be detected: hall effect, mechanical, optical,

etc.

There are two types of endstops on stock in *Fundació CIM*: optic and mechanic. The basic physical principles they use and its main advantages and disadvantages are:

- **Mechanical endstop:** Mechanical endstops are basically a push button adapted to close when an object contacts it. It is widely used because of its simplicity and low price. However, it is less precise than optic endstop because its mechanical actuation make it susceptible to contact bouncing when colliding with a high speed object.

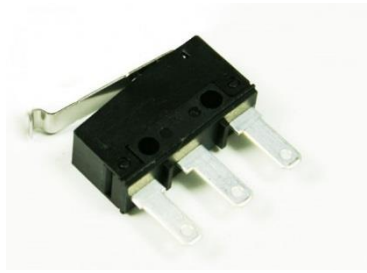


Figure 113 Mechanical endstop

- **Optical endstop:** This endstop uses a photodiode and a light source (usually a LED) separated by an empty space. When the object to be detected interrupts the light flow between the light source and the photodiode, the current coming out from the photodiode decreases and this is detected as a low voltage by the microcontroller. This kind of endstop is more precise than mechanical but way more complex too. It requires some testing to adjust it.



Figure 114 Optical endstop

As it has been seen, even though optical sensors are more precise, mechanical endstops are more reliable and easy to set. Numerically controlled machines such as 3D printers use mechanical endstops and optical endstops depending on the model so they have a proven

precision for this kind of applications. In addition, the only system that needs a narrow precision is the platform of the printing zone as it defines the layer thickness. This would be the only one that could require an optical endstop but as it has been described in the mechanical section, the system that controls the printzone platform is a threaded screw moved by a stepper motor. This mean a slow and really controlled movement which ensures a slow movement that is perfect for mechanical endstop which saves hours of electronic design and testing for an optical endstop sensor.

5.3.1.3. Microcontroller

The microcontroller is the brain of the all the mechanical system. It decides what and how to move each motor, it gathers the information form the endstop sensors and it communicates with the user.

The available microcontroller available at *Fundació CIM* is the Arduino MEGA 2560. This board is the most powerful Arduino board available in the market both in number of digital/analog pins and in processor calculus power.

The number of pins needed to control the system are:

Table 4 Arduino pins

Push buttons	6
Stepper motors	3x2
Endstops	3
Total	15 pins

Arduino mega has 54 output/input pins so it is more than needed on this aspect but grade to have some extra pins to upgrade the system with more advanced user interface or controlling both the laser machine and the recoating system with the same board.

The other important aspect of the microcontroller is the calculation power. On this application this is an important issue for two reasons.

The first one is the quick detection of the endstops when they close the circuit to obtain a good home positioning that will turn into better precision when printing. This is usually achieved by most of the microcontrollers and it is more and issue of how the firmware is implemented than a microcontroller hardware problem.

The second one and the most important one is the calculation frequency. This will affect in the stepper motors maximum available speed and microstepping availability. Every step is a combination of pulses as it has been seen in the stepper motor section. Each step then, has to be calculated in the microcontroller, send to the motor-driver and finally apply the required current in each coil. So basically, faster movement in the motor means more steps which means more calculations per second. This is even more critic when using microstepping. For instance, if each step is divided by 16 in a 1/16 microstepping operation, to achieve the same speed as the full-step configuration, the number of steps per second must be multiplied by 16. This turns into 16 times more calculations than full-step mode. As microstepping is an option that will probably be used to achieve more smoothness, the microcontroller must have a high frequency processor. The Arduino Mega uses an AT2560 processor that performs at 16MHz which is a great value to control the system.

Finally, there are some important issues to be taken in account when working with an Arduino board that will have to be considered when designing the overall electronic circuit. For example, when a pin is used as an input pin to read a HIGH level, a pull-down resistance will need to be implemented between the pin and the ground to force a LOW value while not active. It is also a good idea to work with really low current flowing through the pins to avoid burning out the board. This will be in-deep explained in the overall electronics set up section.

5.3.1.4. Electronic-electric circuit

In this section, the overall electronic and electric circuit is going to be presented in order to analyze each part in a separate section.

In the next pages, there is the schematic of the circuit. The first page corresponds to the Arduino connexions and the second one to the motor drivers. As it was explained above in this section, the main parts are the microcontroller, the steppers along with the motor drivers, the endstops and the pushing buttons. Each of this sub-systems will be analyzed to calculate the values that has been selected for resistances and capacitors.

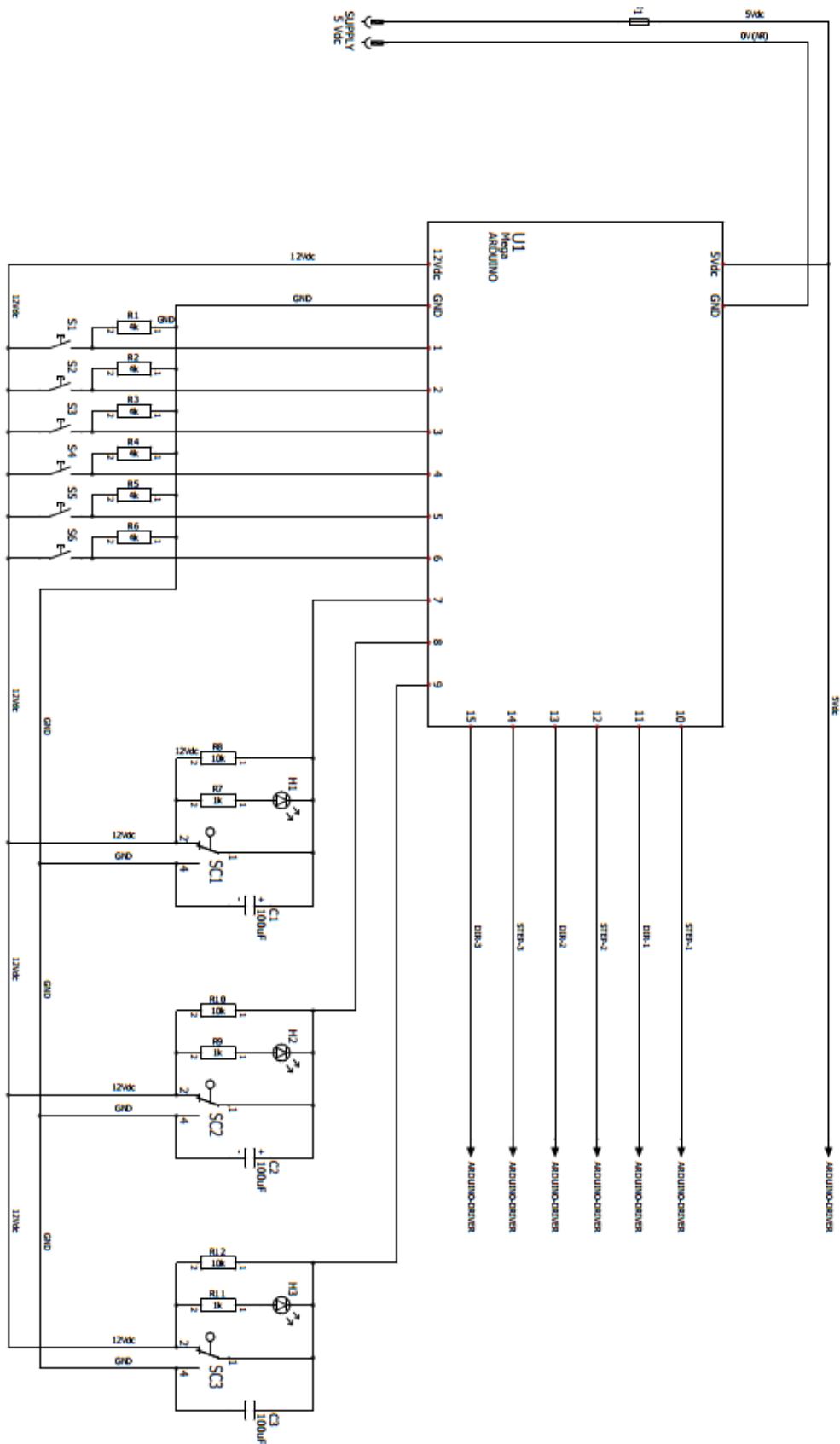


Figure 115 Schematic 1

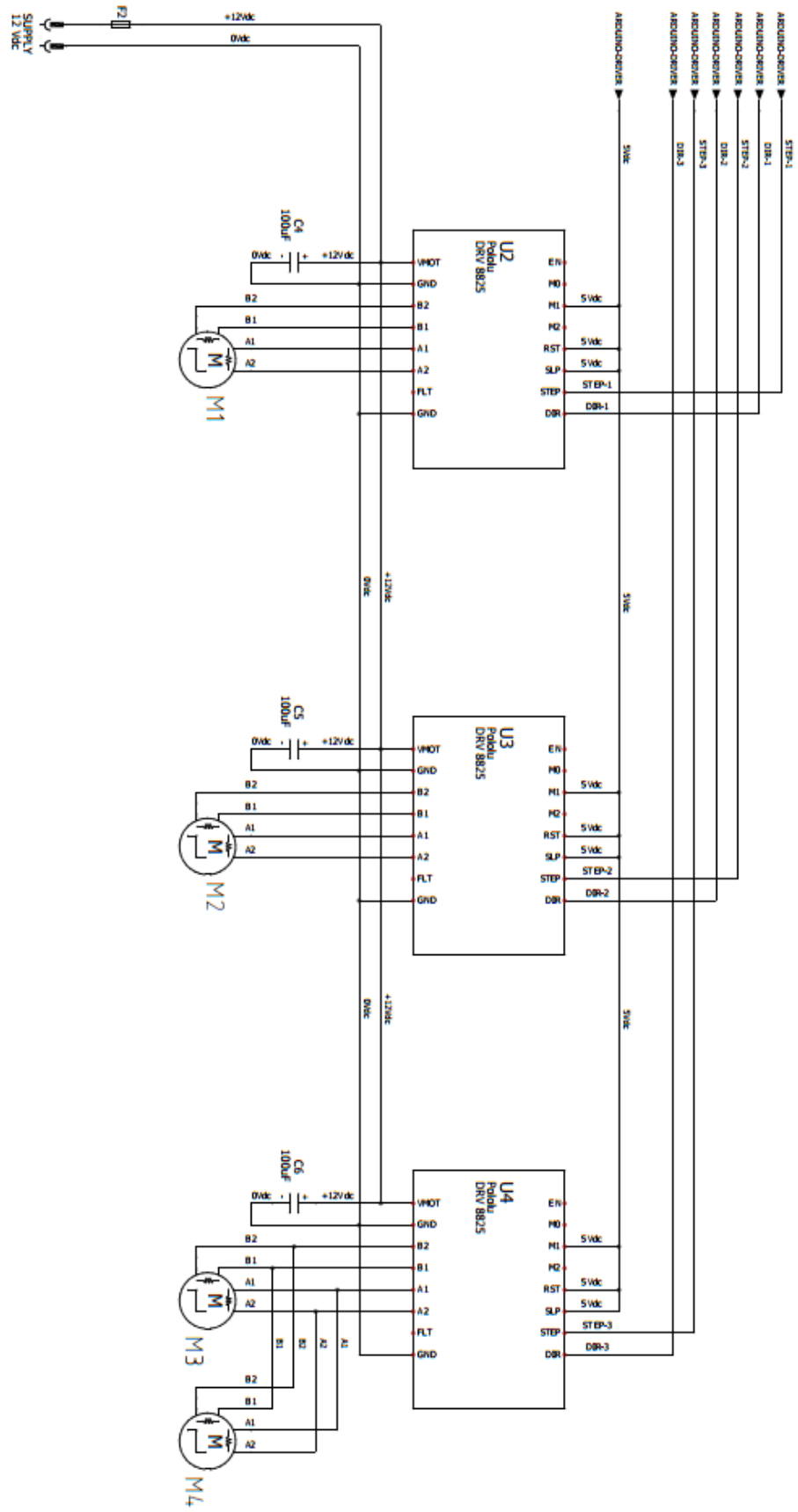


Figure 116 Schematic 2

Arduino Mega 2560 microcontroller considerations:

In order to understand why some of the circuits that are linked to endstops or push buttons there are some considerations to be done related to the Arduino controller.

Undetermined input pin state:

After some initial testing with the Arduino board, it was seen that pins were in an undetermined state between HIGH and LOW when not connected to any wire. This was a problem because when push buttons and endstops are in an open state it is not clear whether the pins will be in HIGH or LOW. To solve this, the best option is to add a pull-up or a pull-down resistor to the pin. The Arduino board can activate an internal pull-up resistor if desired, but it is dangerous for the board and not recommended. So it was decided to implement the pull-up and pull-down resistors physically outside the pin and the board.

Burning out the Board:

There are almost an infinite ways to burn-out an Arduino board. From high current in a pin, high current in the 5V, 3.3V or GND pins or internal malfunction short-circuits. To avoid burning out the board, everything has to be carefully designed and mounted. A good way to do so is measuring the current on the susceptible pins when connecting new parts of the circuit to see if it is dangerously near to its limit.

Endstop circuit:

As it was said before, mechanical endstops are like push buttons. They have three pins which have to be connected to ground, the desired high level (5V in our case) and to the control pin. The control pin will detect whether the endstop is active or not. The simplest circuit would be to do these connections without any other element. However, this wiring scheme would be dangerous for the board as there is only the internal pull-up resistor between the high level power source and ground and a current peak could damage the pin or the whole microcontroller.

To solve this, a pull-up resistor is attached to the endstop to ensure that the current is above the current limit of the pin which is 20 mA the resistor should have a value of:

$$R = \frac{V}{I} = \frac{5}{20 * 10^{-3}} = 250\Omega$$

This 250 Ω value is a lower limit. The resistor can be larger than 250 Ω but with a losing on time response. However, current peaks will appear as a consequence of voltage peaks so in the calculation done before we cannot ensure a voltage level of 5V. This is why the

recommended pull up resistance when working with 5V high logic level can manage voltage peaks of 200V. This resistor would be then have a value of:

$$R = \frac{V}{I} = \frac{200}{20 * 10^{-3}} = 10000\Omega$$

This value will make the circuit work slower but will ensure its integrity.

Another recommendation made by the manufacturer when working with mechanical endstops due to its mechanical movement is to attach a 100 μ F capacitor between the signal wire and the ground wire to filter the mechanical bouncing due to the spring-type electric contact. This capacitor will be able to filter the electrical noise that could appear when the endstops and the electronic system are close to a motor (which will be the case). This is a manufacturer recommendation so it is not going to be calculated.

After testing the circuit and looking in *Fundació CIM* stock, endstop boards with this circuit integrated in a printed circuit. This board saves time and is in fact the same circuit but adding a LED that indicates if the endstop is active. The schematic of this circuit is (Figure 117):

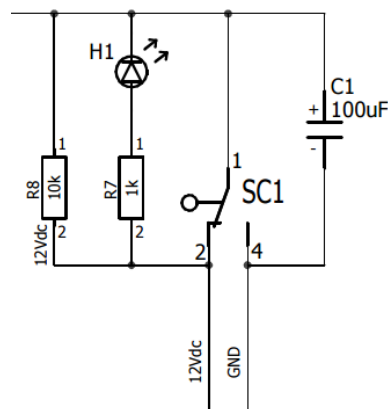


Figure 117 Endstop circuit

Push-buttons circuit:

The circuit that needs to be implemented with the push-buttons is a pull-down resistance to ensure a LOW level when the button is released. This resistor has also a protection function to avoid burning out the board if a peak of voltage occurs and to avoid connecting the pin directly to the 5V logic power supply.

As said in the Arduino webpage, a push-button or a switch can generate voltage peaks of 100V. So the resistor must allow only 20 mA through the pin when 100V are applied

$$R = \frac{V}{I} = \frac{100}{20 * 10^{-3}} = 5000\Omega$$

The circuit is schematic is as follows with 6 push-buttons with its pull-down resistors (Figure 118):

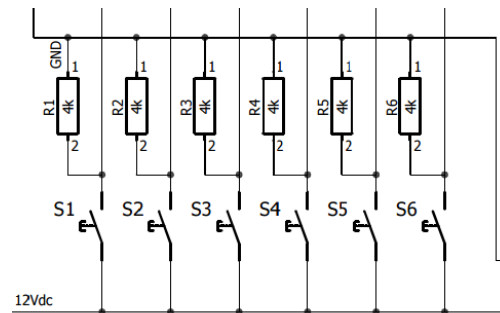


Figure 118 Push buttons circuit

Motor and driver circuit:

The circuit to drive the motors connect the POLOLU DRV8825 with the power supply, the motors itself and the logic control from the Arduino MEGA. The circuit has three principal parts: motor connections, logic connections and power supply. The pins of the POLOLU board are shown on the Figure 119.

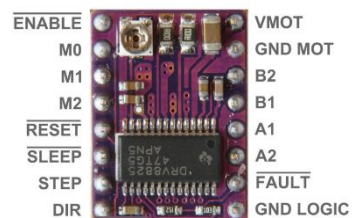


Figure 119 Pololu driver

Motor connections

The motor connections allow the driver to deliver the current pulses to the motor coils. There are four wires (two for each coil) goes from pins A2, A1, B1, B2 to the motor coils. It may seem that this connections are the most simple to be done, but even when properly connected they decide the positive turn of the motor. The colour code to know how to connect the motor is the following (Figure 120):

4 LEAD WIRES	1	2	3	4
Color Code 1	Red	Blue	Green	Black
Color Code 2	Brown	Orange	Red	Yellow
Color Code 3	Red	Red White Stripe	Green	Green White Stripe
Bipolar Driver	A	\bar{A}	B	\bar{B}

The Nema 17 stepper motor used on the project uses the color code 1. However, testing the motors to see its behavior, it was seen that they should be connected as it is seen on the

Table 5 to ensure the right movement of the system:

Left motor of the cylinder		Platforms and right motor of the cylinder	
<i>Figure 120 Color code</i>			
RED	B2	RED	A2
BLUE	B1	BLUE	A1
Left motor of the cylinder		Platforms and right motor of the cylinder	
RED	B2	RED	A2
BLUE	B1	BLUE	A1
GREEN	A1	GREEN	B1
BLACK	A2	BLACK	B2

Table

5 Motor driver wiring

Logic connections

The logic connections have two basic functions: they communicate the microcontroller with the motor drivers and they allow to choose the resolution of the microstepping. To communicate the microcontroller with the driver, the pins DIR and STEP are used. This pins must be connected to the Arduino pins set on the firmware. The DIR pin sets the direction of rotation of the motor and the STEP pin allows the microcontroller to communicate to the driver that a step needs to be done.

The other logical connections are the driver set up and decides how the driver will behave. All the logical pins have an internal pull-down resistor so they are in LOW level for default. RESET, SLEEP and ENABLE are active when the logic level is LOW. So they are active for default. In our case, the motor driver will be always active so RESET and SLEEP pins must be set to HIGH level to disable them as the device will be never on sleep or reset state. So two wires will supply constant 5V to these pins. ENABLE pin will be left in LOW state as it enables the driver to operate in normal conditions. FAULT pin allows the user to detect driver malfunction because of high temperature, high current or high voltage. This pin will not be connected as the machine should not have these kind of problems when operating after the first tests. It is

an option that could be useful if some problems appear during the testing phase of the project.

The other logical pins left to be connected are the three M pins, M0, M1 and M2. These pins are used to set the motor resolution or stepping mode. The Table 6 shows the different state for those pins:

Table 6 Microstepping modes

MODE0	MODE1	MODE2	Microstep Resolution
Low	Low	Low	Full step
High	Low	Low	Half step
Low	High	Low	1/4 step
High	High	Low	1/8 step
Low	Low	High	1/16 step
High	Low	High	1/32 step
Low	High	High	1/32 step
High	High	High	1/32 step

As it will be explained on the electronic testing section, high resolution turns into poor torque and low speed while full step makes the motor to run in a bumpy way and even loosing steps. So after testing the motors the $\frac{1}{4}$ resolution was chosen as a midpoint between these two behaviors. So, to perform a $\frac{1}{4}$ resolution M1 pin must be set to HIGH level by connecting it to the 5V logic power source.

Power supply connections

The 12V power supply is connected to the motor driver by the Vmot and GNDmot pins. In addition, POLOLU recommends to connect a 100 μ F between these pins to filter the signal and avoid destructive voltage peaks that could damage the board.

Finally, the logic and the power supply grounds must be connected between them to make sure there are not voltage discrepancies between logic and power lines (Figure 121).

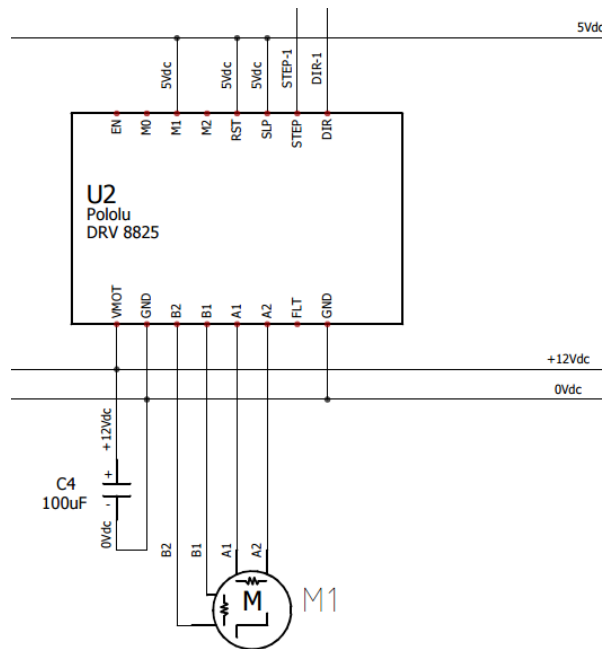


Figure 121 Motor driver circuit

Hardware implementation

After testing all the electronic system with the firmware and seeing that everything works fine, the final electronic set up has to be physically designed. There will be four principal blocks that will connect to each other with fasteners connectors: Arduino, endstops, motors and stripboard.

The stripboard will be used to manage all the connections and will receive the control data from Arduino, direct it to the motor drivers and then to the motors. In addition, it will get the data from the push buttons and endstops and it will direct it to the Arduino board. This stripboard is build to simplify the connections and make it easier to change damaged elements.

The stripboard will have this layout (Figure 122).

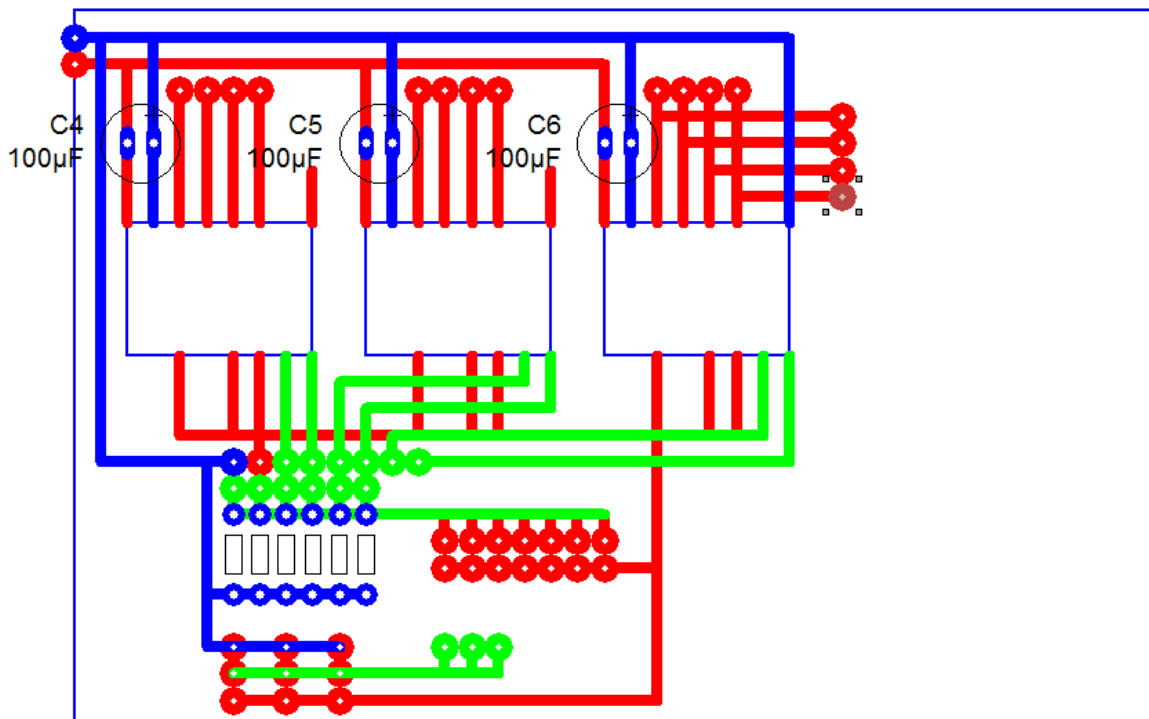


Figure 122 Stripboard

As it can be seen, there is an unused area at the right of the board to add extra features in the future or add some space between the elements if needed. Green pins are the ones that communicates with the Arduino board while the red and blue ones are those that communicates with motors, endstops or simply power supplies.

The three big rectangles represents the motor drivers and the small one represents the pull down resistances.

5.3.2. Firmware

The firmware is the code implemented in the Arduino board that decides how the machine will work and what it can be able to do. Because of this it is as important as the hardware and the mechanical design because if it is not well implemented it could make the machine to malfunction or work under its possibilities.

At first, the idea was to adapt some existing 3D printing firmware such as Marlin to the machine. However, the existing firmwares are quite complete and difficult to readapt. They can be changed to fit a different printer but in the same working principle. As the SLS printer is completely different to the plastic extrusion machines, it was clear that a new firmware was needed.

After deciding to develop a new firmware, there was a way to save time and avoid programming the laser controlling code which would have been a hard work as well as long. To avoid this and seeing that the *laser cutting machine* has its own firmware, it was decided to implement an independent software for the recoating system and then try to link the two software. This should not be difficult as the action is sequential, after the laser has drawn a layer a signal is send to the recoating microcontroller to perform the recoating action.

Due to some delays on the project and on the delivering of the cutting laser machine the last part has not been tested so now both systems work independent so after each layer the user press a button and the recoating system spreads a new powder layer.

During the next chapter the firmware will be analyzed starting with how the user interacts with it and which actions will be available.

5.3.2.1. User interaction and working modes

As it was seen in the hardware section, the user interacts with the recoating system by 6 push buttons. Each button will perform a single action when pressed. This is a basic design concept thought to be improved in a near future. The idea is that when the machine has been tested, the signal providing from the buttons will be generated by the printing G-code as it will be explained later.

Following the physical design, there will be 6 working modes or actions performed by the machine. This modes will do the following actions:

- **Layer:** Performs a complete layer which means printzone lowering, powder feeding and powder spreading.
- **Home:** Sets the home position of the machine to correct and save the origin of the stepper motors.

- **Set up:** Prepares the machine to start printing a new part.
- **Powder cleaning:** Extracts all the powder remaining on the powder feeding platform after extracting a part.
- **Part extracting:** Performs the required actions to help the user when extracting the printed part.
- **Cylinder:** Moves the cylinder forward and backwards. This action was set after seeing it was really useful for the user.

On the next pages, the code will be analyzed in deep including explaining what the functions exactly do.

5.3.2.2. Overall code scheme

When thinking how the code should be it was clearly set that it should be easy to change some key values that affect the printing performance so tests could be easily done. It was also intended to be a simple code, as easy to comprehend as possible so other people could understand it and add as many features as required.

To do so the firmware was divided on three principal parts: variables, set up and function invocation; and function description. The whole code has about 200 lines which is a surprisingly low value. The six actions have been separated on 6 different functions that are invocated on the main loop.

Controlling stepper motors with an Arduino board

The Arduino board is perfect to control almost any system and it is perfectly capable to manage the stepper motors. However, it is a tedious process to control the motors by sending current pulses to the motor coils because some functions have to be created to change speed and to control the position of the motor. Luckily, as Arduino is an open platform project, a lot of users have developed libraries that allows the user to work with stepper motors easier and more efficient.

When choosing which library should be used, it is important to see how the motor driver works. The DRV8825 motor driver has a double H-bridge to control the two coils. Another important aspect is how the library works, the functions that can be used and the efficiency. After reading some information about several libraries and reading different opinions the AccelStepper library will be used to control the motors.

This library is really easy to use and has all the functions needed for the recoating system. It also works with accelerations and decelerations so the movement will be smoother than with other libraries.

The library has to kind of movement which difference cannot be appreciated when the motors are running but that is really important when using the functions on the firmware.

Speed based movement

In speed based movement, the function `setSpeed` set the movement speed in steps per seconds. When the function `runSpeed` is repeatedly called, the motor runs at this constant speed whatever is its position. This way of moving is really useful when performing an uncertain movement, for example, when looking for the home position. However it is not used when the position needs to be controlled.

Position based movement

When the home position is set, the function `setCurrentPosition` is called to make the home position the 0 position for all the motors. After this all the movement will related to this position so, for example, the motor can move 20 steps or -40 and then back to 0. This movement will be made at the maximum specified speed accelerating and decelerating at the specified maximum acceleration value.

It has to be noted that all the variables required for all the functions are related to steps which means speed will be steps/s and acceleration steps/s².

After having explained the basic aspects of the library, the three main blocks of the firmware can be analyzed.

5.3.2.3. Variable declaration

On this part of the code the user can set the different variables to manage the behavior of the machine. This variables are set on “human sized” units that the script will turn into the library units. The user can write speed, accelerations and distances in IS units and then they are converted into step based units. The Arduino pins are also considered a variable so if a future improvement needs to change these pins the only work to be done is to change this variables, what saves a lot of time.

In the next page, the piece of code where all the variables are declared is shown. After this, the calculation section of the code is what calculates the library variables that are used later on the firmware. After the code, Table 7 specifies the meaning of each variable.

```

// Variable declaration

// Arduino Pins
const int recoater1          = 12; //STEP
const int recoater2          = 13; //DIR
const int printzone1        = 10; //STEP
const int printzone2        = 11; //DIR
const int pow_feeding1      = 8; //STEP
const int pow_feeding2      = 9; //DIR
const int rec_stop          = 24;
const int printzone_stop    = 23;
const int pow_feeding_stop  = 26;
const int layer_button      = 50;
const int home_button       = 48;
const int set_up_button     = 46;
const int powder_cleaning_button = 44;
const int part_extracting_button = 42;
const int cilynder_button   = 40;

//Motor steps
const int steps_rec          = 800;
const int steps_pla         = 800;

// Speed to 0 position in mm/s
const long speed_to_0       = 80;
const long recoater_speed_0 = 30;

//Geometrical data
const long bar_coarse       = 1.25; //In mm
const long recoater_move    = 115;  //In mm

//Printing data
const long layer_thickness  = 1;    //In mm
const long feeding_thickness = 2;    //In mm
const long recoater_speed   = 30; //In mm/s
const long platforms_speed  = 20; //In mm/s
const long motor_pulley_teeth = 20; //Teeth
const long belt_teeth       = 5;    //Teeth/cm
const long set_up_z         = 20; //Feeding z start in mm

//Variable Calculations
const long mspeed_to_0      = (speed_to_0/bar_coarse)*(steps_pla/60);
const long mrecoater_speed_0 = (recoater_speed_0*10*belt_teeth/motor_pulley_teeth)*(steps_rec/60);
const long mrecoater_speed   = (recoater_speed*10*belt_teeth/motor_pulley_teeth)*(steps_rec/60);
const long mplatforms_speed  = (platforms_speed/bar_coarse)*(steps_pla/60);
const long steps_recoater    = belt_teeth/motor_pulley_teeth*recoater_move/10;
const long steps_printzone   = steps_pla*(layer_thickness/bar_coarse);
const long steps_feeding     = steps_pla*(feeding_thickness/bar_coarse);
const long steps_feeding_setup = steps_pla*(set_up_z/bar_coarse);

//Powder_cleaning variables
const long cleaning_thickness = 5; //In mm
const long cleaning_steps     = steps_pla*(cleaning_thickness/bar_coarse); //Steps
const long cleaning_recoater_speed = 80; //In mm/s
const long mcleaning_recoater_speed = (cleaning_recoater_speed*10*belt_teeth/motor_pulley_teeth)*(steps_rec/60); //steps/s

```

Table 7 Firmware variables

steps_rec	Cylinder motor steps
steps_pla	Platform motor steps
speed_to_0	Desired speed of platforms homing
recoater_speed_0	Desired speed of cylinder homing
bar_coarse	Bar coarse
recoater_move	Cylinder movement distance
layer_thickness	Printing layer thickness
feeding_thickness	Powder feeding thickness
recoater_speed	Cylinder speed
platforms_speed	Platforms movement speed
motor_pulley_teeth	Number of teeth of the motor pulley
belt_teeth	Teeth per cm of the belt
set_up_z	Powder feeding platform set up height
mspeed_to_0	Internal variable
mrecoater_speed_0	Internal variable
mrecoater_speed	Internal variable
mplatforms_speed	Internal variable
steps_recoater	Internal variable
steps_printzone	Internal variable
steps_feeding	Internal variable
steps_feeding_setup	Internal variable

The internal variables are the ones that are going to be used later in the library functions are step based variables. The formulas used are written more clear here:

Motor speed (platforms):

$$\omega = \frac{v}{pitch} * \frac{motor\ steps}{60}$$

Motor speed (cylinder):

$$\omega = \frac{v * 10 * belt\ teeth}{pulley\ teeth} * \frac{motor\ steps}{60}$$

Steps to move (platforms):

$$steps = motor\ steps * \frac{\Delta x}{pitch}$$

Steps to move (cylinder):

$$steps = \frac{belt\ teeth * 10}{pulley\ teeth * \Delta x}$$

It is important to note that there are certain limits for this variables. Some of those will be tested later, but if this limits are surpassed it can cause motor instability, mechanical damage or malfunction of the machine.

5.3.2.4. Set up and function invocation

This block initializes the stepper motors variables and the Arduino pins. All of the pins must be set up as input as all of them take signals from sensors or buttons. As this block is going to be executed once every time the Arduino is reset or powered on, it is useful to set the maximum accelerations for all the motors in this part of the code. This will optimize the program because when setting the acceleration, a square root must be calculated what takes a lot of resources from the microprocessor. Doing this one time at the beginning saves more calculation time than doing this several times in every general loop.

The second block of this part of the code is the loop function that is executed iteratively. This functions basically looks if there is any button pushed down. If this is true it will execute the function related to that push-button, in other case the loop function will be executed again.

```
// Steppers initialization
AccelStepper recoater(1, recoater1, recoater2);
AccelStepper printzone(1, printzone1, printzone2);
AccelStepper pow_feeding(1, pow_feeding1, pow_feeding2);
```



```
void setup() {
  recoater.setAcceleration(3000);
  printzone.setAcceleration(1000);
  pow_feeding.setAcceleration(1000);
  pinMode(layer_button, INPUT);
  pinMode(home_button, INPUT);
  pinMode(set_up_button, INPUT);
  pinMode(powder_cleaning_button, INPUT);
  pinMode(part_extracting_button, INPUT);
  pinMode(cylinder_button, INPUT);
  pinMode(rec_stop, INPUT);
  pinMode(printzone_stop, INPUT);
  pinMode(pow_feeding_stop, INPUT);
}
```

5.3.2.5. Function description

This part of the code is the one that decides how the recoating system will perform all the actions available. There are six different functions, one for each push-button. The idea when coding these functions was that they could be easily integrated in a different code if in a near future total integration between laser and recoater is required.

home()

This function moves the cylinder, the printzone and the pow-feeding platform to the home position. This is done by speed based movement telling the motors to move each part towards the endstop. When the part activates the endstop, the movement is immediately stopped. Although it is not necessary to set a maximum speed as it is a speed based movement, it is recommended by the library owner to do so in order to avoid some internal problems.

As it can be seen on the code, the first block of the function simply sets the speed for every motor as well as its maximum speed. The second block is three “while” loops that move the three motors until the endstop is activated. This is done sequentially, not at the same time, to make sure that the user can control the process being able to turn off the machine if an unexpected error occurs. There is also a line between each movement to save the current position as the new 0 of the motor.

The speeds of all the different parts are going to be tested to ensure a good positioning with good homing time.

```

//home_ sets all the steppers to its initial position
void home_() {

    printzone.setMaxSpeed(mspeed_to_0);
    pow_feeding.setMaxSpeed(mspeed_to_0);
    recoater.setMaxSpeed(mrecoater_speed_0);
    printzone.setSpeed(-mspeed_to_0);
    pow_feeding.setSpeed(-mspeed_to_0);
    recoater.setSpeed(-mrecoater_speed_0);

    while (digitalRead(rec_stop)==HIGH){
        recoater.runSpeed();
    }
    recoater.setCurrentPosition(0);
    while (digitalRead(printzone_stop)==HIGH){
        printzone.runSpeed();
    }
    printzone.setCurrentPosition(0);
    while (digitalRead(pow_feeding_stop)==HIGH){
        pow_feeding.runSpeed();
    }
    pow_feeding.setCurrentPosition(0);
}

```

Layer()

This function is the basic function that will be repeated during the printing process to add a layer of new material. Like in the home() function, the first block of the function defines the motors max speed. In this case the movement is position based so the speed does not need to be defined.

The second block moves the parts in the following sequence:

1. Lower the printzone the required "layer thickness" space.
2. Rise the pow-feeding platform the required "feeding thickness" space
3. Move the cylinder to the other side of the machine to spread the powder
4. Move the cylinder back to its home position

This function has some variables that will need to be tested like the motors speed or the cylinder speed. This are in fact variables that has a great influence on the final printed part.

```
//layer move the platforms and the recoater to spread one powder layer
void layer(){

    printzone.setMaxSpeed(mplatforms_speed);
    pow_feeding.setMaxSpeed(mplatforms_speed);
    recoater.setMaxSpeed(mrecoater_speed);

    printzone.runToNewPosition(steps_printzone);
    pow_feeding.runToNewPosition(-steps_feeding);
    delay(500);
    recoater.runToNewPosition(steps_recoater);

    delay(1000);
    recoater.runToNewPosition(0);
}

```

Set_up()

The set up function is only used when preparing the machine to print a part. It basically find de home position for each machine part and then moves the powder-feeding platform to the user defined position. After that, the user must fill the platform with the powder required for printing the part. The home function is called to make sure that all the motors are in the 0 position. This is important as they may have lost some steps during previous printings (mostly in the cylinder motors).

```
//set_up moves the platforms and the recoater to the initial printing position to add the powder on the powder platform
void set_up(){

    home_();
    delay(1000);
    pow_feeding.setMaxSpeed(mspeed_to_0);
    pow_feeding.runToNewPosition(steps_feeding_setup);
}

```

Powder_cleaning()

This function makes the task of cleaning the machine much faster and easier by removing the powder remaining on the powder-feeding platform. As all the functions, the first block sets the maximum speed for all the motors.

To remove the powder, the powder-feeding platform rises a user defined height. Then, the cylinder swipes the powder to the funnel where it will be taken for the user and used in posterior printings. This process is repeated until the platform reaches the 0 position.

```
//powder_cleaning extracts most of the powder from the powder platform and throws it to the waste container
void powder_cleaning(){

  recoater.setMaxSpeed(mcleaning_recoater_speed);
  pow_feeding.setMaxSpeed(mspeed_to_0);

  while (digitalRead(pow_feeding_stop)==HIGH){
    pow_feeding.runToNewPosition(cleaning_steps);
    delay(500);
    recoater.runToNewPosition(steps_recoater);
    delay(500);
    recoater.runToNewPosition(0);
    delay(500);
  }
}
```

Part_extraction()

This function simply lifts the printzone platform to extract the part. When programming the function, the idea of make the platform to shake in order to remove part of the powder from the part appeared. This vibration must be introduced by the stepper motor to avoid increasing the price of the machine. After testing this idea with a stepper motor it was seen that the vibration of the machine could destroy either the motor or the machine itself so it was discarded.

```
//part_extraction lifts up the printingzone platform to extract the printed part
void part_extraction(){

  printzone.setMaxSpeed(mplatforms_speed);
  while (digitalRead(printzone_stop)==HIGH){
    printzone.runSpeed();
  }
}
```

Cylinder()

This function was programmed after the first testing of the machine. It was seen that for testing and other future use a complet movement of the cylinder forward and then backward was really useful. So this function simply moves the cylinder, like the layer function, without moving the platform.

```
//cylinder moves the recoating cylinder forward and backwards if required
void cylinder(){

  recoater.setMaxSpeed(mrecoater_speed);
  recoater.runToNewPosition(steps_recoater);
  delay(500);
  recoater.runToNewPosition(0);
}
```

5.3.3. Testing

On this section, some of the most important aspects that appeared when testing the machine will be explained to understand where some values come from. The systems where tested

three times during the designing and building period:

After choosing the elements of the electronic system and designing the outline of the whole electronic and electric system, some tests were performed to choose some fixed physic values, and verify that all the systems would work as expected.

Once the “hardware testing” was done, the firmware was programmed to be able to test the whole system. With the firmware on the board, everything was tested again before being mounted on the machine to verify the correct systems integration.

With all the systems working together, everything was mounted on the machine and tested for the first time with the movement of the different parts. The testing carried on by setting the default speeds and movement distances.

The most important testing results are explained on the following sections.

5.3.3.1. Drivers, motors and Arduino testing

Once it was decide which drivers, motors and microcontrollers were going to be used, some tests were done to learn about the drivers, the motors, the Arduino board and the AccelStepper library.

To do this, a simple circuit was set with a stepper motor controlled by a driver via Arduino. This confirmed the way to connect the motor to the driver and how inverting the phases changes the direction of rotation. After checking the connections and some first testing, some conclusions were drawn:

Instabilities on full step mode:

When the motor runs in full step mode the motor behavior is not acceptable. The vibration is high and could end up damaging the machine. In addition, when trying to run at higher speeds (10-20) rpm the motor entered in a resonance mode and started losing a lot of steps, vibrating and making a really annoying sound.

This was not expected as resonance usually occurs on higher speeds. However, even without the instability problem the motor had not enough resolution to properly move the system.

To solve both problems (instability and resolution) the circuit was changed to be able to work on microstepping. This made the motor to run much smoother and with an incredible resolution. Though, knowing that microstepping lowers the available maximum speed, because of the microcontroller calculation frequency, some tests were performed to decide which resolution was smooth but not too high.

Conclusion:

To avoid instabilities and rough behavior $\frac{1}{4}$ microstepping resolution is required. Higher microstepping does not improve the movement enough to sacrifice torque and speed availability.

Driver current limit

To adjust the motor behavior the current limit was set to 0,5A per coil to avoid burning out the driver or the motor. After having tested the motors and seeing that they demand more current, the limit was set to 1A. After applying some load to the motor axis, it was seen that 1A was enough to have a decent axis torque.

AccelStepper library testing

When being sure that the current limit was correctly set, the library testing showed how easy was to control the stepper motors. The two kind of movements (position and speed based) were tested.

Almost all the functions were tested just in case they needed to be used and to have a deep comprehension of the library.

Conclusion:

As a conclusion, it was seen that position based movement is smoother and more reliable because it uses the acceleration and deceleration modes. Speed based movement simply starts the movement with a high and undetermined acceleration.

In addition, some of the functions are difficult to control and introduce some undesired variability.

5.3.3.2. Firmware testing

To test the firmware, the complete electronic and electric circuit was mounted on a protoboard. This was the longest testing as it was used to detect errors on the electronic circuit, the components and the firmware itself.

Firmware errors

The basic scheme of the firmware worked fine. However, some small details were changed due to malfunction or misinterpretation of what the real behavior of the function in bigger programs.

After this changes, everything stopped working properly. The program basically entered the

different modes even when none of the push-buttons were pressed. This behavior was, at the beginning, associated with a malfunction of the firmware. However, it was in fact an Arduino associated problem that needed to be solved via hardware.

Hardware errors

To solve the problem it was first necessary to know why the firmware was receiving a pushed button when it was released. Measuring the voltages at the Arduino pins it was seen that the pins were in an undetermined state when the button was not pushed. To solve this the pull-down resistor was attached to the pin. The same was done with the endstops but with a pull-up resistor to avoid having the same problem. After this actions the system started working properly again.

5.3.3.3. Machine testing

After having tested the electronic system, testing the machine was only required to confirm that the motors had enough torque to move all the systems, to set the default values for the machine and to test the final electronic set up with the soldered board. Luckily, everything worked fine and only the tests to analyze the machine performing were done. At the end, all the distances were set as well as the speeds or all the parts. To help understanding why the motors do not run as expected when some values are pushed to the limits, an excel calculator was done so the user can convert the international system units to the step based units. The Table 8 shows the final values and its conversion:

Table 8 Variables values

Variable	Value
steps_rec	800
steps_pla	800
speed_to_0	30 mm/s
recoater_speed_0	30 mm/s
bar_coarse	1,25 mm
recoater_move	230 mm
layer_thickness	1 mm
feeding_thickness	2 mm
recoater_speed	30 mm/s
platforms_speed	10 mm/s
motor_pulley_teeth	20
belt_teeth	5 teeth/cm

set_up_z	50 mm
mspeed_to_0	320 steps/s
mrecoater_speed_0	1000 steps/s
mrecoater_speed	1000 steps/s
mplatforms_speed	106 steps/s
steps_recoater	9200
steps_printzone	640
steps_feeding	1280
steps_feeding_setup	32000
cleaning_thickness	5 mm
cleaning_recoater_speed	80 mm/s
cleaning_steps	3200
mcleaning_recoater_speed	2666 steps/s

6. Validation and future steps

After all specific electronic, electric and mechanical tests, full assembly has been tested.

On the mechanical side, recoater system fits perfectly into laser machine's available housing. This involves main frame space requirements as well as carriage's ones, allowing it to move freely without colliding with laser X and Y axis movements. Should be mentioned that all internal systems work as designed.

On the electrical side, whole system works as tested. A new implementation for next prototypes would be to automatize the movement to create a new layer, making it a sequential operation. As a first prototype we fixed this parameter manually in order to reduce accumulative errors and guarantee more control to the user in case of failure.

Having this basic tests passed, it is time to test different materials and validate whole machine's functionality. This is intended to be the next step after the project is done to continue going ahead on the TRL scheme seen in *3.3 Technology readiness level (TRL)*. The natural evolution of all the work reflected over all this report. To do so, here are given the next steps that should be followed. Take this as guiding lines:

1. Test powder feeding system with different materials
2. Test laser machine and adapt machine code to move X and Y axis only inside printing area boundaries.
3. Test laser power needed to print one layer. And adjust focal distance.
4. Test different layers and verify layer welding.
5. Test different layer heights.
6. Print the same layer sequentially in order to obtain a first 3D model.
7. Print a test part in order to be mechanically tested.
8. Adapt recoater's electronics to move platforms sequentially, without user interaction, after each layer.
9. Adapt slicer software to create machine code for all the model. Then you get all different layer codes in different files.
10. Develop computer script to send layer jobs sequentially to laser machine.
11. Printing in this conditions is not suitable for all users and all the procedure can be automated to an easy version, as its seen in other 3D printers, assisted by specific software (e.g. Slic3r or Cura). This kind of software read a 3D stl file and generates whole machine code for printing. Then machine just reads the file and does its job. The problem comes with the laser machine, which runs LaOS firmware. LaOS is designed to manage laser cut jobs, so no layers are expected. To accomplish that, there are two ways that may be considered:

- a. Computer side: Modify a slicer software or design a new one in order to send layer jobs sequentially without user interaction. The natural evolution of the 10th step.
- b. Firmware side: Modify LaOS to accept layer jobs or use Marlin firmware. Marlin firmware works great with open source slicer software. Both LaOS and Marlin are open source and huge amount of content is found on the internet. Going this way recoater system's and laser machine's electronics can be merged in one and use the same firmware. It will make the whole assembly more reliable and unified.

12. Keep evolving on minor improvements.

To sum up, recoater system fits into laser machine and works as expected, opening a new window to test different materials candidate for SLS production. This is not the final stage of the prototype, but a huge progress on SLS automation and testing. Not only having an open source, self developed recoater system, but taking advantage of its reduced production cost. As the nature of the project it is expected to continue evolving along the TRL scheme.

7. Environmental Impact

As the machine designed and built on this Project is a prototype, the environmental impact is really low. However, it is a good exercise to analyse a little bit how this project has affected the environment for future designs.

Methacrylate (PMMA) parts

Methacrylate is one of the only plastics that can be recycled without losing any original property. So, if in a future the tests were over and the machine was disassembled, the methacrylate parts could be recycled to build new methacrylate sheets.

3D printed parts

Polylactic acid was used to print all the 3D printed parts. PLA is an affordable plastic that is widely used in filament extrusion 3D printing. In addition, PLA is an environmentally friendly plastic. It is produced from different vegetables and seaweed. Although it is not recyclable, PLA is a biodegradable material which is a great environmental advantage from other plastics.

Electronics

Electronic parts are not recyclable. However, all the parts follow the RoHS (Restriction of Hazardous Substances) directive. Doing so, it can be ensured that the electronic components do not contain or have used lead, mercury, or cadmium among others hazardous substances.

Electrical power consumption

A lot of electrical energy has been consumed during this project. Two laptops have been used during 270 hours. The average power of a laptop is 50W, so during the project 27KW·h have been used for computer energy. 3D printers used to print the parts, have a consumption power of 300W they have been used during an estimated time of 200 hours so that makes an amount of 60 KW·h. Another electrical consumption has been the soldering hours of the electronic parts. The solder consumes 40W and it was used during 20 hours so the electrical consumption of soldering has been 0,8 KW·h. During the manufacturing process *laser cutting machine* and a lathe were used to manufacture some parts. Both has an estimated power consumption of 15 KW and where used during 3 hours. That means a consumption of 45 KW·h. The total amount of electricity consumed for the project has been 132,8 KW·h. In terms of CO₂ generation that would be 35,46 Kg of CO₂ using the conversion 0,267 Kg CO₂/kWh².

² [http://canviclimatic.gencat.cat/es/reduex_emissions/factors_demissio_associats_a_lenergia]

This is a reasonable amount of energy as, for example, 50L of gasoline are equivalent to 119 Kg of CO₂.

8. Cost analysis

On the following section engineering cost is studied. That means hours invested by mechanical and electric engineers as if the project was hired to an external engineering company. This study covers different project steps done (Human resources, Table 11), computers, printers and software licenses (non-expendable elements, Table 10) and building materials (consumables, Table 9).

Table 9 Consumable equipment

Consumable equipment			
Concept	Quantity	Unit cost	Total cost
608ZZ Radial bearing	2	0,98 €	1,96 €
Belt pulley	2	2,05 €	4,10 €
Coupling 5 to 8 mm	2	2,15 €	4,30 €
DIN125 M3	14	0,05 €	0,70 €
DIN125 M5	4	0,05 €	0,20 €
DIN125 M8	4	0,05 €	0,20 €
DIN912 M3x10	60	0,10 €	6,00 €
DIN912 M3x12	18	0,10 €	1,80 €
DIN912 M3x18	2	0,10 €	0,20 €
DIN912 M3x6	10	0,10 €	1,00 €
DIN912 M4x25	16	0,10 €	1,60 €
DIN912 M5x10	4	0,10 €	0,40 €
DIN913 M3x30	4	0,10 €	0,40 €
DIN934 M3	36	0,05 €	1,80 €
DIN934 M4	16	0,05 €	0,80 €
DIN934 M8	4	0,05 €	0,20 €
Endstop	3	3,45 €	10,35 €
IGUS JFM-0810-038	6	0,55 €	3,30 €
IGUS JFM-0810-06	8	0,55 €	4,40 €
LM8 Linear bearing	8	1,23 €	9,84 €
Magnet	8	1,10 €	8,80 €
SY42STH47-1684A_Real Colors (curt)	4	6,23 €	24,92 €
Selfoil 4-8-12-2-10	6	0,32 €	1,92 €
Selfoil 4-8-12-2-4	6	0,37 €	2,22 €
Z-axis spring	2	0,34 €	0,68 €
Pololu DRV8825	3	5,32 €	15,96 €
Arduino Mega	1	30,00 €	30,00 €
Condensador 100uF	4	0,20 €	0,80 €
Power supply	1	6,67 €	6,67 €
Push button	3	0,40 €	1,20 €
Electronic cable	1	4,00 €	4,00 €
Conector DC	1	1,13 €	1,13 €
Interruptor DC	1	1,45 €	1,45 €
Methacrylte	1	41,30 €	41,30 €
Laser cutting	1	12,32 €	12,32 €
PLA plastic (coil)	1	15,00 €	15,00 €
		Total	221,92 €

Table 10 Non – expandable equipment

Non - expendable equipment			
Concept	Cost	Amortization	Total
Computer	2.000,00 €	10%	200,00 €
Solidworks license	2.000,00 €	15%	300,00 €
BCN 3D+	800,00 €	10%	80,00 €
		Total	580,00 €

Table 11 Human resources

Human Resources			
Concept	Hours	€/hour	Total
Documentation	66	15,00 €	990,00 €
Design	630	45,00 €	28.350,00 €
Prototype building	30	17,00 €	510,00 €
		Total	29.850,00 €

		Total project cost	30.651,92 €
--	--	---------------------------	--------------------

9. Project masterplan

In order to achieve the main goals of the Project in the expected schedule, a Gantt's diagram (Figure 122) has been done. This involves from the first project idea to the next steps to follow.

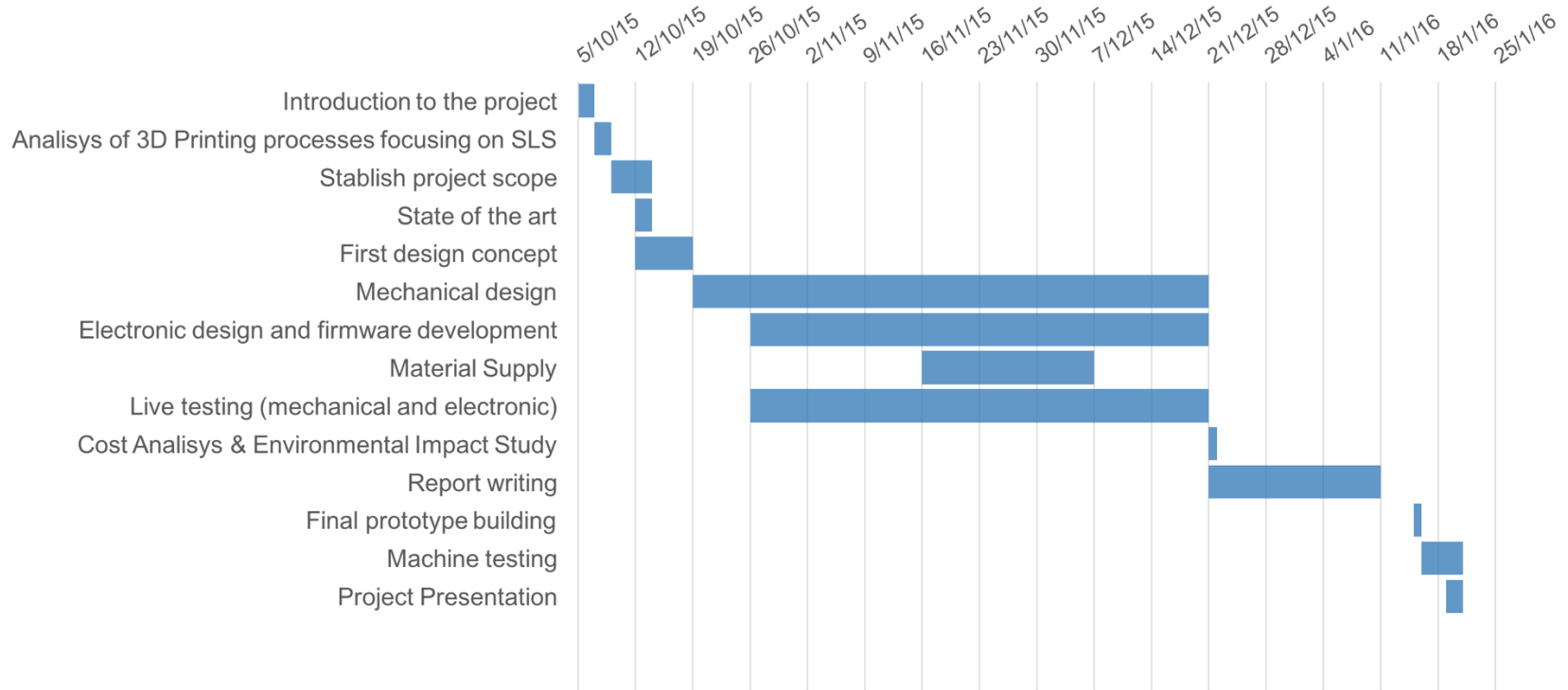


Figure 123 Gant diagram

10. Conclusions

The target of this project was to design and build a recoating system adapted to an existing *laser cutting machine* to turn it into a selective laser sintering 3D printer. To do so, both the mechanics and the electronic system had to be designed.

In addition, the design needed to be as cheap as possible by using parts from others machines in the *Fundació CIM* when possible. The design was successfully done although the laser cutting machine was only available during the last part of the project. This added some difficult to the project as the design was done without knowing the machine architecture. In fact, during the last part of the project, some pieces had to be redesigned for a better adaptation to the laser cutting machine.

The manufacturing process of the machine was really innovative as it was all done by 3D printing and rapid prototyping techniques such as laser cutting and milling. The whole design was thought to be built with these procedures and that is one of the most innovative aspects of the machine. In addition, the machine is really easy to build, and therefore, to be modified. The builder only needs a couple of Allen keys to assemble the machine as all the nuts are fixed inside the different parts.

In personal terms, this “easy to do” design was a challenge for both designers and we are really satisfied as this way to design the parts saved us a lot of time. This project has also improved our skills to design parts that are easy to mount, cheap to build and aesthetically nice. We have also developed the skills to design parts that can easily be 3D printed with fused filament 3D printers.

It has also a big challenge to distribute the work to optimize the working hours. We wanted to avoid situations in which one of the students was working and the other one stuck due to the unfinished work.

All of this personal achievements have improved our time management and our team working skills that were acquired during our previous experiences in *ETSEIB motorsport* and *AMPEER* motorsport teams.

11. Acknowledgments

Finally, we want to acknowledge all the people who made this project possible, these who have been present along all the journey. This project would not have been executed without the help and support of *Fundació CIM*. We want to thank our tutor Roger Uceda and Tomeu Ventayol who gave us the chance to do it and that had the idea of this project. Also Bernat Poll and Xavi Faneca to bring us, in first instance, the possibility to develop a cooperative project with BCN3D Technologies.

We would also like to thank the workers from the SAT, Technical Assistance Service, specially Fabián, Ramón, Jorlan and Nacho to help us with the 3D printers and all we asked for. We really hope that the machine can be a helping tool to develop the SLS machine in the future and that it will save hours of development. In addition, thanks to Ignasi Sagre and Alex Garcia for its patience and good job in *Ateneu de fabricació Ciutat Meridiana* and *BCN3D Technologies'* RD Department, respectively.

Also, we want to mention all the people, friends and coworkers, from the student teams in which we took part before engaging this project, *ETSEIB Motorsport* and *AMPEER Team*. We know this project would have not been the same without this incredible background, Including the technical part, team working environment and personal development side.

We cannot forgive, of course, our families and closest friends for their unconditional support and to bear us in our most freakish moments.

Our apologies to all the people we have forgot to mention and who gave us support as well.

Thank you all.

12. Bibliography

- [1] SCHAEFFLER. *Technical pocket guide*. Herzogenaurach (Deutschland), Schaeffler technologies, 1st edition March 2014
- [2] JOAQUIM AGULLÓ I BATLLE. *Mecànica de la partícula i el sòlid rígid*. Barcelona (Catalunya, Espanya), Publicacions OK punt, 3a edició 2002.
- [3] GENERALITAT DE CATALUNYA. *Factor de emisió associat a la energia elèctrica: el mix elèctric*. [Online] Catalunya (Espanya), [http://canviclimatic.gencat.cat/es/reduex_emissions/factors_demissio_associats_a_lenergia]
- [4] JESÚS FRAILE MORA. *Máquinas eléctricas*. Madrid (Espanya), McGraw Hill Americana de España, Quinta edición 2004)
- [5] CARDONA I FOIX, SALVADOR; CLOS COSTA, DANIEL. *Teoría de máquinas*. Barcelona (Catalunya, Espanya), Edicions UPC, 3a edició 2000.
- [6] JEFATURA DEL ESTADO. *Ley 21/2013, de 9 de diciembre, de evaluación ambiental*. [Online] Espanya, [<http://www.lamoncloa.gob.es/espana/eh15/medioambiente/Documents/LEY%2021-13.pdf>]
- [7] DEPARTAMENT UPC D'ELECTRÒNICA. *Apunts d'Electrònica M5 - T32*. Catalunya (Espanya)
- [8] 3D PRINTING INDUSTRY. *The free beginners guide to 3D printing* [Online], (USA), [<http://3dprintingindustry.com/wp-content/uploads/2014/07/3D-Printing-Guide.pdf>]
- [9] JOSÉ MANUEL RUÍZ GUTIÉRREZ. *Arduino: Manual de programación*, [online] (Espanya), [<http://3dprintingindustry.com/wp-content/uploads/2014/07/3D-Printing-Guide.pdf>]
- [10] SOLARBOTICS. *Stepper motor basics*, [Online], (USA), [<http://www.solarbotics.net/library/pdflib/pdf/motorbas.pdf>]

- [11] MIKE McCAULEY. *Accelstepper library for Arduino*, [Online] (United Kingdom), [<http://www.airspayce.com/mikem/arduino/AccelStepper/>].
- [12] SCHAEFFLER. *Technical pocket guide*. Herzogenaurach (Deutschland), Schaeffler technologies, 1st edition March 2014
- [13] GENERALITAT DE CATALUNYA. *Factor de emisió associat a la energia elèctrica: el mix elèctric*. [Online] Catalunya (Espanya), [http://canviclimatic.gencat.cat/es/reduex_emissions/factors_demissio_associats_a_lenergia]
- [14] DEPARTAMENT UPC D'ENGINYERIA MECÀNICA. *Apunts de sistemes de fabricació*. Catalunya (Espanya)
- [15] DIETMAR DRUMMER, MAXIMILIAN DREXLER, FLORIAN KÜHNLEIN. *Effects on the density distribution of SLS - parts*. Insitut of polymer technology (LKT) (Deutschland),