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DESIGN AND CONSTRUCTION STUDY OF A SPEED REDUCER WITH 3D PRINTER

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DESIGN AND CONSTRUCTION STUDY OF A SPEED REDUCER WITH 3D PRINTER

Report

Bachelor's degree: Degree in Industrial Technology Engineering

Submission date: April 27th of 2020

Student: Cristhian Yepez Velasco

Director: Montserrat Sánchez Romero

Co-director: Rafael Weyler

Aquí ficar agraiments.

Gracias.

SUMMARY

The choice of this topic of the final degree project is determined by my passion in the automotive field and modern technologies. Today, modeling objects in 3D printers have become an ordinary practice for some engineers, which is why I was captivated by the idea of being able to merge the world of cars with 3D printing. Throughout this program, the aim is to carry out an extensive documentation on the creation of a speed reducer, which in this case will be a gearbox, to acquire all the necessary capabilities to produce one.

In order to provide an understanding of the theoretical work, a reducer will be designed with the Solidworks program. This will then be printed piece-by-piece on a 3D printer and assembled.

ABSTRACT

L'elecció del tema del treball de final de grau està determinat per la meva passió a l'àmbit automobilístic i a les noves tecnologies. Avui en dia, modelar objectes en impresores 3D s'ha tornat una pràctica habitual per alguns enginyers/eres, és per aquest motiu que em va captivar la idea de poder fusionar el món dels turismes amb la impressió 3D. Al llarg d'aquest programa es pretén realitzar una àmplia documentació sobre la creació d'una reductora, que en aquest cas serà una caixa de canvis, amb la finalitat d'adquirir totes les capacitats necessaries per crear-ne una.

Amb l'objectiu de donar com a entés el treball teòric, es dissenyarà una reductora amb el programa Solidworks. Posteriorment aquesta serà impresa peça a peça en una impresora 3D i ensamblada.

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1. Introduction

1.1 Objective

The aim of this project is to study and design a speed reducer and then to print the different parts using the 3D printing technology and assemble all the parts.

1.2 Scope

The scope of this project will include:

- Study the speed reducers and its types.
- Study the 3D printing technology and its types.
- Decide the type of reducer and its functionality.
- Do the mathematical calculations.
- Design the reducer using a 3D design software.
- Do the dimensional drawings of the reducer parts.
- Learn how to use a 3D printer.
- Print all the parts with the 3D printer.
- Assemble the speed reducer.

1.3 Requirements

To carry out the project it's necessary to consider some different specific requirements.

- Use a 3D printer to produce/build the speed reducer parts.
- Design the parts considering the size of the 3D printer provided by the UPC.
- The designed speed reducer must have and actual functionality.
- Consider the resistance of the printing material.
- Do the necessary modifications on the 3D printer to improve its functioning.
- Stick to the economic subvention provided by the UPC to carry out all the printing tasks.

2. State of the Art

The needs to be covered in the project are related to two different engineering fields. The first one is the speed reducer, which is a common gear system that has been around for a lot of years and that helps to carry out many tasks of our daily life. The second one is the field related to the 3D printing technology, which is a brand-new technology that is being developed and improved a lot nowadays.

The speed reducers, or also known as gearmotors, are one of the most antic inventions in history that's still in use in our daily life in many ways and applications: starting from a common analogic watch to most of the vehicles out there, lifts, and so on. All these mechanical systems use reducers or gearmotors in many different sizes to achieve the desired system speed. During this project, it will be briefly explained the functioning and the technical considerations to be totally operational.

On the other hand, 3D printing is a technology that is barely used nowadays for industrial processes. But it is also a technology with a lot of potentials that when it would be fully developed it will be possible to print any kind of thing, made of any material, in any part of the world, in a short time, and not requiring a long and complex manufacturing process. As part of the project, it will be explained the 3D printing basics, and it will also be used to build actual elements designed from scratch. This will be one of the most challenging elements of the project since designing a piece to be 3D printed is a very difficult and tricky process due to its size and technical limitations.

3. Theoretical Framework

3.1 Speed Reducer Definition

Speed reducers are aimed to transmit mechanical energy from an electric or combustion motor to an output device, mostly in industrial machinery, but they are also used in household machines. This occurs by using an assembly of gears to change the speed-torque and/or direction of the mechanical energy. (1) (2) (3) (4)

3.2 Speed Reducer Types

3.2.1 Parallel Shaft Reducers

These reducers are the simplest and they can have vast amounts of combinations to obtain the desired speed or torque. They are famous for having some of the highest performance rates (96-99% for each transmission) and are used exclusively for parallel shaft drive shafts. (5) (6)

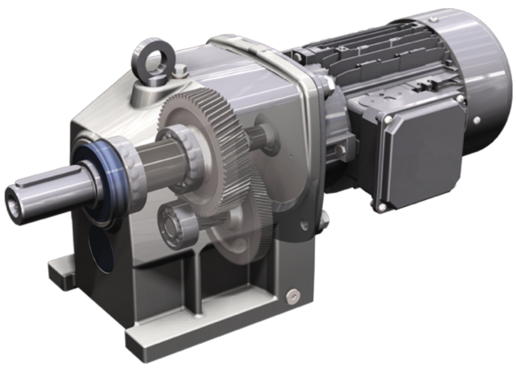


Figure 1: Parallel shaft reducers.

This type of reducers can house two different types of gears: spur gears or helical gears.

Spur gears are the most common and the easiest and cheapest to manufacture that exists. They are usually used only to transmit small and medium speeds, but for large, high-power reductions. Since their teeth are parallel, there are no axial forces, and they turn out to be quite stable without misalignment.

Some basic concepts are explained below since later this type of gear will be used in the project.

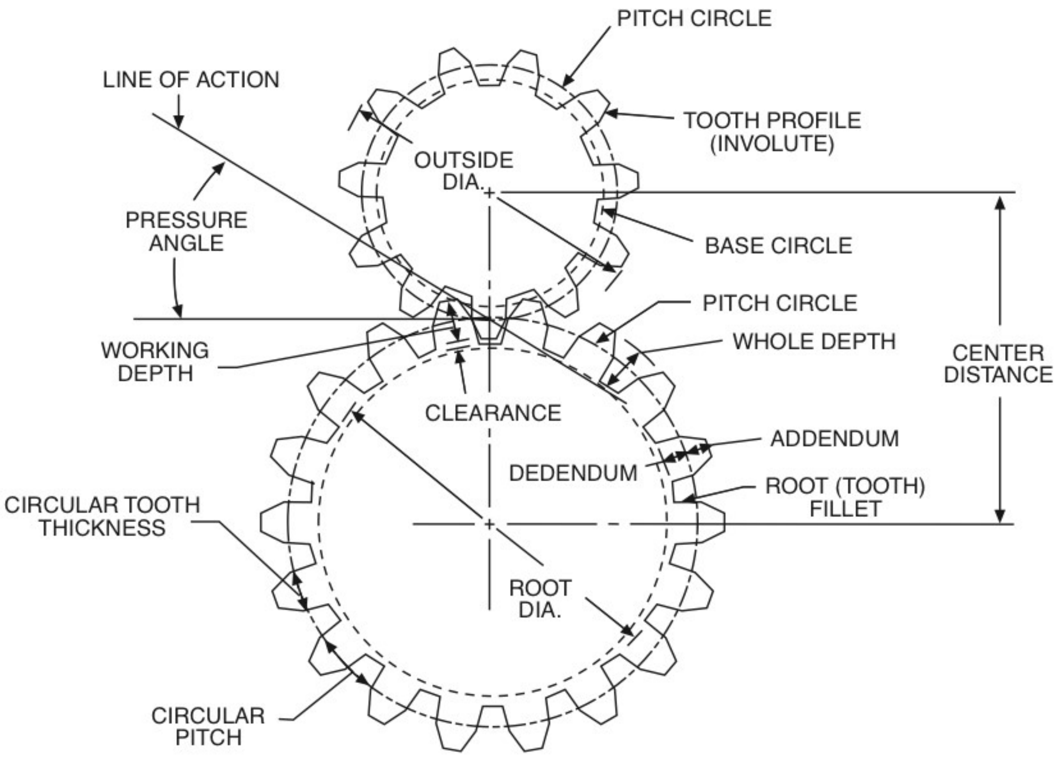


Figure 2: Spur gear parts.

- **Root Diameter:** Diameter of the gear without the teeth.

- **Pitch Diameter:** Diameter where all the points of the gear will fit with another gear. The pitch diameters of a pair of gears that mesh is always tangent, thus the sum of the radius is equal to the distance between shafts.

- **Outside Diameter:** Total diameter of the gear considering the teeth.

- **Module:** Ratio that exists in a gear between the primitive diameter and its number of teeth. This relationship is proportional between the pitch of your teeth and the number π.

These reducers are used in a variety of industries from industrial to medical applications.

Advantages:

- High torque.
- Overhung load capability.
- High efficiency, ideal for continuous duty applications. Because of their ability to dissipate heat.
- Back drivable.

Disadvantages:

- Size: are the least compact.
- Torque limited by the strength of the gear.
- Noise.
- Holding break is needed if the gear box is required to hold the position.

3.2.2 Planetary Reducers

These reducers are some of the most reliable and best performing and are therefore widely used. It does not require exhaustive maintenance and involves a lot of precision. (7)

A planetary gear reducer is made up of a central gear called **sun**, or also known as planet, around which other gears rotate. These rotational gears are called **planetary gears** and are always the same size. The shafts of these satellites are located on a piece called **planetary carrier**, which forms a coaxial axis with respect to the axis of the sun or planet. Wrapping this system there is the **crown**, or internal gear ring, which is a ring with the teeth on the inside and in contact with the satellites.

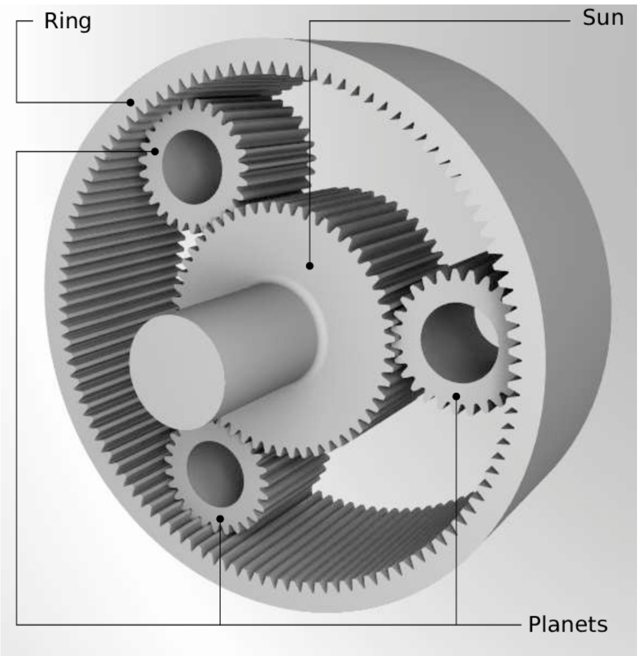


Figure 3: Planetary speed reducer.

Having the control over these mechanisms it is possible to achieve different transmission relations, whether blocking the ring or the carrier.

They are used in a wide variety of industries such as commercial, medical, and agricultural applications. This kind of speed reducers is the main part of the automatic changes of most automobiles.

Advantages:

- High torque.
- Compact package.
- By sharing the load between several planet gears that allows the reducer to handle the same torque that a larger parallel shaft reducer handle.
- High efficiency (95%).
- Resistance to elastic deformation.
- The contact between the Sun gear and the multiple planet gears gives it a torsional stiffness three times greater than that of a parallel shaft reducer.

- The coaxial alignment requires no output shaft offset and the rotational direction that matches the motor removes the need for an idler gear as in a parallel shaft gearbox.

Disadvantages:

- Best use in Intermittent duty applications, due to its size these reducers have low heat dissipation
- Holding break required to hold position. It needs a holding break as it back drives at all ratios.
- Long length in higher ratios, the gear box can get very long due to the high ratio of length to diameter when using multiple stages
- Cost more than the same size parallel shaft reducers, because more gears are required for a given ratio. But will have more load capacity within those matching sizes.

3.2.3 Right-Angle Reducers

Are great for application where size and space are at a premium. With the ability to turn 90-degree corner this gearbox is a good solution for many industries including food and beverage, automotive, and packaging.

Right-angle worm gear reducer

The worm gear reducer is maybe the most popular right-angle reduction system and one of the easiest to understand.

It is made up of a **worm shaft** aligned with the motor shaft that transmits the mechanical movement perpendicularly to a **worm gear**. The worm shaft also has at each end ball bearings to assist in smoother the rotation. This type of mechanism is not reversible since if you try to rotate the worm gear it will not work as a multiplier by moving the worm shaft. Worm gear reducer provides a movement transmission between right-angled shafts that achieves a very high ratio of reduction.

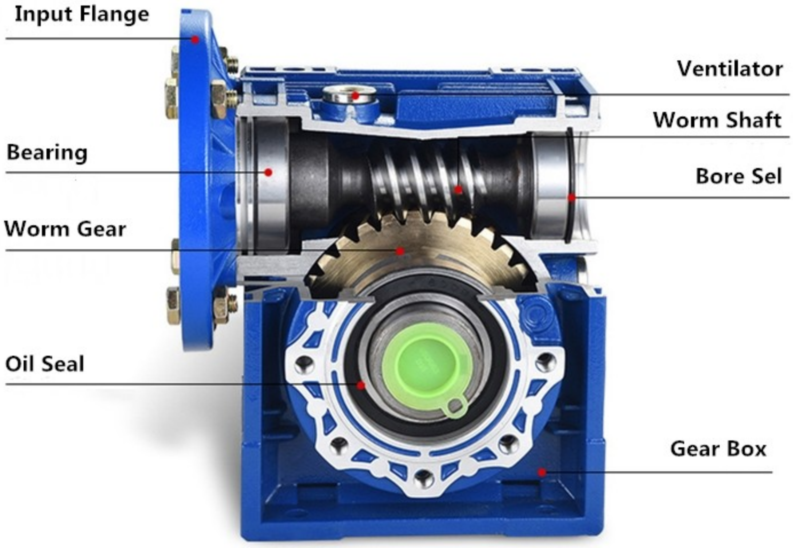


Figure 4: Worm gear reducer.

In standard cases, for each turn of the worm shaft makes the worm gear advance by one tooth. This means that by knowing the number of teeth in the gear, you know the turns that the shaft has made to achieve a whole revolution. Having understood this, the transmission ratio of the system can be easily calculated.

For the worm shaft to fit correctly with the worm gear, it must have special teeth that respect the shape of the shaft. Many forms have a slight negative ripple at the top and are sometimes also inclined, to correctly transmit movement without causing unwanted friction.

Although his reduction system is sometimes not considered a gear system, in this work it has been included within the types of speed reducers because the worm gear does not stop being a gear that fits with the "tooth" of the worm shaft.

Advantages:

- Overhung load capacity.
- Compact.

- Ratios over 30 to 1 are non-back drivable, to guarantee full non back drivability a break should be used.
- The quietest.

Disadvantages:

- Low efficiency (50%), Are the least efficient.
- Holding break needed at certain ratios.
- Have high sliding in the gear mesh which can generate excessive heat.

Bevel Gear Reducer

The helical bevel gear refers to a teeth line on the crown wheel and to a straight bevel that does not pass through the top of the cone.

Straight bevel gear pair has relatively few teeth in the transmission at the same time and then the transmission is no stable and the noise is large. The large and small gears of the helical gear pair have equal and opposite spiral angles. The coincidence ins are significantly greater than the straight bevel gear pair.

Figure 5: Bevel gears.

Therefore, the noise and the vibration are significantly reduced at a high-speed operation, and the number of teeth of the helical gear ratio and a compact structure;

When the helical gear teeth are engaged, the gear meshing line is changed, the load is gradually added, and then gradually removed, so the transmission is relatively stable, and the impact, vibration, and noise are small, which is suitable for high speed and heavy load transmission.

Excels in intermittent applications but can quite capably handle many continuous duty applications.

Advantages:

- High torque.
- High efficiency (90%).
- Back drivable.
- Quiet.

Disadvantages:

- Size.
- Holding brake needed.

3.2.4 Cycloidal Speed Reducers

It is a system that has an eccentric cam and a set of bearings, a cycloidal disc, and the output shaft. It is a system that has less friction than normal gear systems.

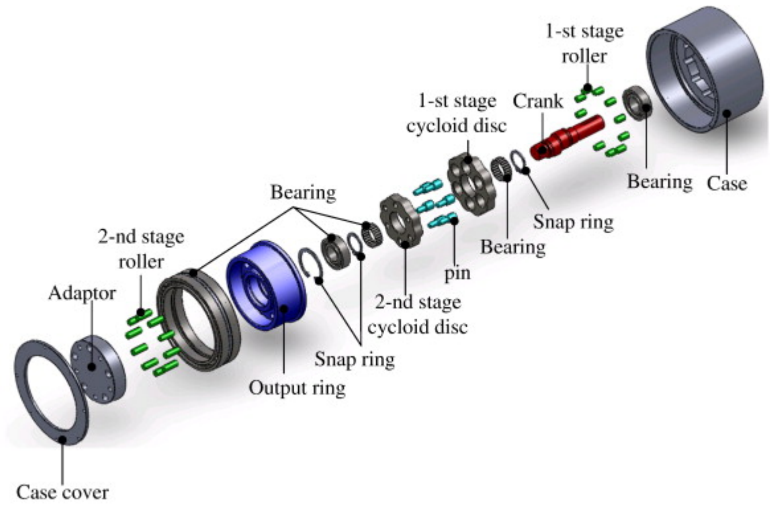


Figure 6: Cycloidal speed reducer.

3.3 Gear Types (8)

3.3.1 Spur Gears

Gear teeth are straight and parallel to gear axis.

Figure 7: Spur gears.

Advantages:

- Simplicity in design.
- Economy of manufacture and maintenance.

- Absence of end thrust.
- Can be used at almost any speed.

Applications:

- Clocks.
- Electric screwdrivers.
- In many household appliances such as washing machines, blenders, oscillating sprinklers clothes, dryers, etc.
- They are used in aircraft engines.
- Railways trains where noise is not an issue.
- Sliding mesh gear box.
- Conveyors.
- In power stations to convert wind or hydroelectric energy into electrical energy.

3.3.2 Helical Gears

Teeth inclined to the gear axis in the form of a helix.

The angle of the helix on the both meshing gears must be same in magnitude but opposite in direction, i.e., a right-hand pinion meshes with a left-hand gear.

Figure 8: Helical Gear.

Advantages:

- High speed gears.
- Can take higher loads than similarly sized spur gears.
- Smoother and quieter motion.

Applications:

- Heavy load applications.
- Transmission gear boxes.

3.3.3 Double Helical Gears (Herringbone Gears)

- Like two helical gears placed side by side.
- Double helical gears.
- Thrusts are counterbalanced.
- No thrust loading on the bearings.
- Smooth power transmission.
- Used in heavy machineries.

Figure 9: Herringbone Gears.

3.3.4 Bevel Gears

- Two non-parallel or intersecting, but coplanar shafts. It means both the shaft axis are in same plane and intersecting to each other. (9)

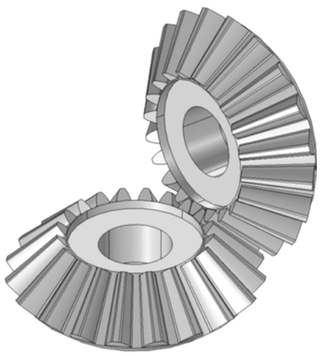


Figure 10: Bevel Gear.

Classified by geometry

Straight Bevel gears

- Have conical pitch surface and teeth are straight and tapering towards apex.

Spiral or Skew bevel gears

- Spiral shaped tooth.

- Are quieter and can take up more load as compared to straight bevel gears.

Zero bevel gears

- Are similar to straight bevel gears but their teeth are curved lengthwise.
- The curved teeth are arranged in a manner that the effective spiral angle is 0.

Hypoid bevel gears

- Like spiral bevel gears but the pitch surface is hyperbolic and not conical.

Miter gears

- Two equal bevel gears having equal teeth and connect two shafts whose axes are mutually perpendicular.

Applications:

- Locomotives.
- Marine.
- Differential gear box.
- Main mechanism of hand drills.
- Rotorcraft drive systems.
- Are also used as speed reducers.

3.3.5 Worm Gears

- Are used to transmit power at 90º and where high reductions are required.
- The axis of worm gears shafts cross in space.
- The shafts of worm gears lie in parallel planes and may be skewed at any angle between 0º and 90º.
- One gear has screw threads. Due to this worm gears are quiet, vibration free and give a smooth output.

Figure 11: Bevel Gear.

- Worm gears and worm gears shafts are almost invariably at right angles.

3.3.6 Rack and Pinion Gears

- A rack is a toothed bar or rod having infinitely large radius of curvature.
- Torque can be converted to linear force by meshing a rack with a pinion.
- Pinion turns and the rack moves in a straight line.

Figure 12: Rack and Pinion Gears

Applications

- Used to convert rotary to translation motion or vice versa.
- In automobiles as the steering mechanism.
- In rack railways.

3.3.7 Internal and External Gears

- External gear: is the one with the teeth formed on the outer surface of a cylinder or cone.
- Internal gear: is the one with the teeth formed on the inner surfaces of a cylinder or cone.

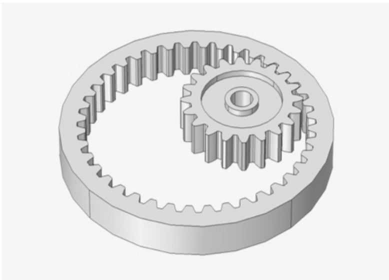


Figure 13: Internal and External Gear.

3.3.8 Face Gears

- Transmit power at (usually) right angles in a circular motion.
- Are not very common in industrial applications.

Figure 14: Face Gear.

3.4 Types of 3D printing technologies

Classified by types of processes (10) (11)

3.4.1 Fused filament fabrication (FFF)

Also known as FDM (Fused deposition modeling) is the world's most common 3D printer process. FFF printers use a thermoplastic filament, which is heated to its melting point and then extruded layer-by-layer to create the three-dimensional object.

This technology is highly standardized and there are plenty of affordable printers available on the market. They can print a multitude of materials with a melting temperature between 50ºC and 300ºC. Some FFF 3D printers even have the ability to print in more than one material since they can have multiple extruders and can print a single piece made up of various colors and/or materials.

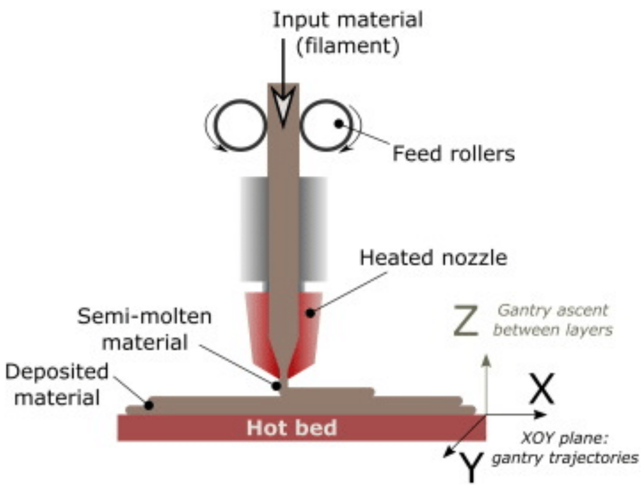


Figure 15: Fused filament fabrication parts.

3.4.2 Stereolithography (SLA)

Stereolithography was the first 3d printing process created, and it describes a process where you have a vat of liquid, photo-polymer resin, that turns solid when it is exposed to UV light in selective ways. And then pulling that print out and changing the light, layer-by-layer, to make sure that you create each layer of your object as you pull it out. In this way objects of great precision and quite good mechanical properties are achieved. Print times are not the fastest, as apart from printing, then you need a curing process. Now a days, there are a couple of different ways to do this, but they all fall under that same basic idea.

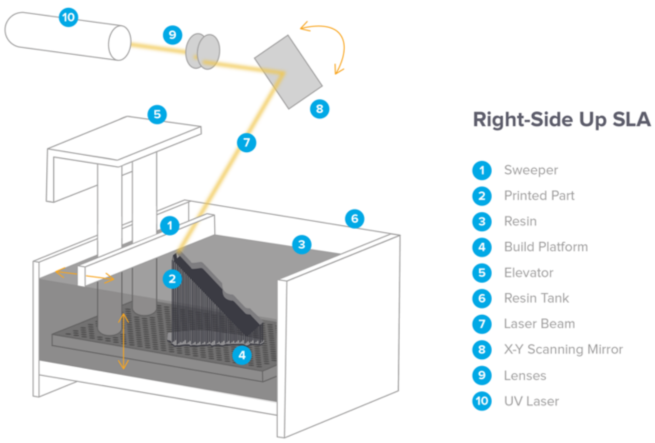


Figure 16: Stereolithography parts.

However, it does have a couple of disadvantages. First of all, you can only use a single type of material in Stereolithography. The UV curing polymers are sometimes a little bit hard to work with and can be a little bit toxic. Also, these 3d printers tend to be a little bit expensive and the materials for them also tend to be expensive as well. There is also some common knowledge that these materials continue to cure so the prints that you get from there, if you continue to expose them to light, will change and eventually break down.

3.4.3 Selective Laser Sintering (SLS)

A laser is used to sinter powder layers of a few tenths of a millimetre that are typically nylon or polyamide. In this case, solidification is not achieved by melting the material, it only sinters it, this means that it heats it with enough temperature so that the powder remains molecularly bonded without actually melting. The layer to be solidified is preheated a few degrees below the melting temperature of the material, thus the laser does not require such a high peak power.

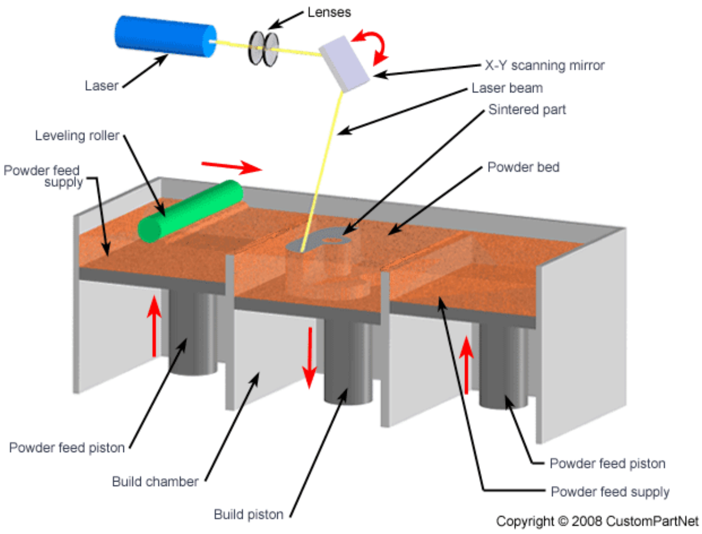


Figure 17: SLS parts.

Unlike other technologies, the part to be printed does not require supports as it is held in place thanks to the non-solidified powder. At the end of the printing, it is only necessary to remove this non-solidified powder to obtain the printed part. As it is not possible to melt, there are pieces with little dense and porous characteristics.

There a related technique that is called Selective Laser Melting (SLM) which is considered a subcategory of SLS with the difference that it is used only for metals and it does melt the material. With these technique more compact and solid pieces are built.

3.4.4 Binder Jetting

This is a 3D printing technology that works by solidifying the selected parts of fine-grained powder layers using heat and a melting agent (binder) and another detailing agent to obtain three-dimensional objects.

Having good temperature control, a reaction similar to the melting of the material can be obtained. All kinds of objects in fully complex shapes can be printed easily, the properties of which will be optimal. This process is much faster than other printing systems, but at the moment it is only available to very few. Mostly, because the companies who are doing it are held by a few companies who still have control over the patents of them.

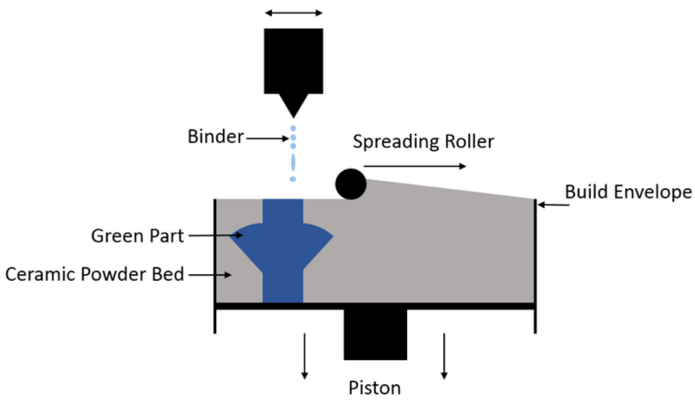


Figure 18: Binder Jetting parts.

3.4.5 Material Jetting

This is the process where a head, like an inkjet printer, squirts out a material that is liquid but that can be solidified afterward. The droplets of material are then immediately cured using a UV light source mounted to the print head.

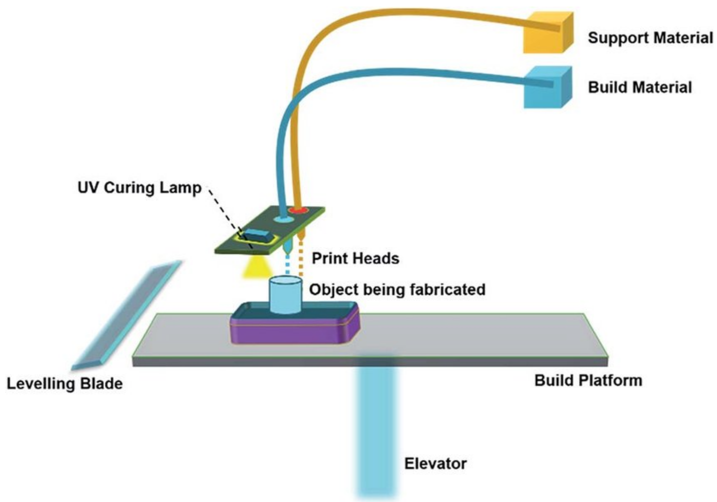


Figure 19: Material Jetting parts.

For instance, they have multiple heads that can print out a rigid material and a flexible material and then print out another material that is water-soluble afterward, so that it will just dissolve away. So this means they can build something that's partially rigid and partially flexible that has great support that disappears afterward.

4. Practical Framework

Once at this point, the idea was to put into practice some of the concepts explained in the theoretical framework and to explain the entire procedure that has been followed to carry out this study of design, printing, and construction of the gearbox with different relations of speed transmission. But, due to the current situation in which we find ourselves with the COVID-19, the 3D printing part has not been possible to carry out since there was no access to the 3D printer that the school was supposed to provide. Then, all the problems and complications that have arisen in the project and the solutions that have been given will be explained. This second part will be illustrated with images of the 3D design that has been done during this project.

4.1 Speed Reducer Type Selection

This second part will start by explaining the selection of the type of speed reducer that the development of the project of the design and construction study of a speed reducer with 3d printer will be about. Justifying why this type of speed reducer is chosen and the reasons why other types mentioned in the theoretical framework are discarded. All of this, bearing in mind that the printing part could not be carried out in the end as has been mentioned before.

Bearing in mind that I had a clear vision of what I wanted to do, I explain why other options were not considered.

To begin with the study, the first thing to consider is that the selected gearbox can be fully built with the 3d printer, considering them apart from the complementing mechanical, structural, holding, or enforcement parts such as rods, threaded rods, bearings, wires, etc. So, the main objective is that the reduction and the transmission of the movement are carried out by the printed parts. At this point, the decision is to use gears to make this possible. First, by discarding the planetary gears because of the complexity to make the system work, and the precision needed for it. Also, because it was a project already carried out by a student and it was shown to me as an example, thus I didn't want to copy it.

Next, the Right-angle worm gear reducer is thought of, it turns out to be a subject also previously explored by Professor Rafael Weyler without success. Even though it is a very simple reduction method that only consists of two elements, it has great difficulty in designing which is the worm shaft. First of all, the design is complicated since both the worm gear and the worm shaft must fit perfectly to be able to transmit the movement orthogonal and efficiently. So far, there would be no problem. In fact, the interesting thing about the project would be the 3D designs of the two pieces, because interactions between the worm gear and a cylinder would have to be used to define the shape of the worm shaft.

The problem comes when it comes to printing the worm shaft. With the common and affordable methods, it is almost impossible to print the worm shaft in one piece since it has no flat part and due to its geometry, it is not possible to deposit layer-by-layer and that they fit well and not spilling. Even so, it could be possible to design a worm screw in a couple of pieces that could be printed and assembled, but it was also discarded since solving this problem ends the content of the design and construction study because, as previously stated, only It is two pieces and is a very simple reduction system.

Regarding the cycloidal reducer, it is not a good choice due to the complexity of printing the different parts. And because it should have many elements, such as bearings, shafts, etc., that could not be 3D printed and will be hard to find and integrate into the design.

Finally, the proposed choice consists of doing the design study of a speed reducer with spur gears with simple parallel shafts, but with 5 transmission ratios of speed. This study design can have a lot of juice both to make a system that allows housing the different speeds, and a system to be able to select the gear and to be able to change speeds easily. Furthermore, in this case, there was no apparent restriction.

4.2 3D Printer Type Selection

Regarding the selection of the 3D printer type it was an easy and clear choice from the beginning of the project since the School provided the option of using their available 3D printers and the filament materials at no cost.

The printers available in the department are a Mendel Max (with a 200x300 hotbed) and a CFRAX (with a 200x200 hotbed), which are variants based on the RepRap project (12). They are FDM printers with technical specifications similar to the Prusa i3 (13), although the CFRAX has a different movement configuration (the bed moves in Z with a single motor and there are two motors combined for X-Y movements).

Despite this was a very clear choice, due to the global pandemic that we are surrounded in, none of these printers could be used to carry out the printing part of the project. So, the scope of the project is slightly affected due to the suppression of this part.

4.3 Design Calculations

Once having the objective set the next thing to do is to think about how to execute it. The idea was to build a spur gears reducer, a gearbox, having an inlet shaft, a middle movable shaft, the one in charge of changing the reductions positions, and an outlet shaft.

The main axis or inlet would have five fixed gears meshing with the middle or changing shaft, containing five gears moving along the axis. At the same time, the secondary axis or outlet would again have another five fixed gears meshing at the same time with the middle shaft that transmits the power through the main and secondary shaft.

The other thing to have in mind was to do everything with integers so as not to complicate the calculations or the 3D modelings. So, we started by trying to have the pitch diameters with integers to provide a wheelbase without decimals. Therefore, the only way to make this possible was to take the appropriate module to design the gears and with a pitch diameter without decimals to calculate an exact number of teeth. The first module to think about is module 1 since you get the same number of teeth as the value of the pitch diameter. But it was not possible since there would be too many teeth in a single gear to be 3D printed in proper conditions. As a result of these 3D printer limitations, the next module to think about is module 2 that reduces the number of teeth by half, helping so to better printing.

With the module decided, the reduction should be a bit big but, knowing this, the size of the gears must be controlled to have proper printing and not exceeding the size limits. So, the first reduction between the motor shaft and the main shaft to be set was 2/3, to have only a little reduction on the main shaft. This reduction is made with a 20 mm diameter and a 30 mm diameter reaching so a reduction percentage, something around 30%. These diameter sizes allow good printing.

After this selection, it is easy to set the wheelbase just by adding the pitch radiuses. Then as the objective was to have five different increasing speed relations. So, in this main axis as there would be five different gears, the first three would be the same size, 70 mm diameter, then another 90 mm diameter gear and finally a 110mm diameter gear all of them using module 2. The outlet shaft like the main has five gears but this time in opposite order to achieve the goal of increasing the speed every time you go up a gear position. Having so, a 110 mm diameter gear, a 70 mm diameter gear, and a three 70 mm gear diameter (always talking about the pitch diameter). In the middle shaft, there would be also five gears united by a tube, that allows them to move along the axis at the same time, and with diameter sizes from left to right of 30, 50, 70, 50, and 30 mm.

This selection of gears sizes is based on the distance desired between shafts that are 70 mm. So, the first reduction, apart from the one between the motor shaft and the inlet shaft, would be 3/11, the second 5/9, the third no reduction, the fourth 9/5, and fifth reduction 11/3, clearly seeing the decreasing of the reduction but increasing the outlet speed.

Calculation:

Knowing that: $$Module = \frac{\emptyset\ Pithch}{n^{o}\ teeth} \rightarrow n^{o}\text{teeth} = \frac{\emptyset\ Pitch}{Module}$$

Pitch gear (1) 20 mm: $n^{o}\text{teeth} = \frac{20\text{mm}}{2} = 10 \text{ teeth}$

Pitch gear (4) 30 mm: $n^{o}\text{teeth} = \frac{30\text{mm}}{2} = 15 \text{ teeth}$

Pitch gear (3) 50 mm: $n^{o}\text{teeth} = \frac{50\text{mm}}{2} = 25 \text{ teeth}$

Pitch gear (7) 70 mm: $n^{o}\text{teeth} = \frac{70\text{mm}}{2} = 35 \text{ teeth}$

Pitch gear (2) 90 mm: $n^{o}\text{teeth} = \frac{90\text{mm}}{2} = 45 \text{ teeth}$

Pitch gear (2) 110 mm: $n^{o}\text{teeth} = \frac{110\text{mm}}{2} = 55 \text{ teeth}$

In parenthesis the number of this size of gear that there are in the reducer.

The next figure shows a sketch of how the gears will be arranged in the reducer.

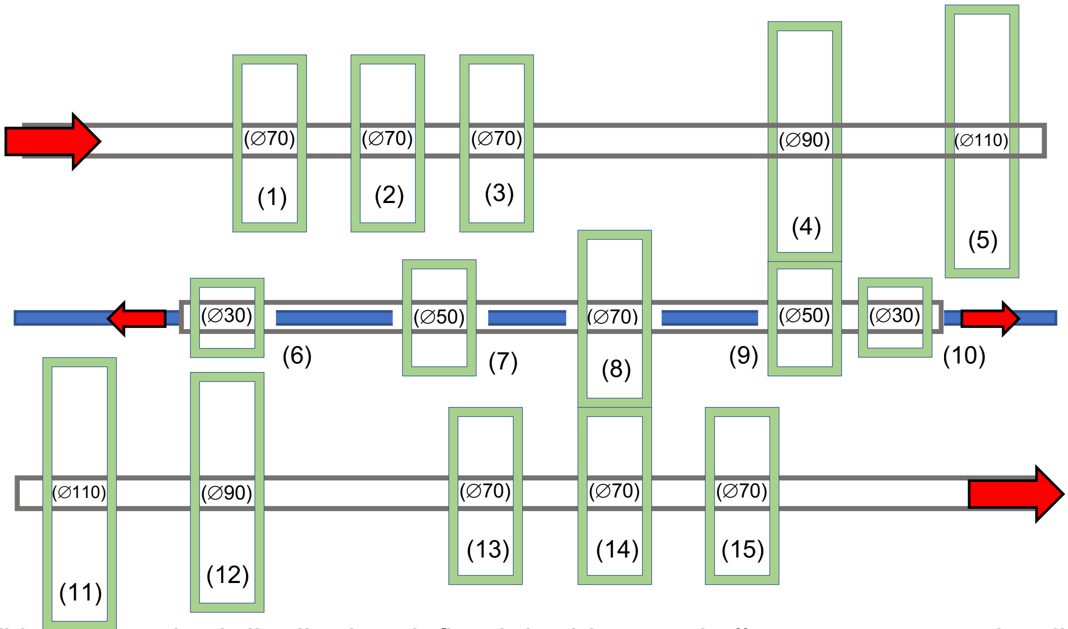


Figure 20: Sketch of the reducers and the diameters of the gears.

With the standard distribution defined the biggest challenge was to set the distances between gears in each shaft to make every position through shafts to mesh perfectly and smoothly. This was made by first placing the third relation in the middle aligned with 70 diameter gears of each shaft (3, 8, 13).

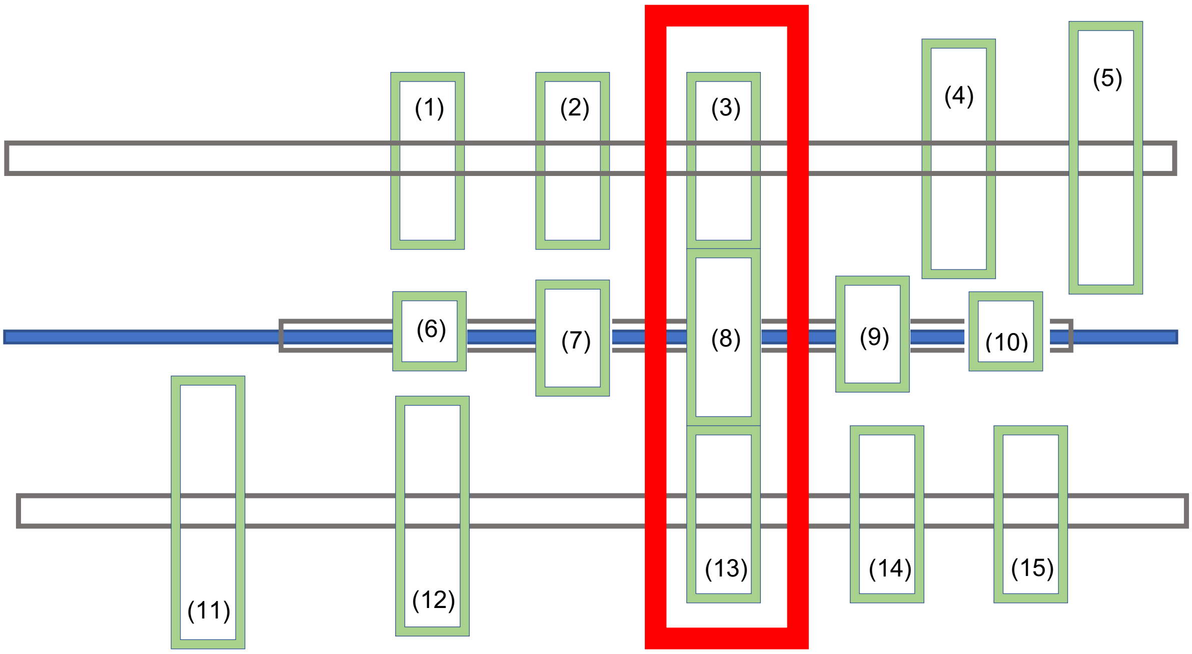
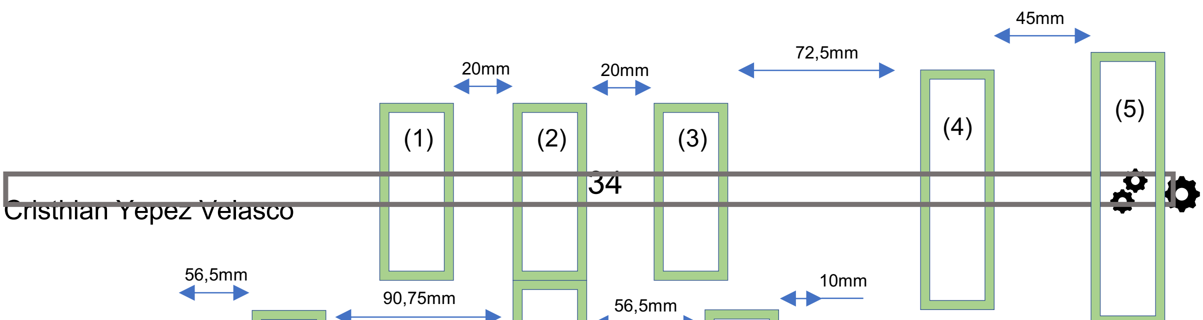


Figure 21: Sketch of the third alignment.

Then, taking this as a reference, and knowing that the minimum distance between gears in a single shaft must be at least the same as a gear width since it needs to have enough space to move the middle shaft to the next meshing position, the decision was to put 20 mm distance as a minimum reference. The width of the gears is 15 mm.

After several tryouts, the final distancing between gears and the whole arrangement will look like as below, leaving always a free gap of 5 mm between positions.



Now, after clarifying the whole arrangement of the gearbox, each gear position will be as follows:

<u>1st Gear</u>

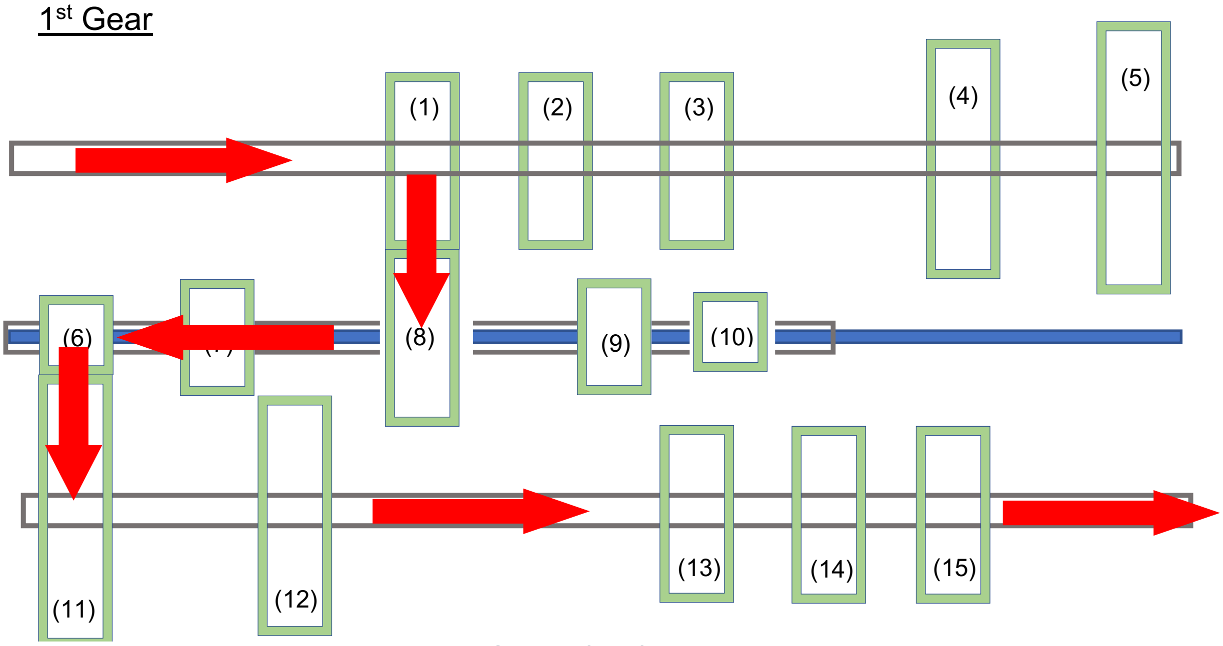
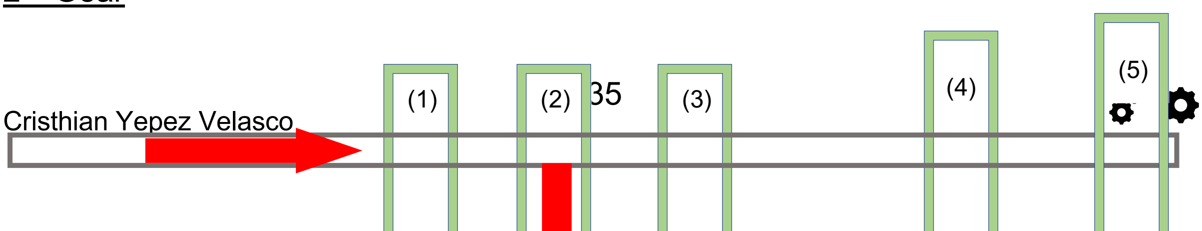


Figure 23: Sketch of the first gear position.

Receiving the rotational power through the inlet shaft and transferring it through gears 1, 8, 6, and 11 to the outlet shaft.

<u>2nd Gear</u>



Receiving the rotational power through the inlet shaft and transferring it through gears 2, 8, 7, and 12 to the outlet shaft.

3rd Gear

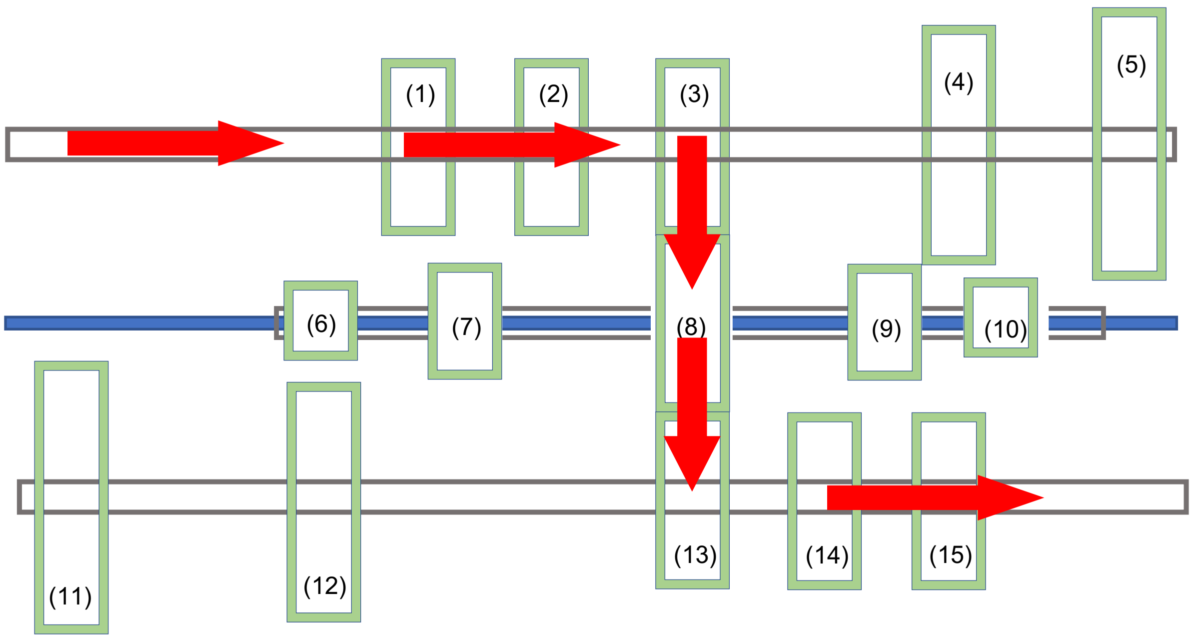


Figure 25: Sketch of the third gear position.

Receiving the rotational power through the inlet shaft and transferring it through gears 3, 8, and 13 to the outlet shaft.

4th Gear

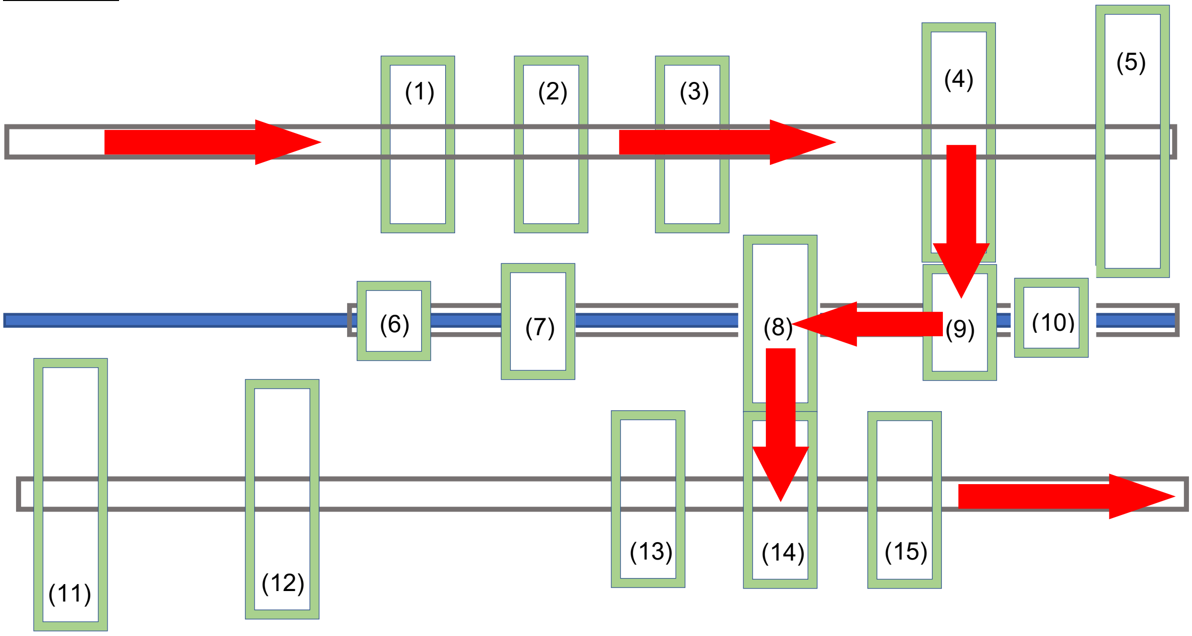


Figure 26: Sketch of the fourth gear position.

Receiving the rotational power through the inlet shaft and transferring it through gears 4, 9, 8, and 14 to the outlet shaft.

5th Gear

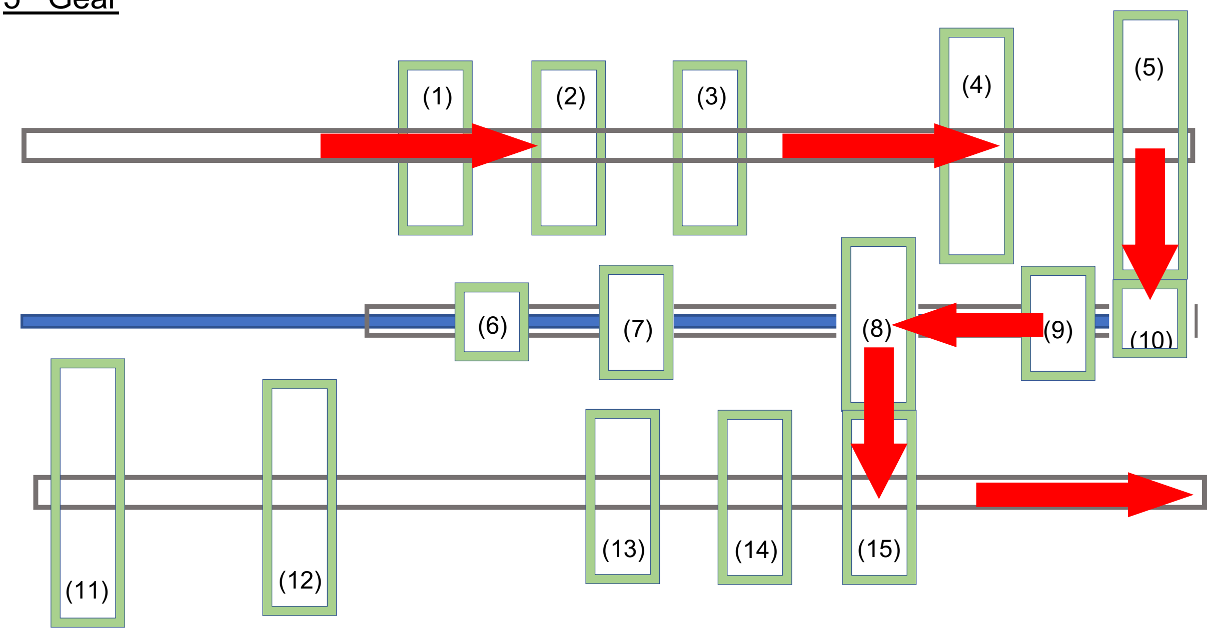


Figure 8: Sketch of the fifth gear position.

Receiving the rotational power through the inlet shaft and transferring it through gears 5, 10, 8, and 15 to the outlet shaft.

All these lateral movements of the middle shaft are projected to be done by a gear lever placed between the 8th and 9th spur gear.

Remarkably, due to the global pandemic of COVID-19, 3D printing of this project could not be carried out. Therefore, in order for the project to have a little more body, some enhancement in the design was requested. So, at this point, it was decided to think about placing a possible reverse gear.

For this enhancement, the solution was to place a fourth shaft between the middle and outlet shaft, holding one little spur gear to reverse the movement of the outlet. The hard thing here is to find a three gear relation that fits in the 70 mm wheelbase, and so, to find the distance where to place the little shaft.

After thinking about this expects the solution was to place another 70 mm diameter gear in the inlet shaft and then a 30 mm gear in the support shaft and a 50 mm gear in the outlet shaft. Having a final configuration as it is shown below.

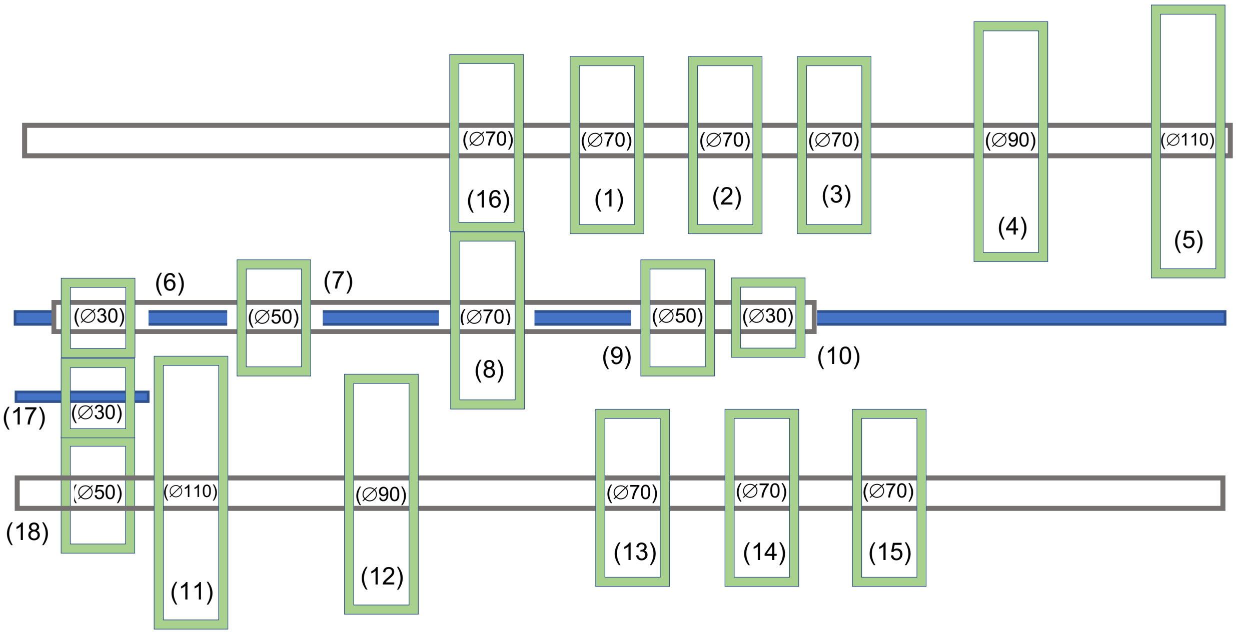


Figure 9: Sketch of the final arrangement of the gearbox.

After this process, this would be the sketch to be followed to carry out the 3D design of this project.

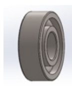
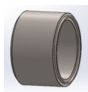
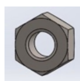
4.4 3D Design

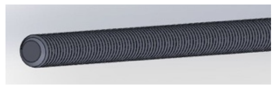
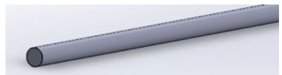
Below, the steps that have been followed to make the first design of the gearbox with different speed changes will be explained. We will try to explain it as clear as possible and by subsets that make up the reducer. Before starting, it should be commented that it is a process in which some initial dimensions are given, but then all the pieces are constantly changing, since any introduction of a new part, or modification of another, involves adapting most of the rest of the parts. (14)

4.4.1 Structural and complementary element

The project intends to make everything possible printed in 3D, but some structural or complementary elements have been incorporated that should not be 3D printed and that were essential to keep the pieces correctly in place or to rotate them at no friction.

These elements will be used and announced along the explication of the design and assembly of the project. Below we have a list of the element used.

Element	Quantity
Bearing DIN 625-1 	4
Bearing DIN 5405-1 K12X15X10 	2
Washer ISO 10673 7,4 mm 	10
Washer ISO 10673 4,55 mm 	2
Nut M6 	4
Hex screw M4 	2

Hex screw M6		6
Threaded rod D6mm		2
Smooth rod D6mm		3

4.4.2 Electrical Motor

Searching the internet, a bit, we found a site where they sold different engines. A motor that works without load at 12v and 360 mA was chosen, achieving a rotation speed of 2600 rpm. The dimensions are 50 mm in diameter and 59 in length. At the outlet, it includes a 5 mm and 13.2 mm long shaft, ideal for gear design measurements.

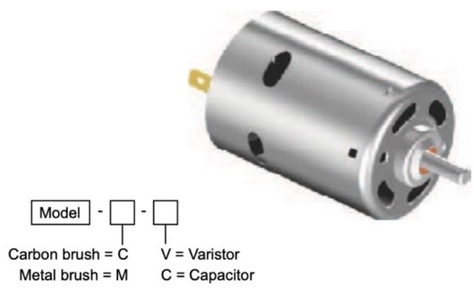


Figure 27: Selected motor

Table 1: Selected Motor data (19)

Part name	750-32160-C
Diameter (mm)	42.4
Length (mm)	59
Nominal voltage (V)	12
Nominal speed (rpm) *	2600
Nominal torque (mNm) *	37.9
Nominal current (A)	1.4
No load speed (rpm)	3200
No load current (A)	0.36
Stall torque (mNm)	209.8
Starting current (A)	6.1
Output (W)	11
Efficiency (%)	65
Operating temperature (°C)	-10..+60

(*) Nominal speed and nominal torque have a tolerance of ± 15%

Knowing the speed of the motor shaft we can calculate the different speeds on the outlet shaft of the gearbox.

Reverse: 2600 rpm x (2/3x7/7x3/3x3/5) = 1040 rpm (17,3 rounds per second) Doing the inverse of the rounds per second it takes 0,056 seconds to go around.

1st Gear: 2600 rpm x (2/3x7/7x3/11) = 472,7 rpm (7,9 rounds per second) Doing the inverse of the rounds per second it takes 0,127 seconds to go around.

2nd Gear: 2600 rpm x (2/3x7/7x5/9) = 962 rpm (16,05 rounds per second) Doing the inverse of the rounds per second it takes 0,062 seconds to go around.

3rd Gear: 2600 rpm x (2/3x7/7x7/7) = 1733,3 rpm (28,9 rounds per second) Doing the inverse of the rounds per second it takes 0,035 seconds to go around.

4th Gear: 2600 rpm x (2/3x9/5x7/7) = 30120 rpm (52 rounds per second) Doing the inverse of the rounds per second it takes 0,02 seconds to go around.

5th Gear: 2600 rpm x (2/3x11/3x7/7) = 6355,6 rpm (105,9 rounds per second) Doing the inverse of the rounds per second it takes 0,009 seconds to go around.

4.4.3 Gears

This assembly feature allows us to enter the properties of the gears that we want to model, and it builds them automatically. It is an easy-to-use tool, which removes problems in calculating pressure angles, diameters, etc. And it is a way to model the gear very quickly and the most important with no errors. You just have to enter the module, the pressure angle, the number of teeth, which is related to the pitch diameter, the face width, and the nominal shaft diameter, and then it generates it automatically. You can also select the keyway if necessary, to help to transmit the power from the shaft to the gear. (15)

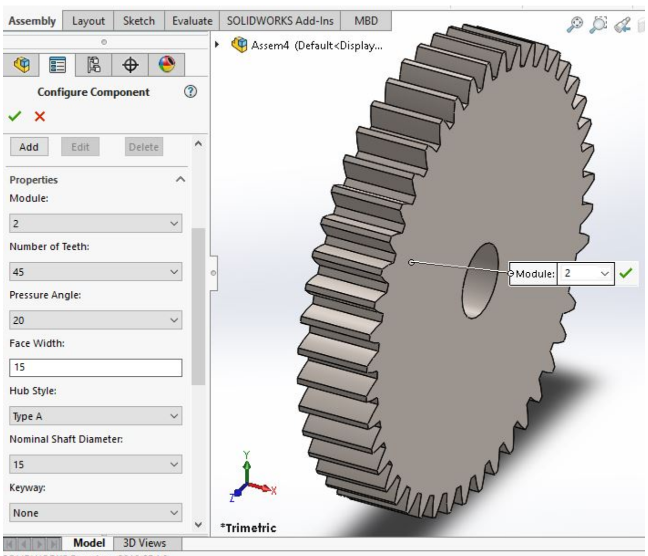


Figure 28: Toolbox feature.

This method is perfect, but it has a small problem, which is that you can't edit it as a part, you can only edit it as an assembly using the toolbox. So, if you wanted to design a shaft with all the gears in a single part, or split into two parts, to add a joining shaft you would have to first place all the desired gears and mate them concentrically in the assembly and save it as a part, not being able to edit them afterward. Then, opening the part you can extrude a joining shaft between gears to have it as a single piece, if necessary. So, in the first subassemblies, we should place the distance mates between gears that have been calculated above.

Using this feature the inlet shaft, the middle shaft, the outlet shaft, and the gear of the electric motor are designed. Modeling so, eighteen gears of six different sizes, 20, 30, 50, 70, 90, and 110 mm of the pitch diameter and 15 mm of face width.

4.4.4 Pinion

The pinion is the gear that is placed on the motor shaft. Starting from the previously modeled 20 mm gear, it is the fastest part to make, since it only requires one operation; a straight through-hole shaped like the shaft of the selected motor that snaps into it.

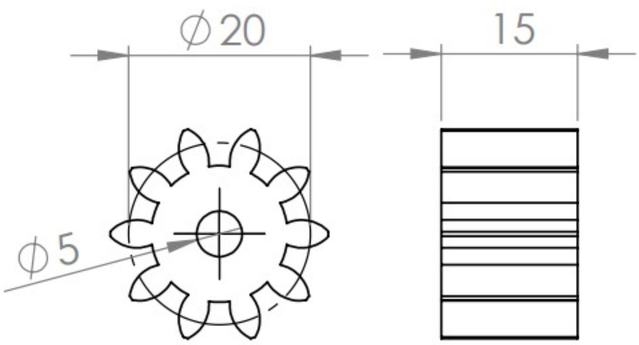


Figure 29: Pinion views and dimensions.

This pinion meshes to a gear from the main shaft to do the first reduction. The gear from the inlet shaft is a 30 mm gear and this meshing provides a reduction ratio of 2/3.

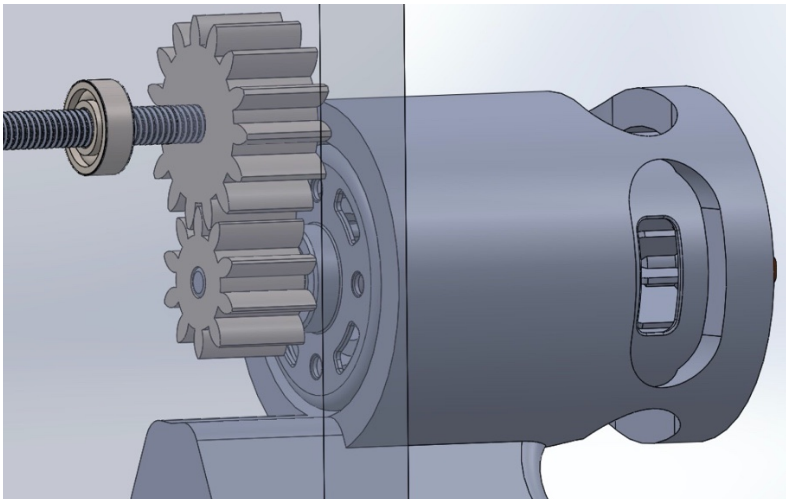


Figure 30: Screenshot from the first reduction.

4.4.5 Inlet shaft

Using the previously designed gears (four 70 mm gears, one single 90 mm gear, and another single 110 mm gear) we proceed to build the main shaft. It will be designed in a single part joining the six gears with a joining shaft, this way it will be most easy to transmit the torque and the speed from the pinion. This union shaft will be crossed by an M6 threaded rod, and then the whole piece will be screwed to it.

This structural piece will then be fitted to the holding case where it will snap with the bearings that will help the rotation.

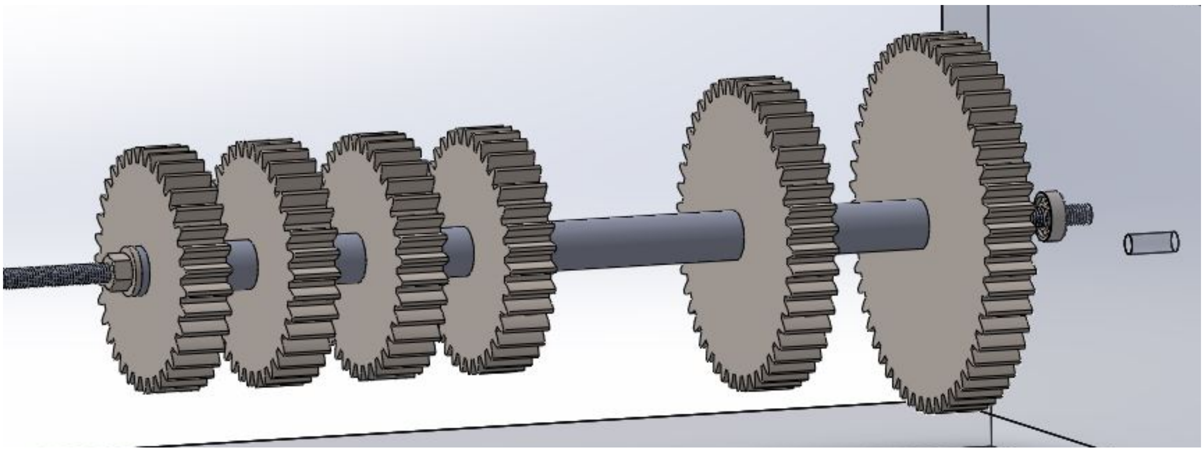


Figure 31: Inlet Shaft.

4.4.6 Outlet shaft

For the outlet shaft, we followed the same idea as in the inlet shaft and using the previously designed gears (one single 50 mm gear, one single 110 mm gear, one single 90 mm gear, and another three 70 mm gears) we proceed to build the secondary shaft. It will be designed in a single part joining the six gears with a joining shaft, this way it will be most easy to transmit the torque and the speed from the pinion. This union shaft will be crossed by an M6 threaded rod, and then the whole piece will be screwed to it.

This structural piece will then be fitted to the holding case where it will snap with the bearings that will help the rotation.

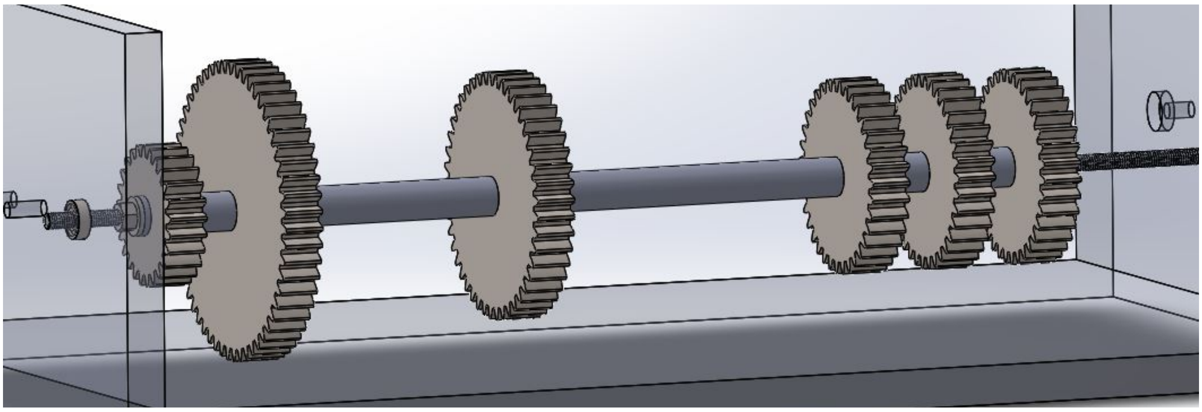


Figure 32: Outlet shaft.

4.4.7 Middle shaft

The middle shaft was designed a bit differently from the inlet and outlet shaft. Using the previously designed gears (two 30 mm gears, two 50 mm gears, and a single 70 mm gear) we proceed to build the middle shaft. In this case, the gears won't be designed in a single part together with the joining shaft due to the need for this middle shaft to slide along the axis to select the different meshing positions. This was done by designing a guide shaft crossed by a 6 mm diameter smooth rod over which this will slide alongside. Then the gears will be placed on their respective bearings which are at the same time are placed and snapped on the guide shaft.

This shaft is designed this way to provide the needed sliding and the free rotation of the gears to transmit the torque and the speed between the inlet shaft and the outlet shaft. For this reason, there is a hole in between the (8) and (9) gear to place a gear lever with the help of an industrial 6 mm diameter rod.

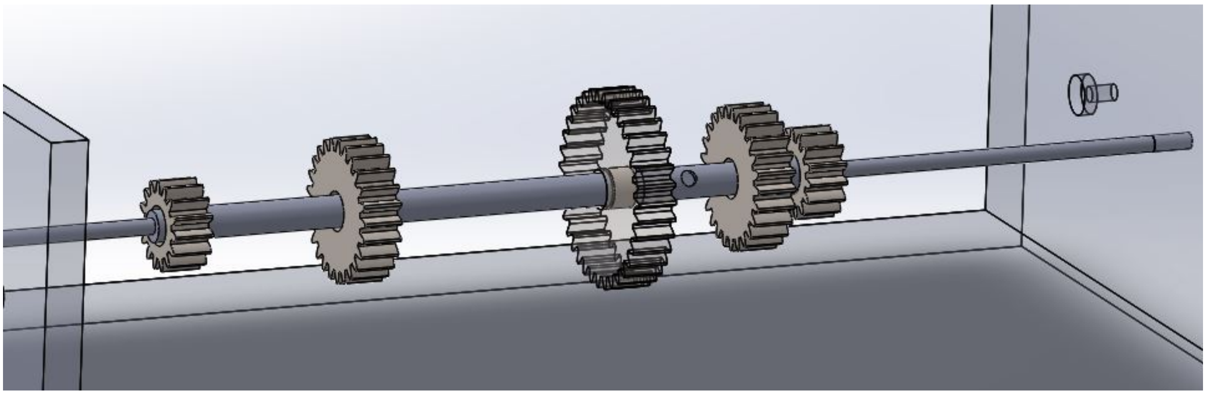


Figure 33: Middle shaft

4.4.8 Reverse shaft

To design this reverse shaft the idea was to put a little shaft holding a 30 mm diameter gear between the middle and outlet shaft to reverse the direction of the rotation of the outlet shaft.

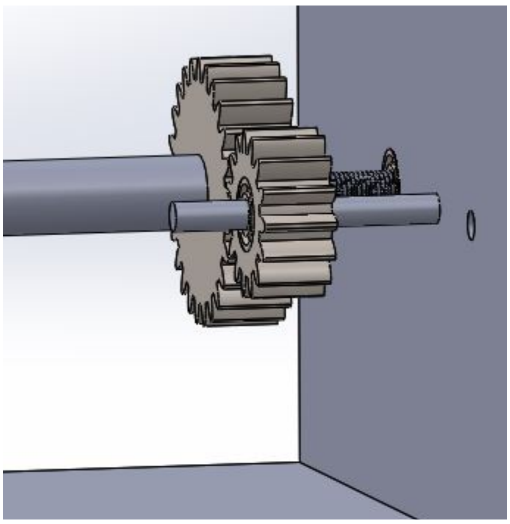


Figure 34: Reverse shaft.

With this arrangement, it is suggested to make support between the two gears, so that the axis is like a beam mounted on two supports and is not only supported by one end that generates more backlash and could break more easily. The solution was to place a kind of triangular support that is bolted to the base of the box and that houses a bearing for the gear shaft.

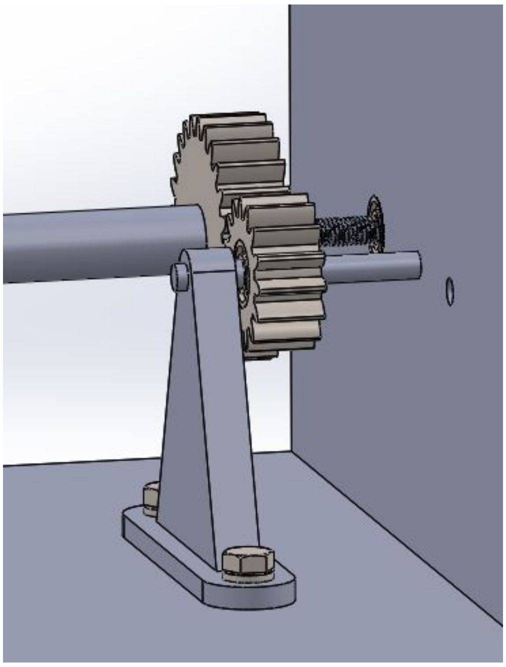


Figure 35: Reverse shaft support.

4.4.9 Supports

Having all the shafts defined the next part to design is the box that will house the whole gearbox system. The decision was to build an easy square box where the rods will fit, as well as the bearings. It was no chosen to place supports in between the box to reinforce the system, just because only with the steel rods the system will be reinforced enough. After the croquis we proceed to extrude the box.

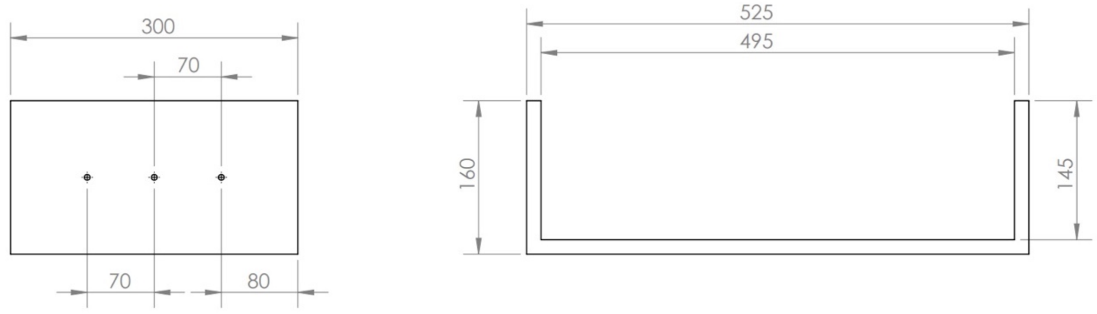


Figure 36: Box dimensions

It was decided to only place a bearing on the box walls for the main and secondary shaft, as shown below.

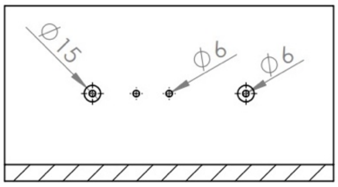


Figure 38: Wall diameter holes.

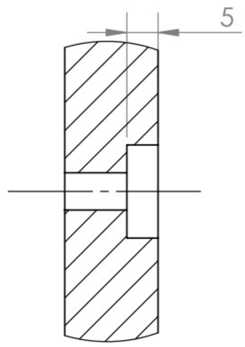


Figure 37: Section showing the housing of the bearings.

For the electric motor support, it was decided to design a box following the shape of the motor. Starting for getting the motor outside diameter (50 mm) and also respecting and adapting our design to the vent holes.

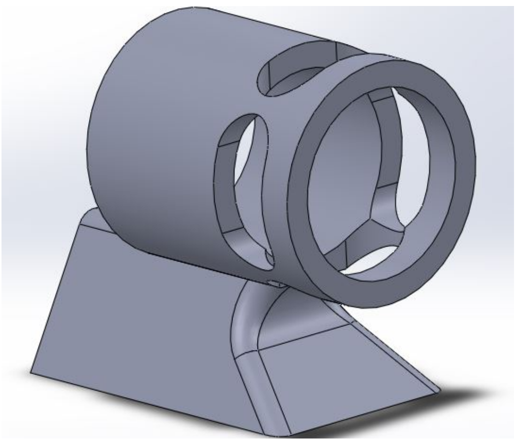


Figure 39: Motor box.

For the base of the box, it was decided to give a nice view adding fillets and rounded ends. We gave it a tangent extruded cut on the side face with an 8 mm diameter circle.

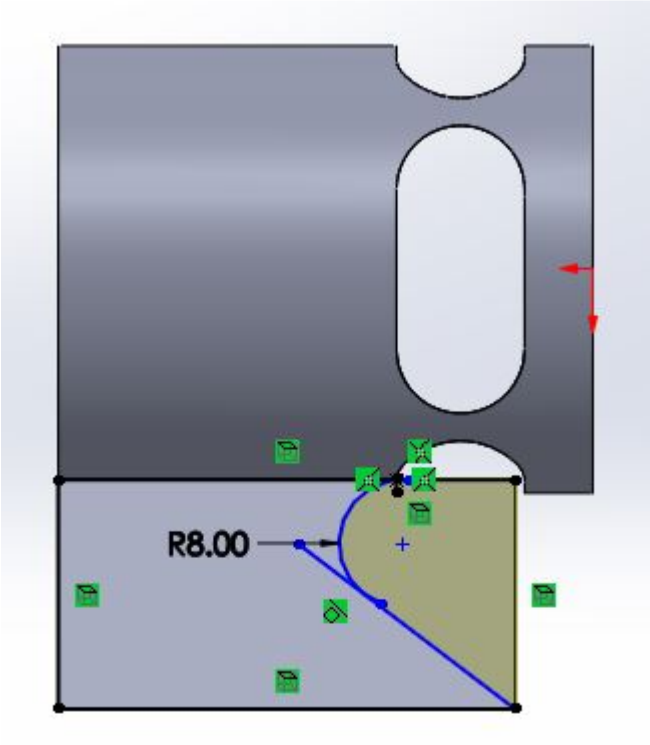


Figure 40: Side face extruded cut.

Then we extruded the back to make it join with the reducer's box.

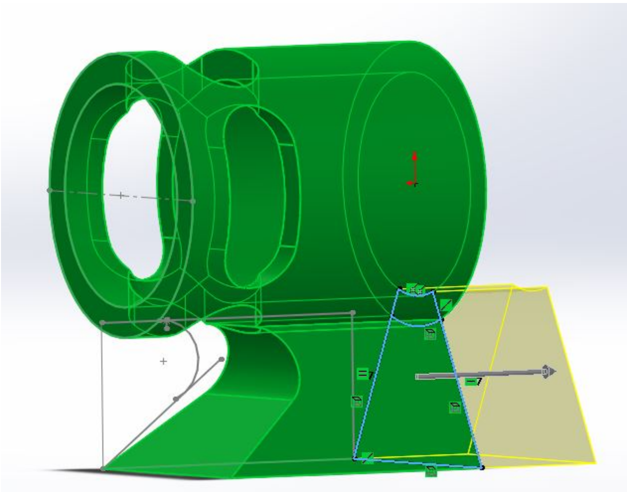


Figure 41: Back extrusion.

Finally, we place two M4 screw clearances holes to bolt the motor box to the gear box, joining and snapping everything as below.

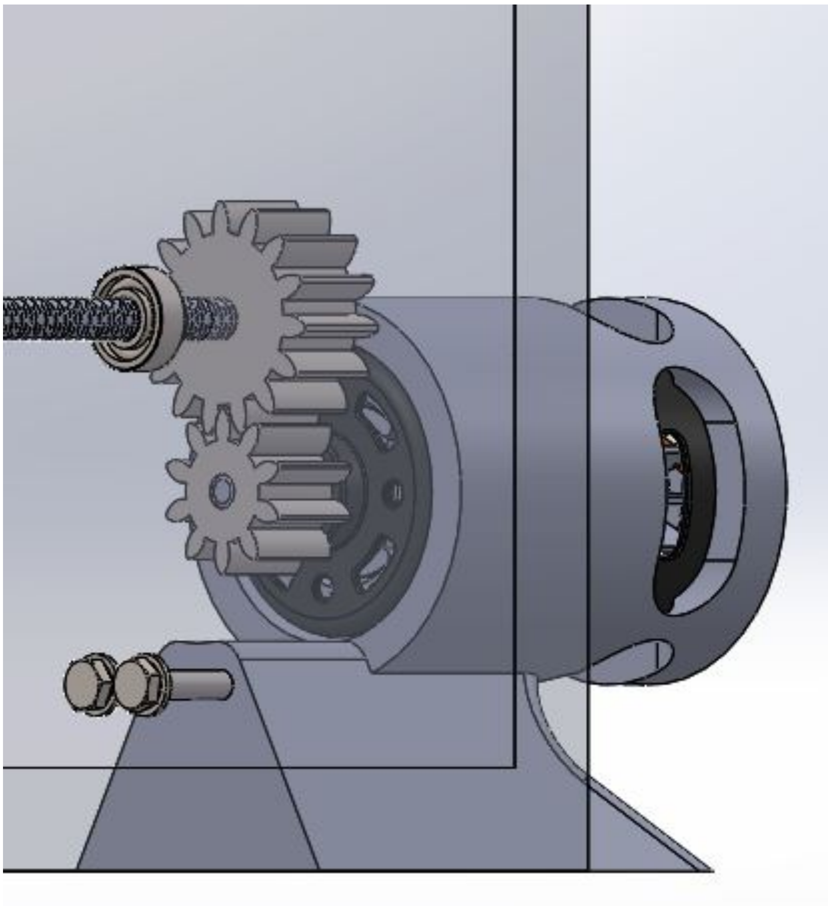


Figure 42: Motor box final assembly

4.4.10 Gear lever

On this part, the idea was to place a 6 mm rod on the middle shaft and then design a spherical knob and assemble all the three parts. It was decided to use an industrial rod for the lever to avoid printing cylindrical long parts unless it was printed square. If it is circular, a bar should be printed on the z-axis (the weakest direction). If it is square, it could be printed on the x-y plane, which is more resistant, but it is one of those things that must be evaluated if it is not better to use a commercial profile, and in this case, we decided so, as well as the joining shafts that will also be industrial steel tubes.

This is how the assembly looks.

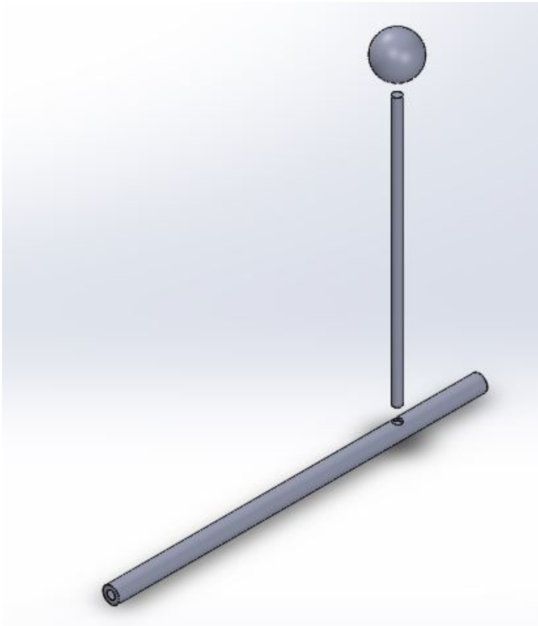


Figure 43: Gear lever.

4.4.11 Box cover

At this point in the design, all the mechanical elements necessary for the gearbox to function have already been modelled. But it is still missing to design the box cover that will have the design with the channels with the different gear positions.

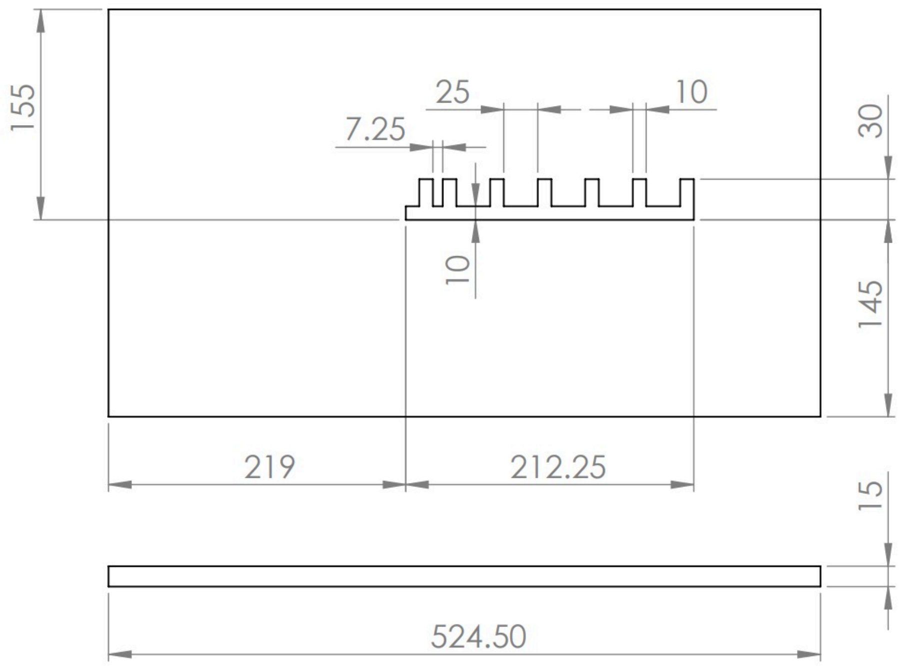


Figure 44: Box cover drawing.

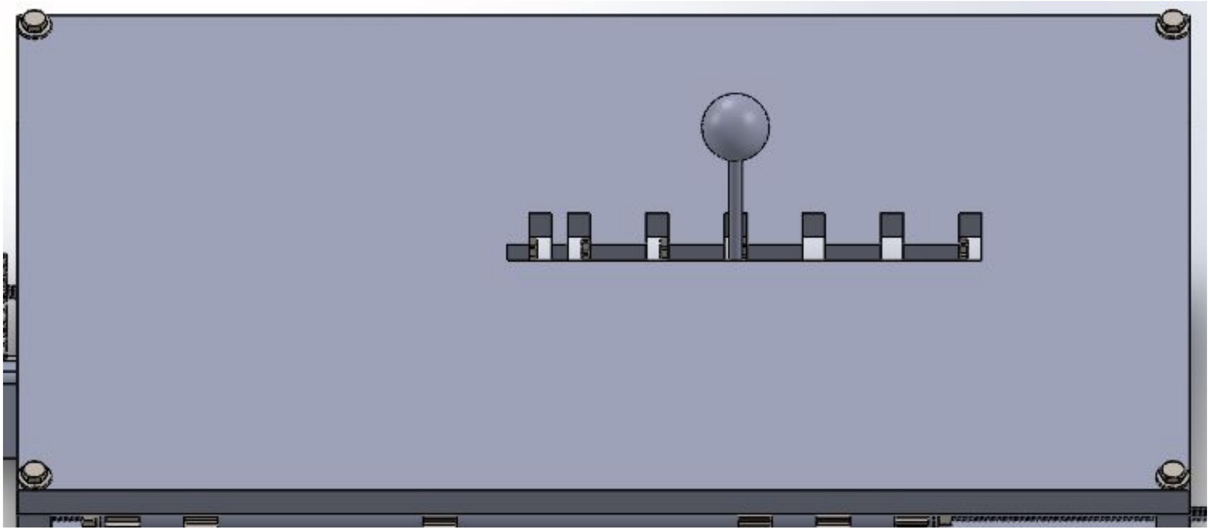


Figure 45: Box cover assembled.

4.4.12 Final Assembly

After this las part and having all the mechanical and structural parts defined we can have the whole gearbox assembled.

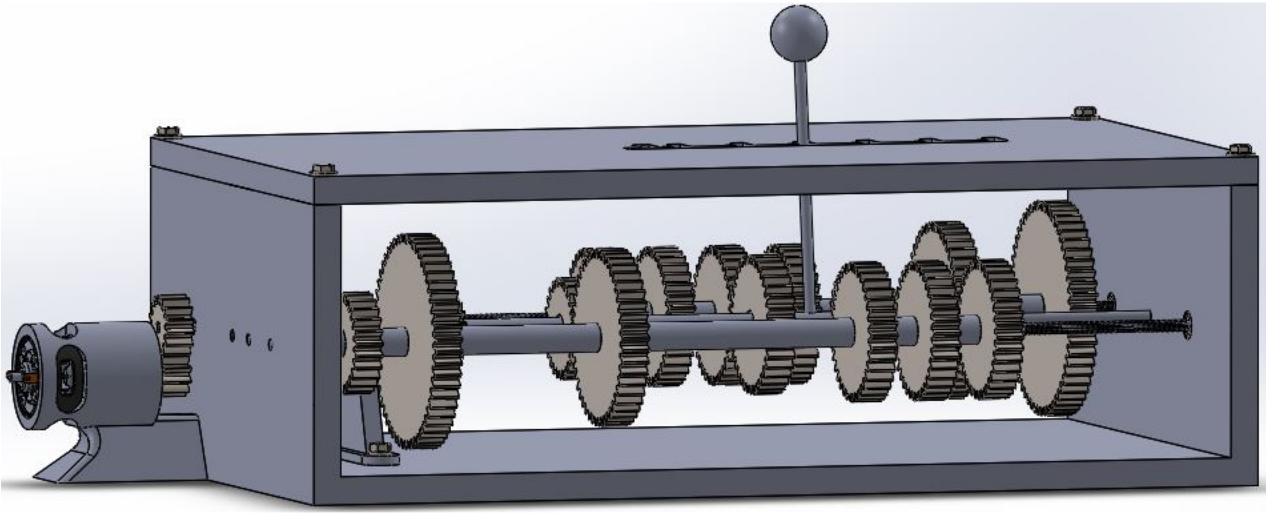


Figure 46: Final assembly

Here is how the inlet and outlet shaft are bolt to the threaded rod. Using plain washers between the shaft and the hex nut.

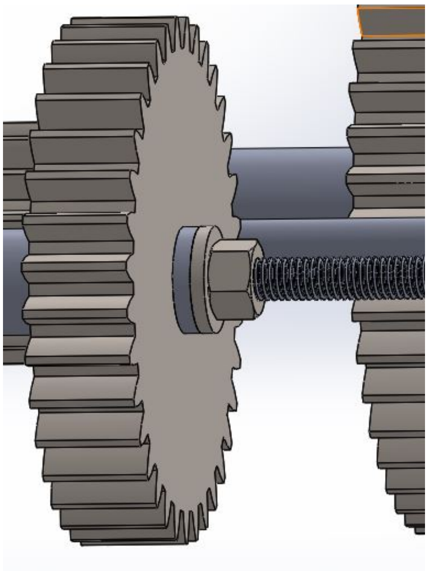


Figure 47: Bolt between the shaft and the treaded rod.

5. 3D Printing Environmental Impact

After a certain time has passed since this new technology has been introduced in our society, we can already measure the ecological footprint from different points of view. Depending on the scale of production, the materials, and, finally, depending on the life cycle of the products.

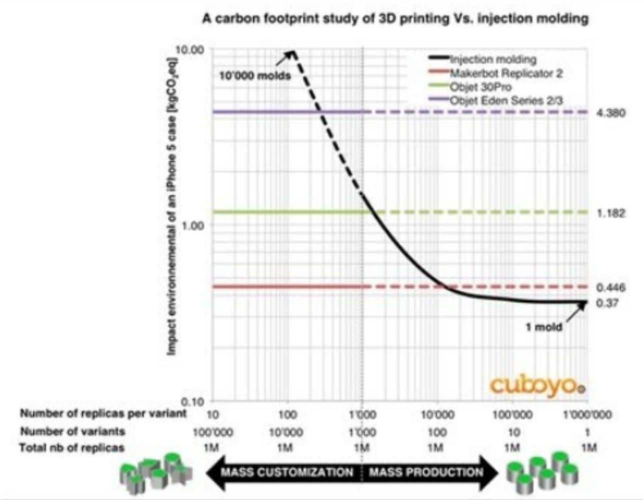
Regarding the production scale (16), a study carried out in Cuboyo in 2013 compares production in 3D printers with conventional production, which is based on injection into molds.

The hypothesis of the study was that the 3D printer would help reduce the utility of mass production.

In the study that was carried out, polypropylene and polylactic acid were used as materials for both types of production. The standard production time of the study was 50 minutes for both methods so that energy cost and mass production could be calculated and compared with custom production.

The results of the study, recorded in the graph below, showed that conventional manufacturing is not prepared for low production volumes, always speaking in terms of environmental impacts. However, 3D printing cannot cope with conventional printing when it comes to high volumes.

Table 2: Carbon footprint comparing 3D printing Vs. injection molding. (20)



In conclusion, when we talk about production scale, 3D printing technologies would be interesting in small productions. In addition, the ecological footprint of the 3D printer is less in productions less than 300 replicas.

In terms of materials, the two most commonly used by printers today are ABS plastic, which is derived from petroleum, and bioplastic PLA, derived from corn starch. (17)
If we look at the materials from an environmental point of view we can say that it is favorable in two aspects. For the same composition of materials and for the amount of material used. The cost of material and waste is much less compared to traditional manufacturing. This is so because only the necessary material is used to build the part. (18)
It is also necessary to highlight another great advantage of 3D printing, the lightness of the pieces. This is important when we talk about the automotive sector since they can reduce the weight of the parts by up to 50% and in turn reduce the use of fuel and polluting emissions.
On the contrary, there is some aspect in which 3D printing is not so favorable. Printers that use heat or an energy source such as lasers to melt plastic consume 100 times more electrical energy than conventional manufacturing. For this they are already looking for alternatives, for example, photovoltaic cells as an energy source, using chemical substances to promote adhesion or using a camera that thermally isolates the printer. Finally, use renewable energy sources, although they still cannot provide enough energy to manufacture large quantities.
Another disadvantage of this type of printing is that they are based on the extrusion and deposition of a thermoplastic material that emits ultrafine particles with a diameter of less than 100nm, and these can be deposited in the airways.

Finally, regarding the life cycle of the product, we can take advantage of the 3D printer. Having the possibility of printing a part in isolation in order to extend its life cycle without having to buy a new product, as it would be in the case of parts manufactured by injection.

It also allows you to add new parts or replace them for better ones, thus extending the life of the product.

6. Conclusions

The main objective of this project was to carry out a practical project related to the different subjects of the Department of Strength of Materials and Structures in

Engineering in order for the student to be able to observe the relationship that exists between the theoretical contents that have been learned and its application to reality.

In conclusion, it can be said that part of the objective has been successfully met. I have designed a speed reducer with the idea of being 3D printed. The second part could not be completed successfully, because the conditions in which we found ourselves when proceeding with this part (force majeure) did not allow this action to be carried out.

In this project, it has been designed a speed reducer with five-speed relations and a reverse gear using the CAD software called SolidWorks, which helped designing and assembling the different designed parts. The initial idea was to design only a five-speed gearbox that should have then been printed afterward, which didn't happen as spotted above. Then to try to enhance the weight of the project I decided to add reverse gear, which supposed a challenge related to where to put it and how to hold it.

To conclude, it can be affirmed that with the realization of this project, the knowledge learned at the university has been deepened and it has contributed a great amount of new knowledge that is very useful in the present and in the future.

7. Future Lines

While doing this project I realized that the system may not work. My guess is that it only would work if the engine stops to change gear position. Because if you make a change of the gears to disengage and mesh the speed between gears is different since the transmission relation is different. This would then cause the teeth of the gears to be engaged to being running at different speeds and an impact would occur between them that, apart from not engaging the gear correctly, could cause damage to the gear or break it, this is why I put 5 mm gap between gears. But since I could not test the operation of the gearbox, I could not confirm this theory.

Then I had an idea in mind related to the design of the gearbox that could, for example, be included in future projects or even enhancement of this one. The idea was to add a kind of clutch to help these changes to be smoother not needing to stop the motor.

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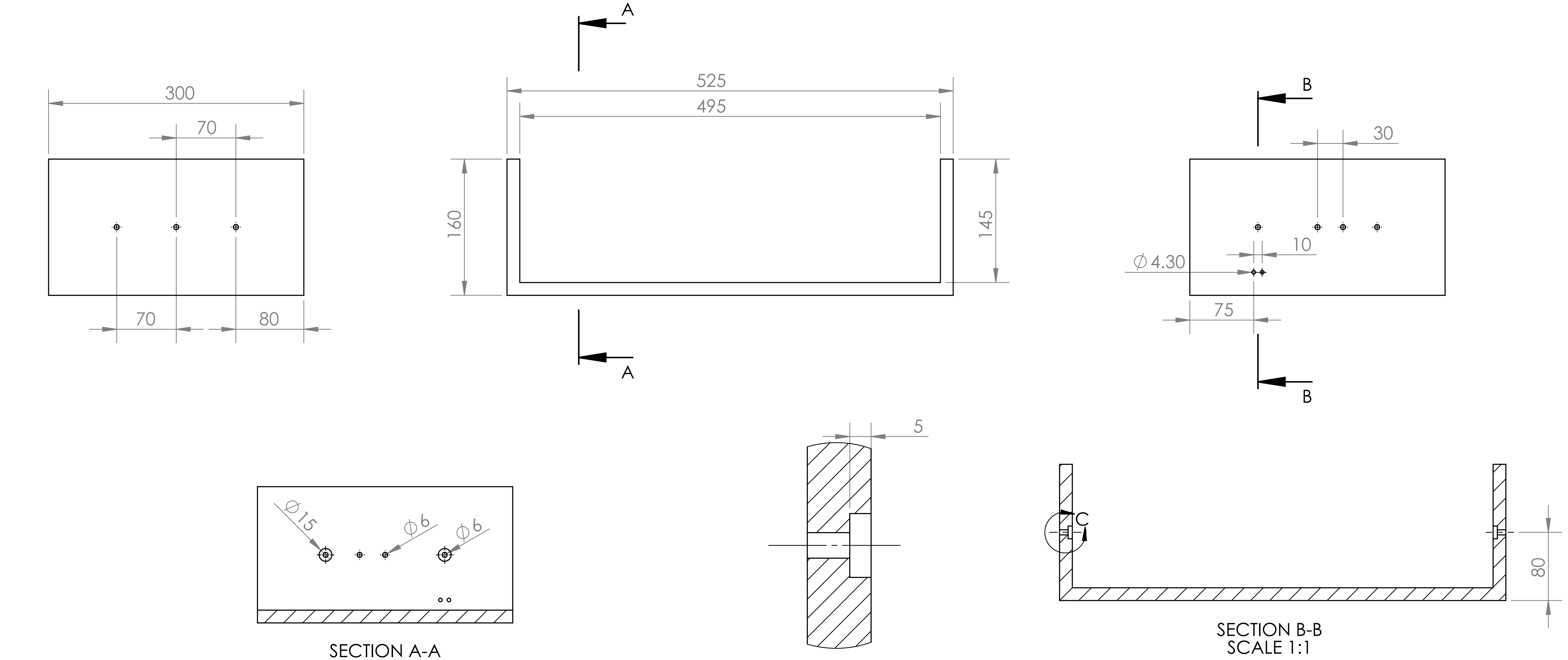
9. Annex

9.1 Part Drawings



SECTION A-A
SCALE 1:1

DETAIL C
SCALE 5:1

SECTION B-B
SCALE 1:1

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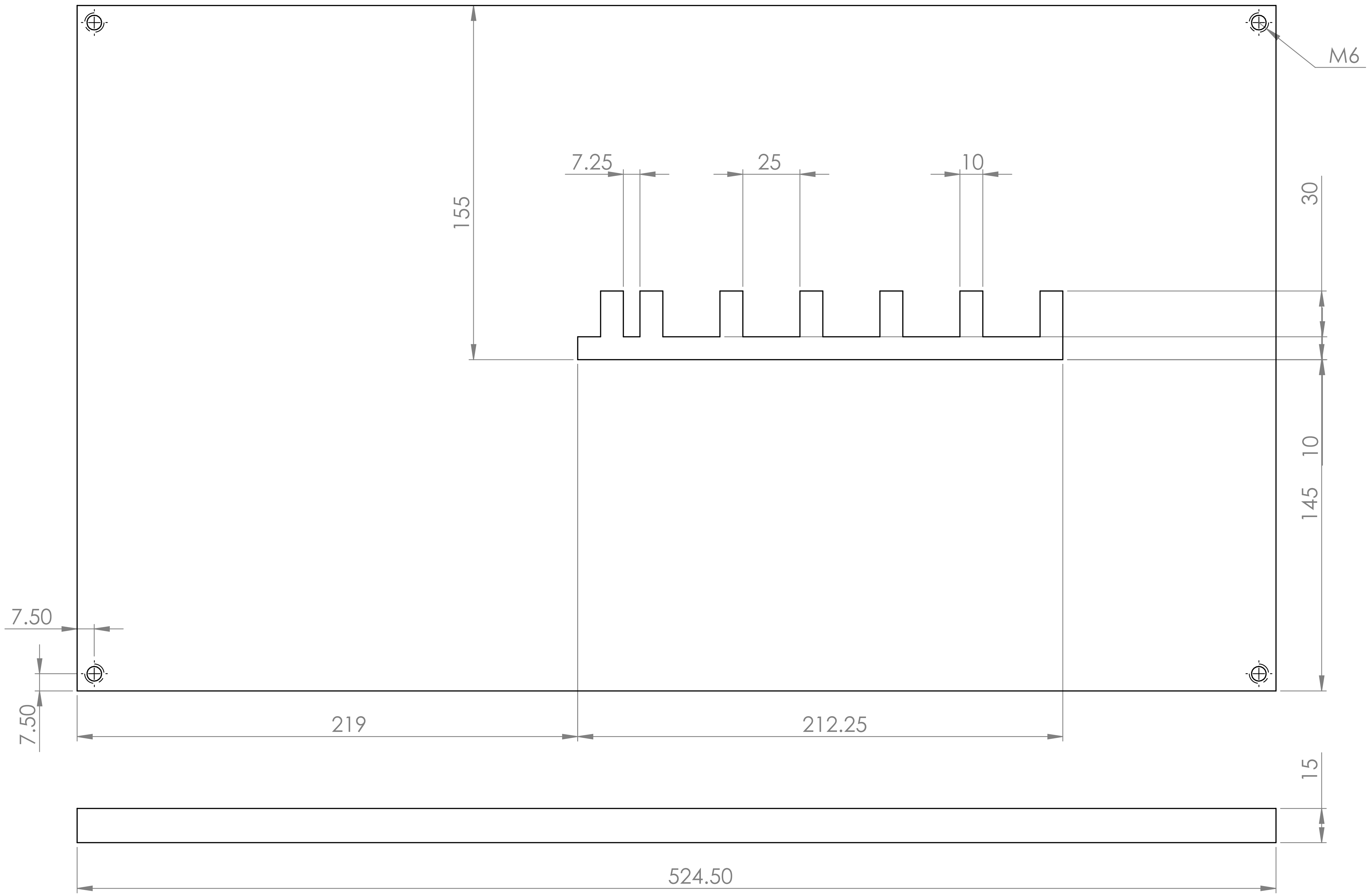

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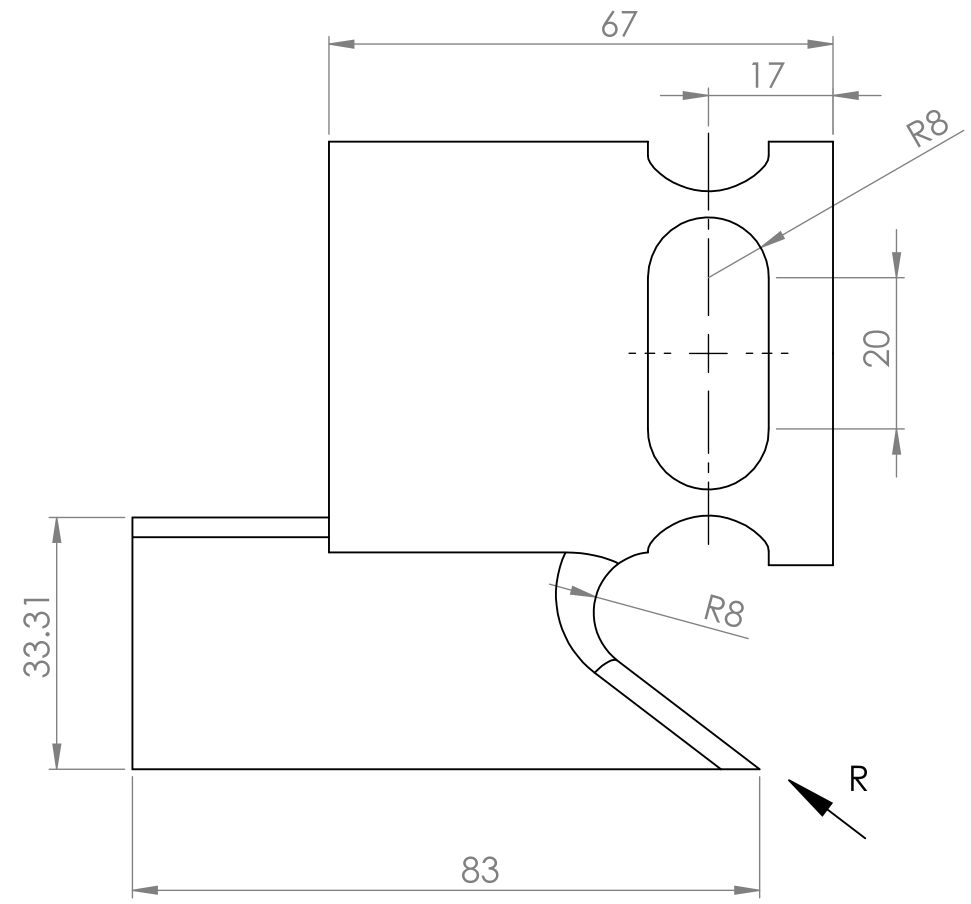

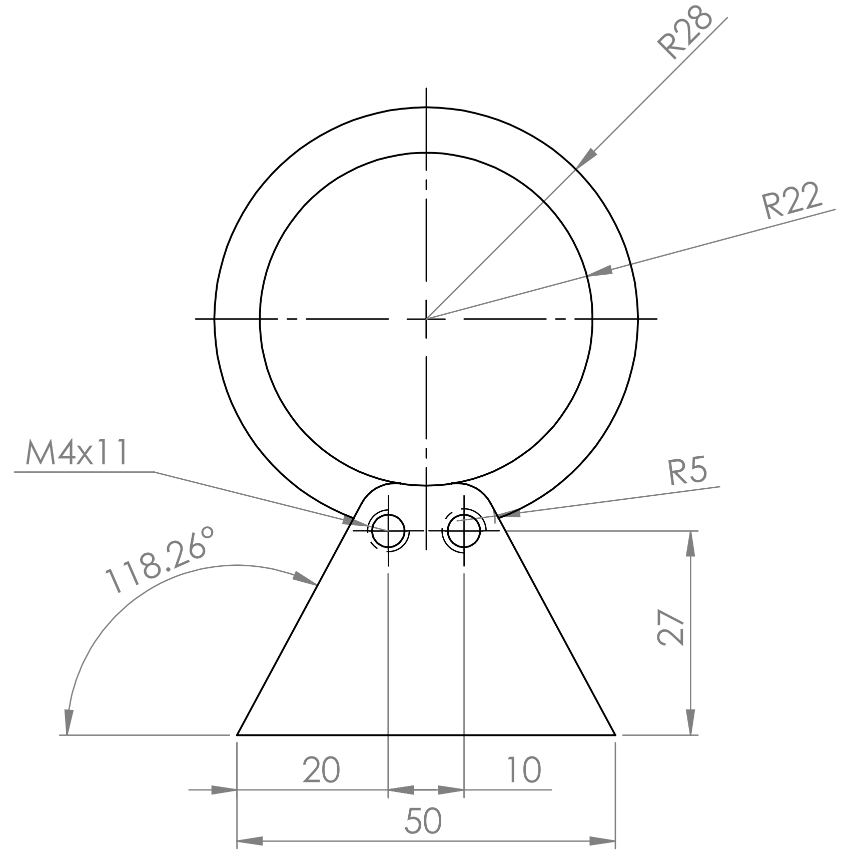

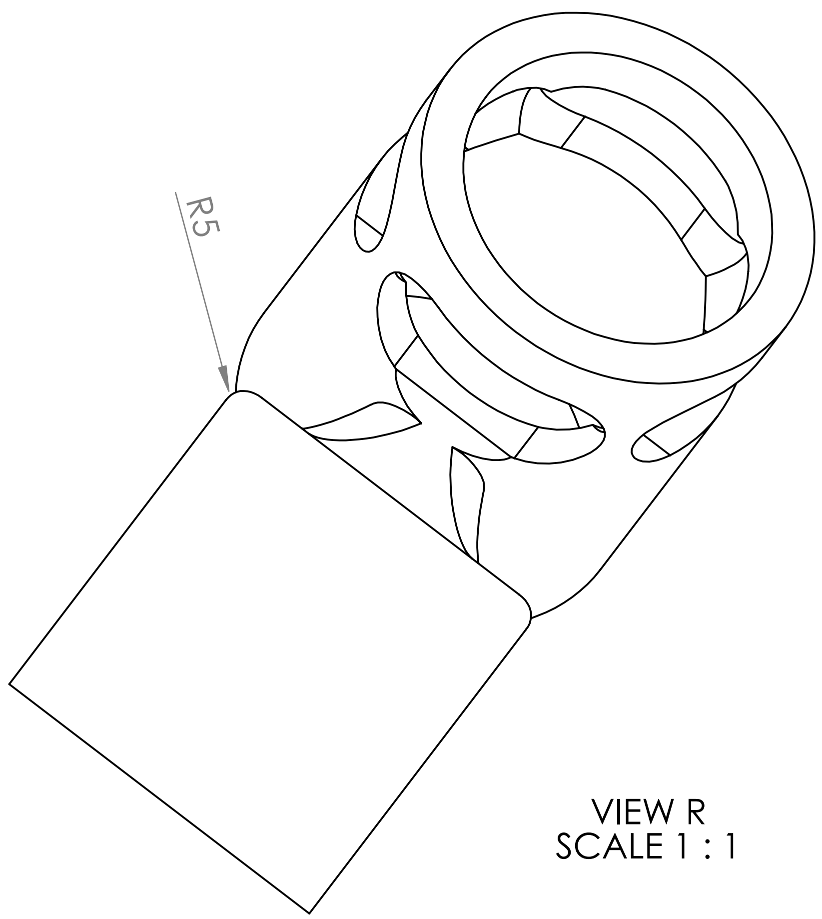

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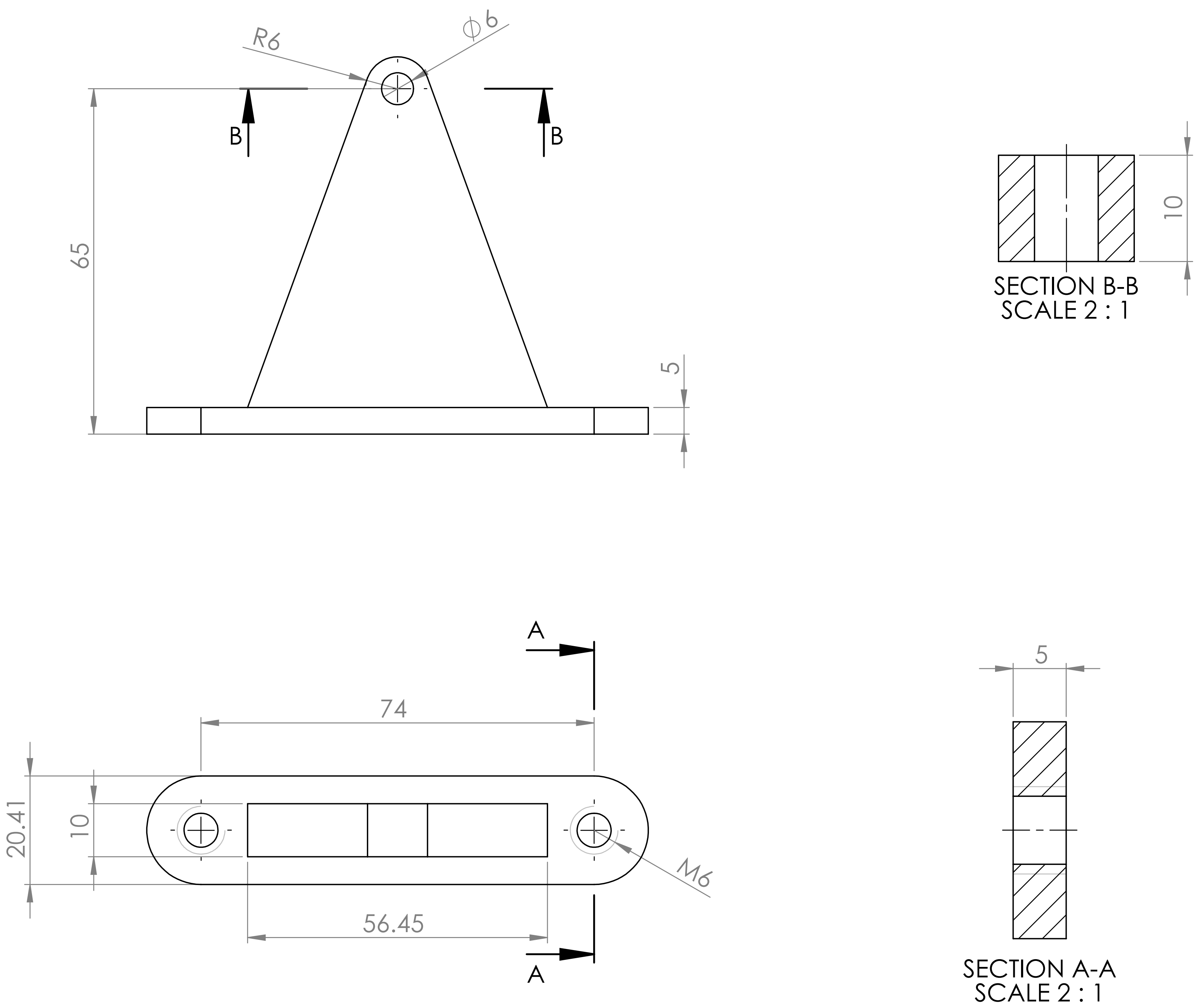

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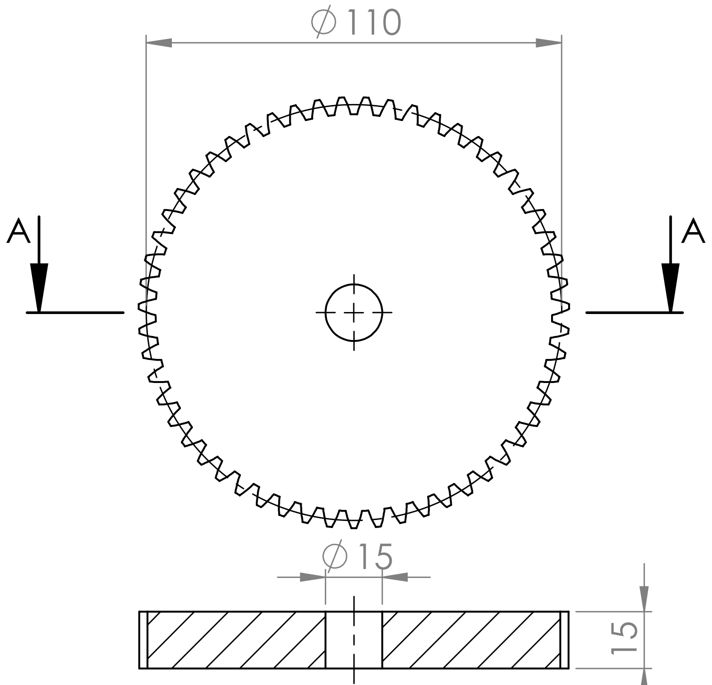
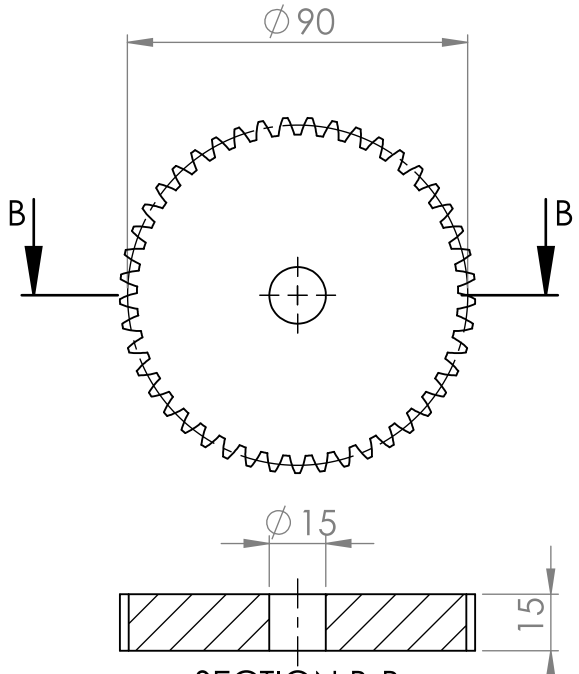


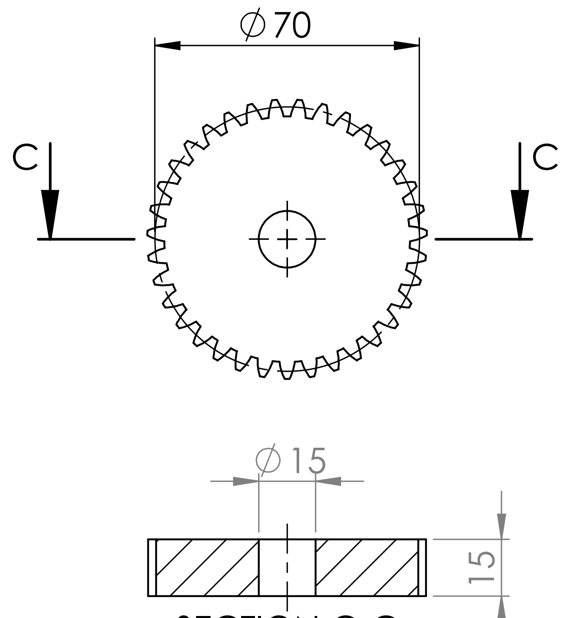
SECTION A-A

Data	Gear D110
Module	2
Number of Teeth	55
Pitch Diameter	110 mm
Outside Diameter	114 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm



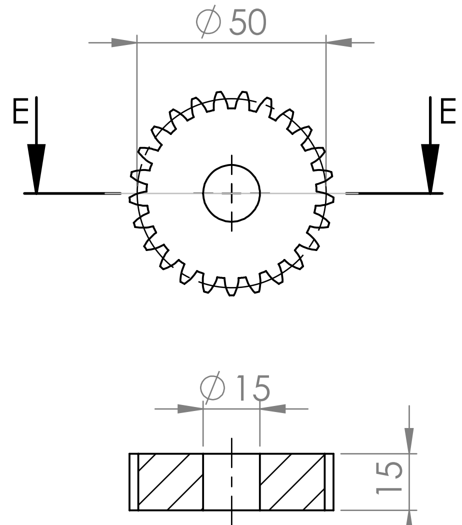
SECTION B-B

Data	Gear D90
Module	2
Number of Teeth	45
Pitch Diameter	90 mm
Outside Diameter	94 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm



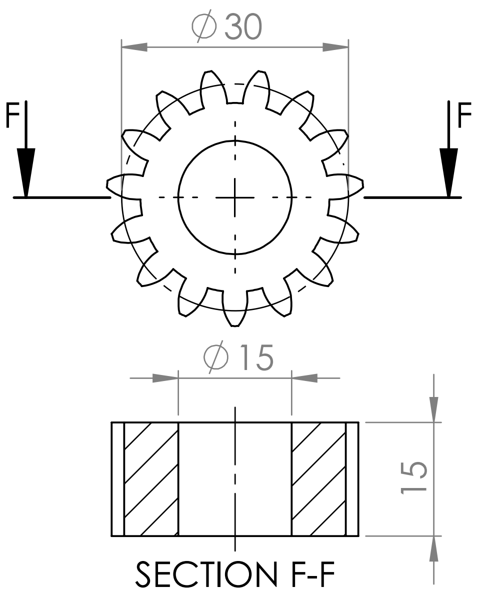
SECTION C-C

Data	Gear D70
Module	2
Number of Teeth	35
Pitch Diameter	70 mm
Outside Diameter	74 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm



SECTION E-E

Data	Gear D50
Module	2
Number of Teeth	25
Pitch Diameter	50 mm
Outside Diameter	54 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm



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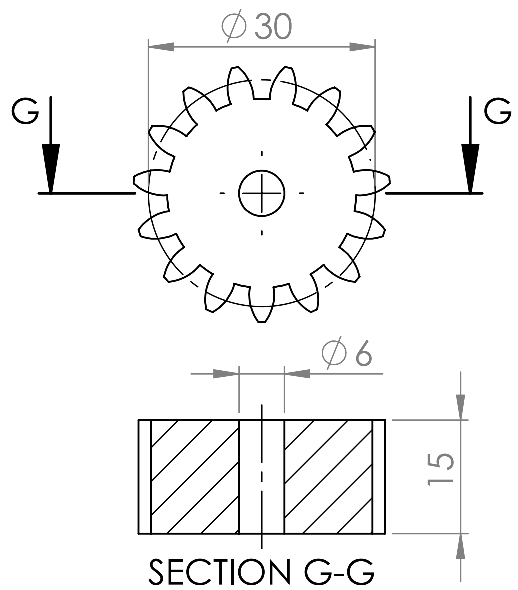

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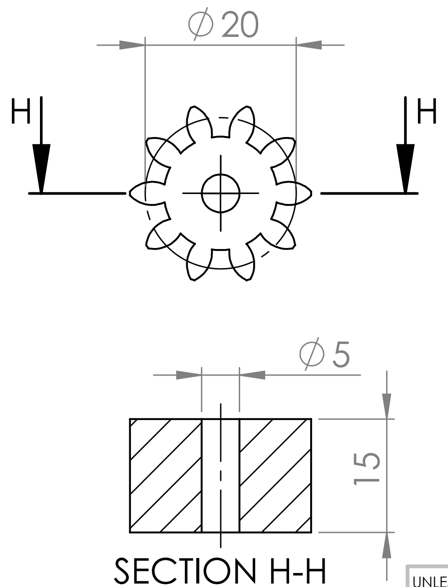

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Data	Gear D20
Module	2
Number of Teeth	10
Pitch Diameter	20 mm
Outside Diameter	24 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm

Data	Gear D30
Module	2
Number of Teeth	15
Pitch Diameter	30 mm
Outside Diameter	34 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm

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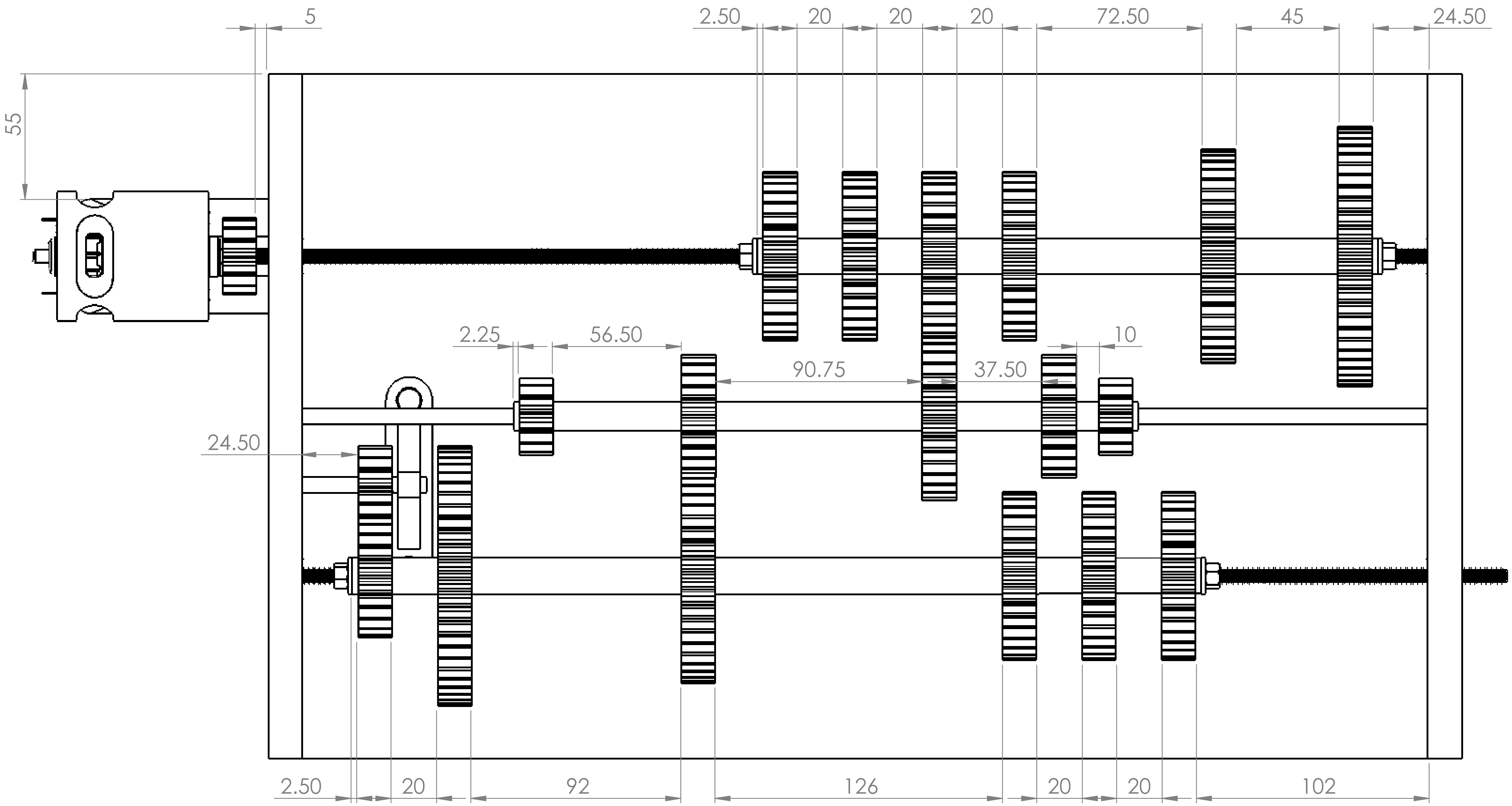

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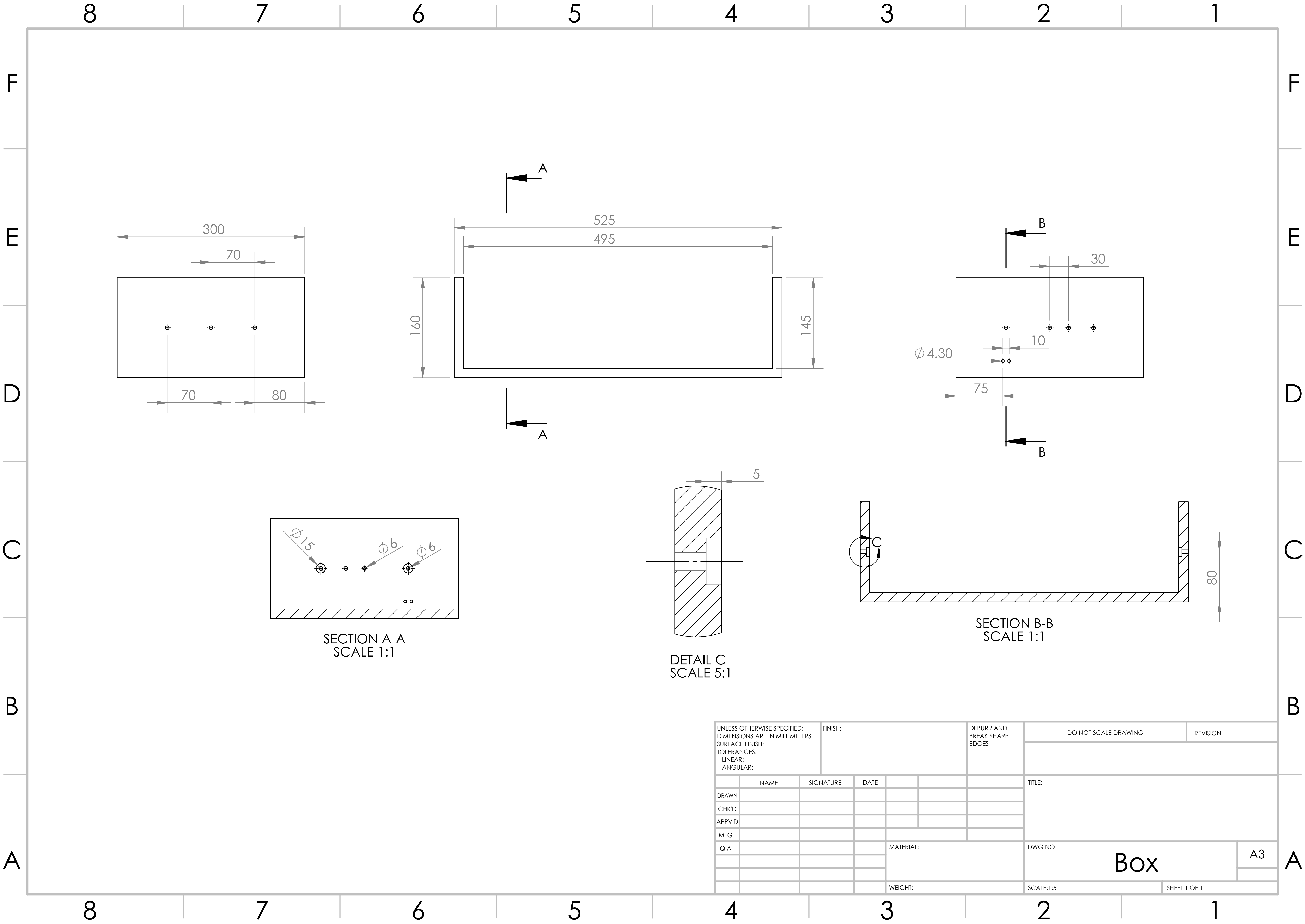
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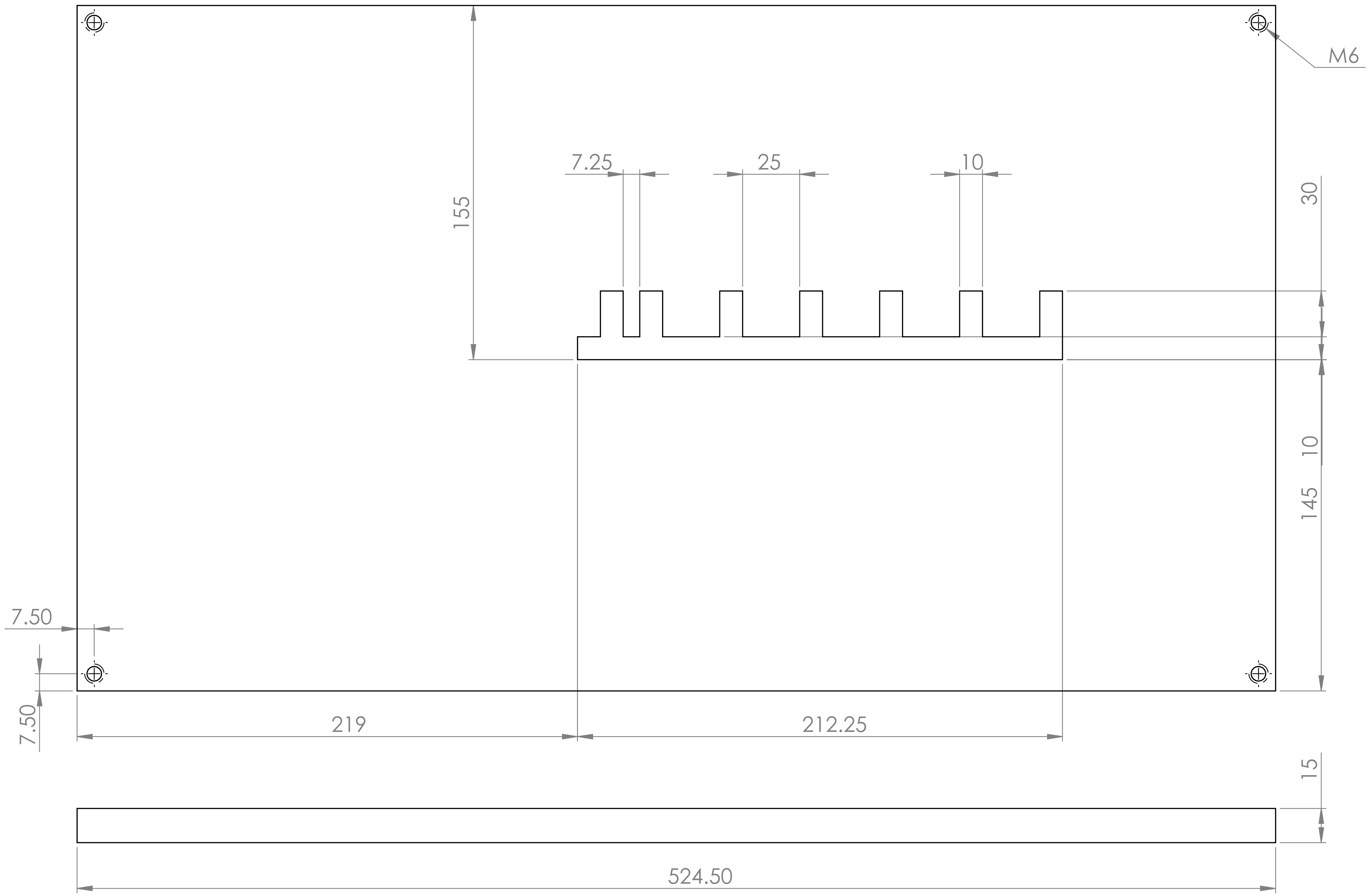

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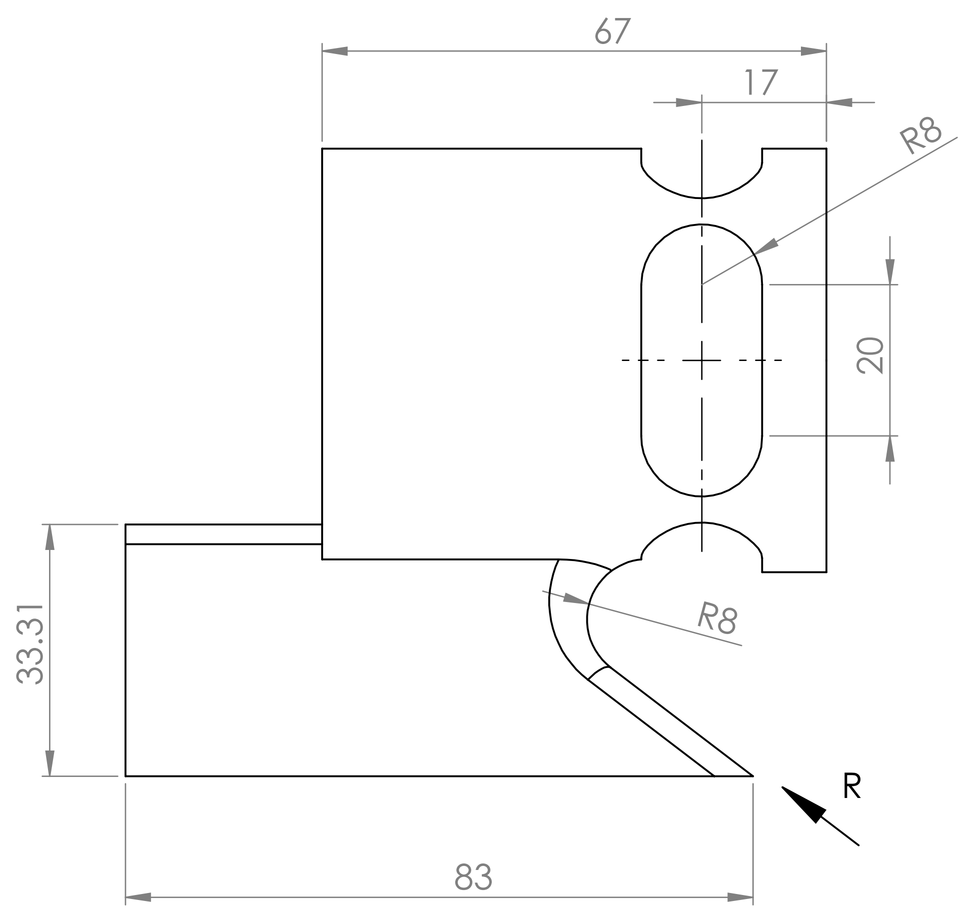

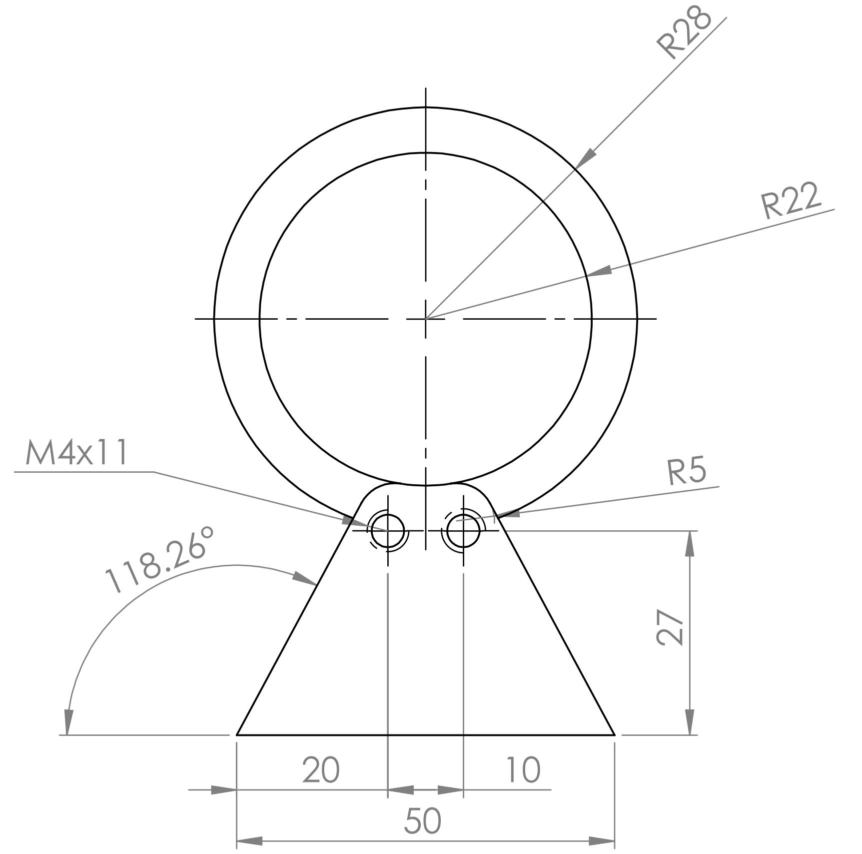

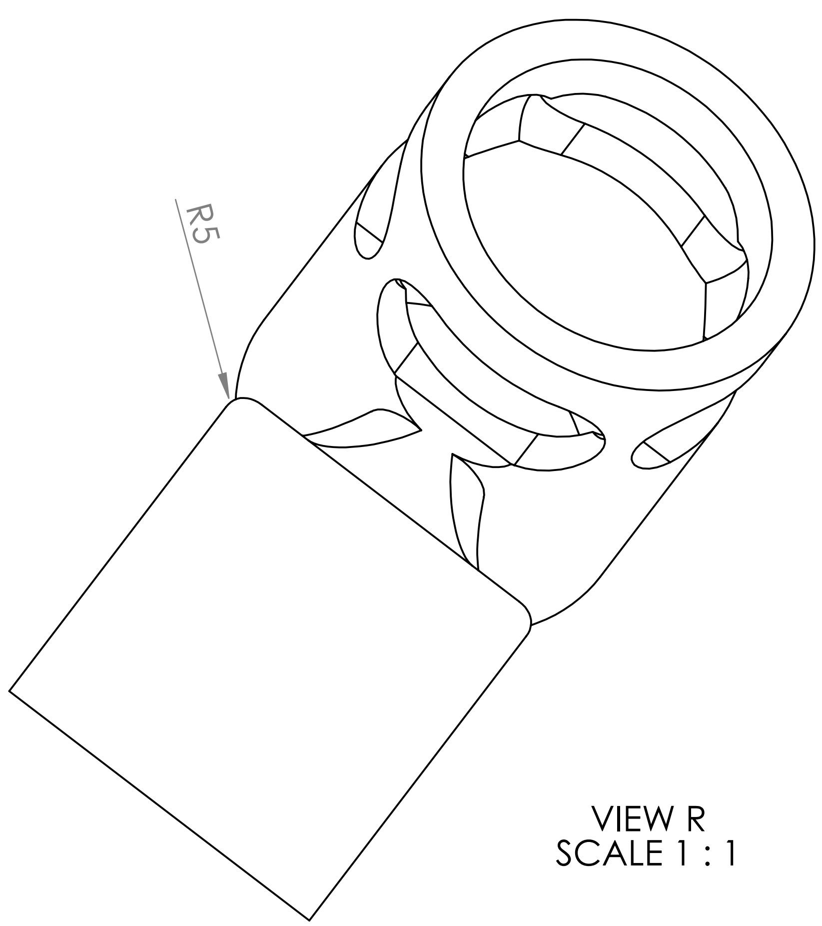

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APPV'D			
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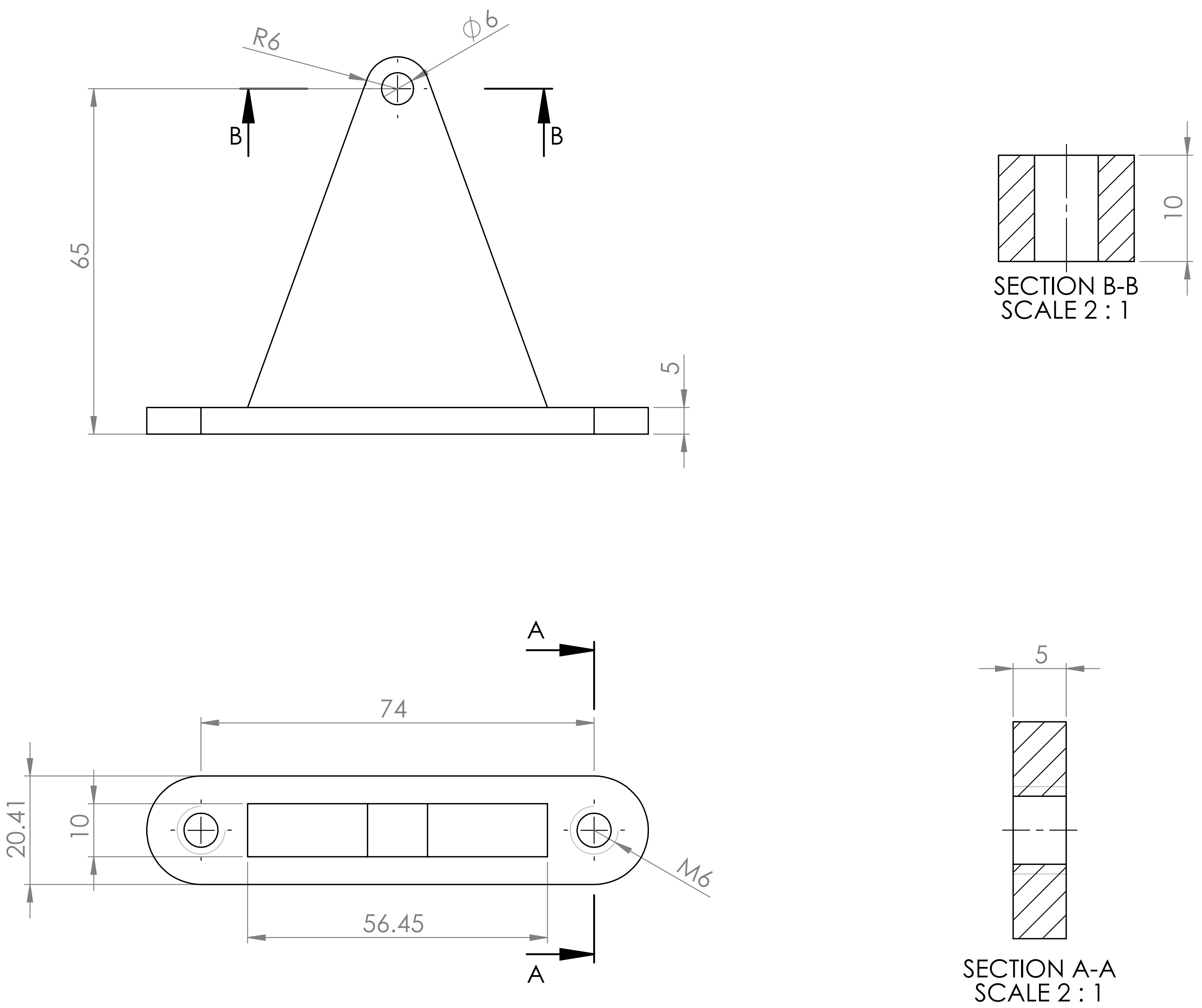

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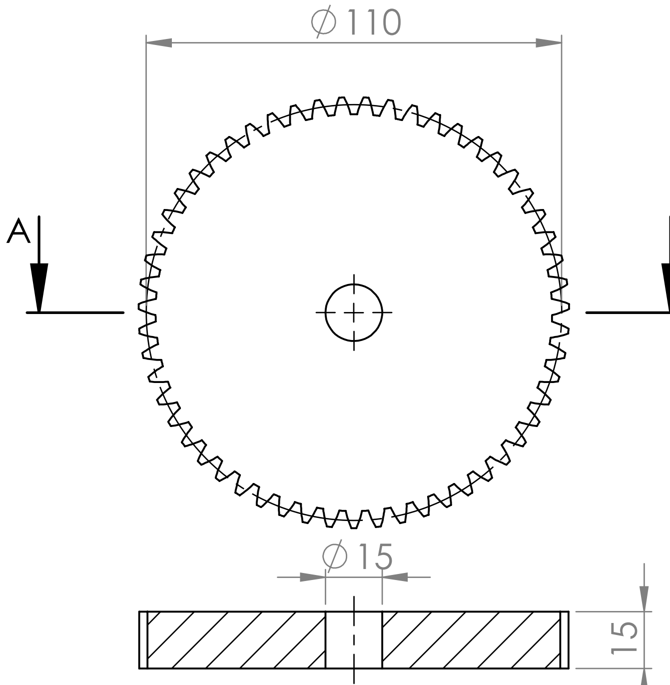
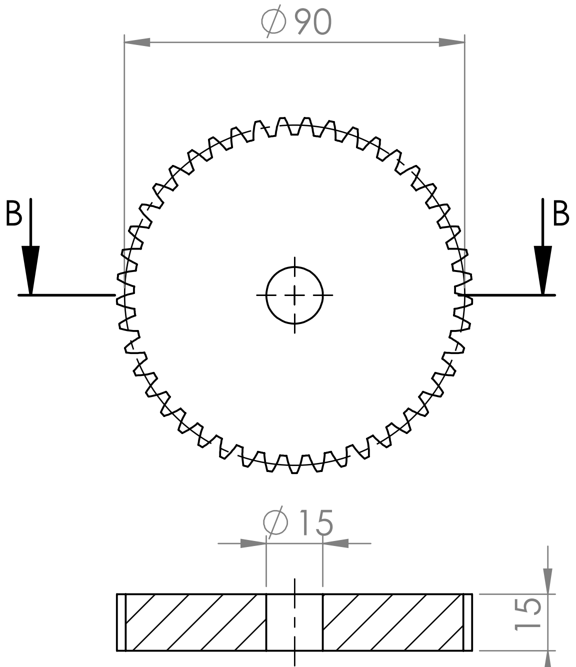


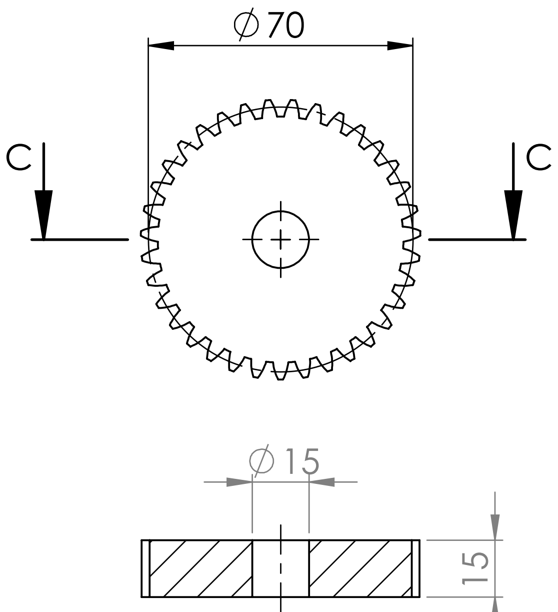
SECTION A-A

Data	Gear D110
Module	2
Number of Teeth	55
Pitch Diameter	110 mm
Outside Diameter	114 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm



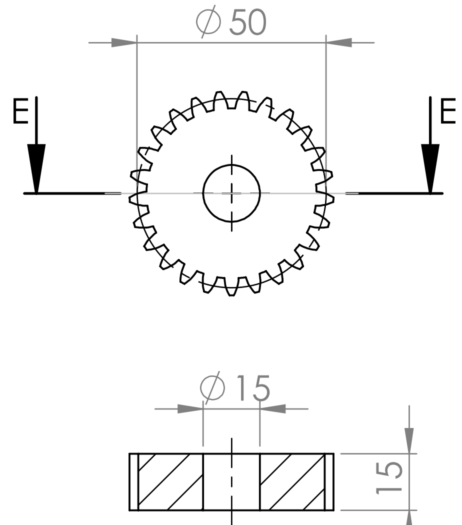
SECTION B-B

Data	Gear D90
Module	2
Number of Teeth	45
Pitch Diameter	90 mm
Outside Diameter	94 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm



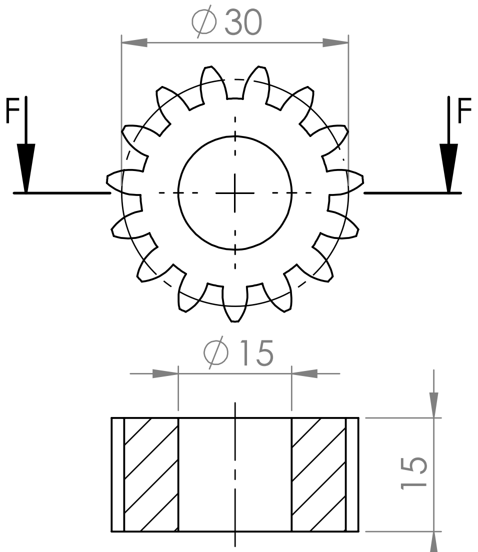
SECTION C-C

Data	Gear D70
Module	2
Number of Teeth	35
Pitch Diameter	70 mm
Outside Diameter	74 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm



SECTION E-E

Data	Gear D50
Module	2
Number of Teeth	25
Pitch Diameter	50 mm
Outside Diameter	54 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm



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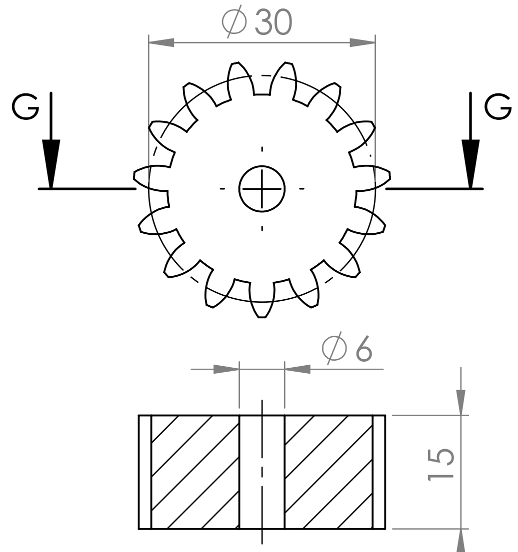

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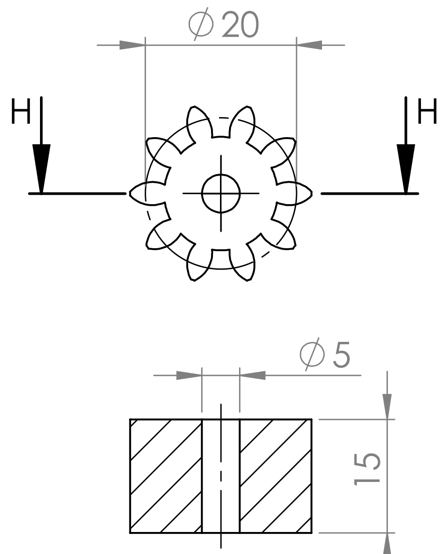

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Number of Teeth	10
Pitch Diameter	20 mm
Outside Diameter	24 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm

Data	Gear D30
Module	2
Number of Teeth	15
Pitch Diameter	30 mm
Outside Diameter	34 mm
Pressure Angle	20°
Whole Depth	4.33 mm
Circular Pitch	6.28 mm

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

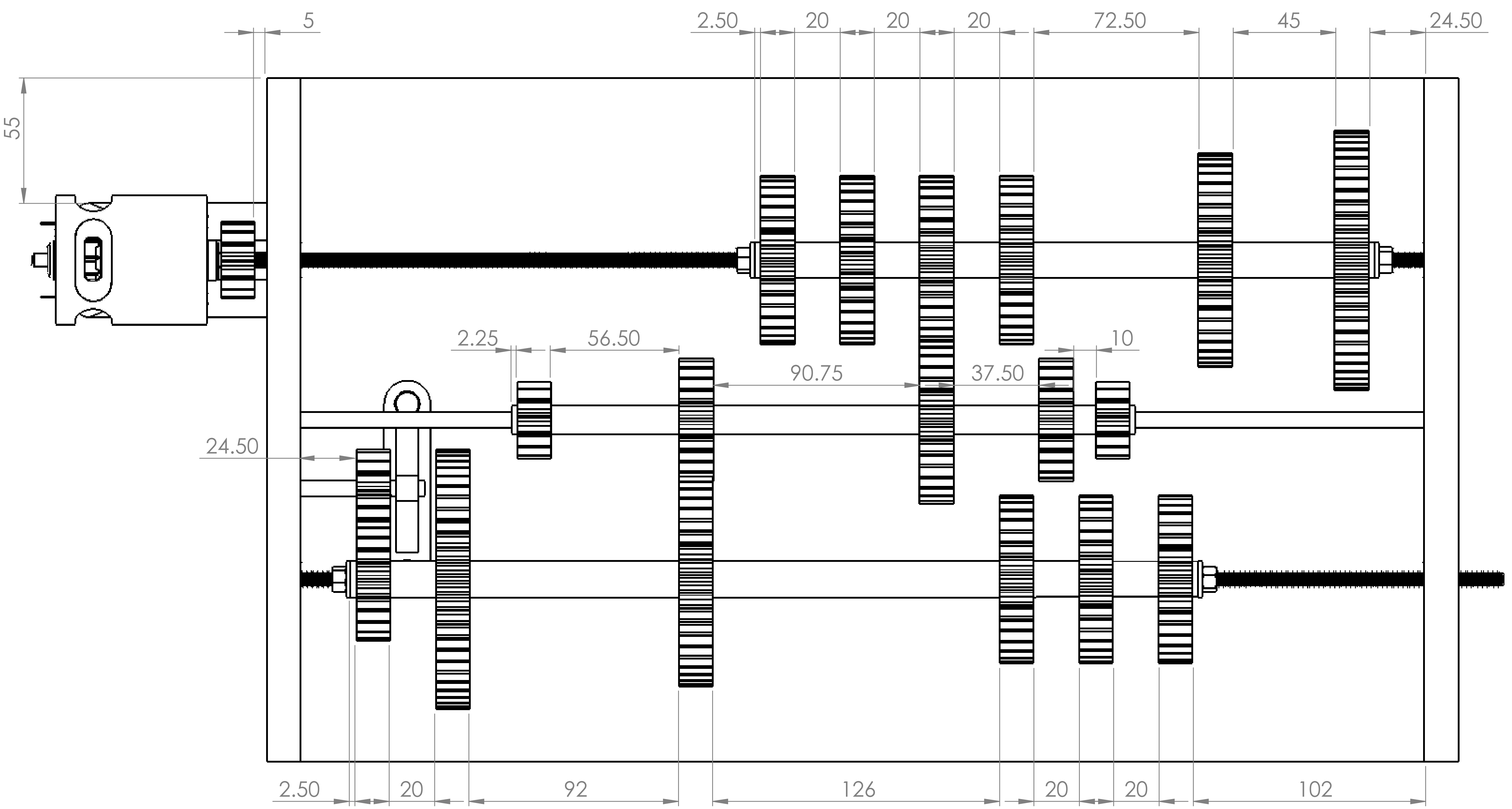
Gears

A3

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

Final Assembly

A3

WEIGHT:

SCALE:1:5

SHEET 1 OF 1