Mechanical design of a robot's gripper

Degree of industrial technologies

Final individual Project

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Date of submission: June 2015

GRATITUDES

First of all, I want to acknowledge the help received from my tutor Krzysztof Bieńkowski and the opportunity that he gave me to introduce myself in the world of robotics and 3D printing. I would like to thank also help with the printing of the design and the assembly of the pieces received from Mariusz Hildebrand.

Finally, I want to thank the support of my mother from the beginning to the end, it has been very important during the development of the project.

It has been great to be part of this project, I really enjoyed it and I have learned a lot about robotics and 3D printing. I would like to continue working in this area in the future.

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MEMORY

1.1 Introduction

My Project consists in the mechanical design of a robot's gripper. This gripper is composed of two servomotors that allow the movement of the wrist and the movement of the grippers. Due to these two movements, we would be able to take every object we want. First, we will design the robot's gripper through the program "Autodesk Inventor Professional 2012" and the tool used for its print will be the 3D printer "Velleman K8200". The servomotors were chosen by my tutor and me with the goal of getting a cheap gripper.

¿Why I choose this individual project?

In my opinion, the world of the robots is the future. In the last years, the demand of robotic products is increasing a lot. This is because with the robot, we can reduce the time of producing objects, we can be more precise, more efficient… The use of robotics provides the following advantages:

- Improves considerably the safety of the company: A robot can perform some activities that are dangerous for the human like handle potentially hazardous products, manipulate heavy loads…
- Allows the possibility of doing many different activities: A robot can be programmed to do a lot of different kind of activities. This increases his profitability.
- Allows the realization of optimum quality jobs: The precision of a robot is better than human's precision
- The level of incidents is very small: We must only to do a basic maintenance of the robots to keep them running smoothly.
- Increases the productivity of the company.
- The efficiency of the company is higher.
- With the robotic, humans have been able to devote their time improving the quality of life applying the robots to do hard works that humans did before of this discovery.
- One of the most important things of the robotic for me is that it can be used to help disabled people ant make the life of this people much better.

Because of all of these reasons, I am very interesting in this world and this project allows me to start with the design of the robots. In my case, my project is only a mechanical design but I think is a good beginning to introduce me in this area. If I had the opportunity in my future I would like to design products like in this project to improve the life of the people.

1.2 Goals

The main goal of this Project is the design, manufacturing and construction with a 3D printer of a robot's gripper.

However, this is not the only goal, this project has other secondary goals:

- It could be a guide for everyone who wants to introduce in the world of the robotic and robot's design.
- Another goal is to create a structure easy to insert changes and improvements inside it.
- One personal goal is to pass successfully my individual project and to learn a lot about robots and design.
- It could be great to help people with health problems to take objects that they can't take.
- We can test this gripper in a robot's arm and use it like part of the robot.
- This kind of robot's grippers could be used in the companies and they would have the next advantages for the companies:
    - Increased productivity.
    - Quality improvement.
    - Increased speed: It is due to the automatic repetition of the movements of the robot with speed optimization.
    - High uptime without failure.
    - Reduced maintenance.
    - Substantial optimization of the employment and equipment that runs the machine.
    - Rapid return of the investment.

1.3 Resources used

To carry out the project I have needed the following resources:

- A computer with a Windows system operative.
- The computer software Autodesk Inventor Professional 2012.
- The 3D printer Velleman K8200.
- The plastic material PLA (Polylactic acid).
- Two servomotors Silnik DC Dagu DG02S-2M.
- The tools necessaries to build the robot's gripper.

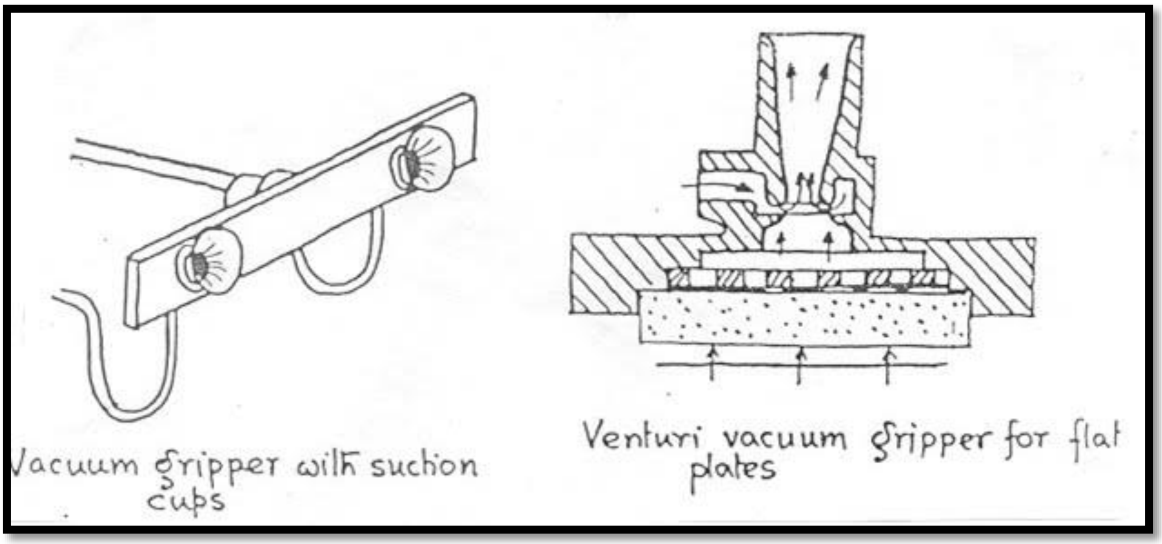
1.4 Selection of my gripper

Before starting my design of the robot's gripper, I was investigating about the current types of grippers that you can see in the market. After this investigation I discovered that there are four kinds of grippers classified according to his way of grip:

1. **Pressure gripper:** This kind of gripper is used for pieces that can be pressed by the gripper without being deformed.

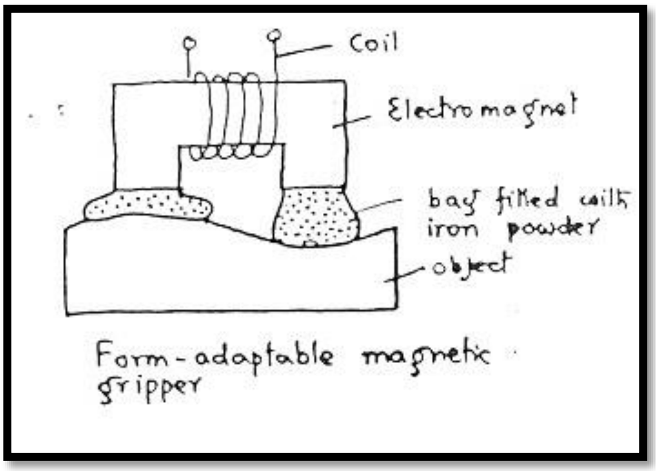
2. **Coupling gripper:** This kind of gripper is used for pieces of big dimensions that can't be pressed by the gripper.

3. **Vacuum gripper:** Vacuum grippers are used in the robots for grasping the non – ferrous objects. It uses vacuum cups as the gripping device, which is also commonly known as suction cups. This type of grippers will provide good handling if the objects are smooth, flat, and clean. It has only one surface for gripping the objects. Most importantly, it is not best suitable for handling the objects with pores.



[1] – Example of a vacuum gripper

4. **Electromagnetic gripper:** Magnetic grippers are most commonly used in a robot as an end effector for grasping the ferrous materials.

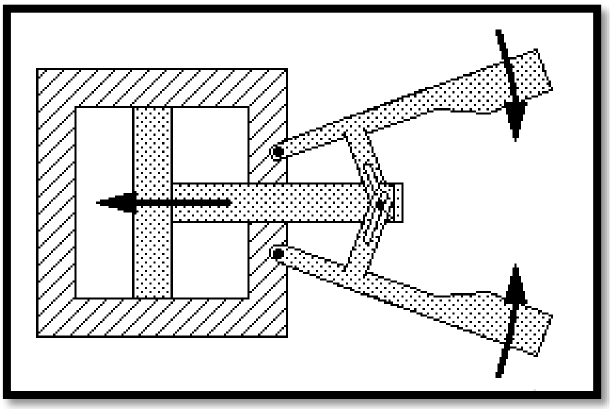


[2] – Example of a electromagnetic gripper

Because we want to build a cheap gripper and the type of pieces which normally we will take (pieces that we can press and non ferromagnetic), I selected the first kind of gripper, **the pressure gripper**.

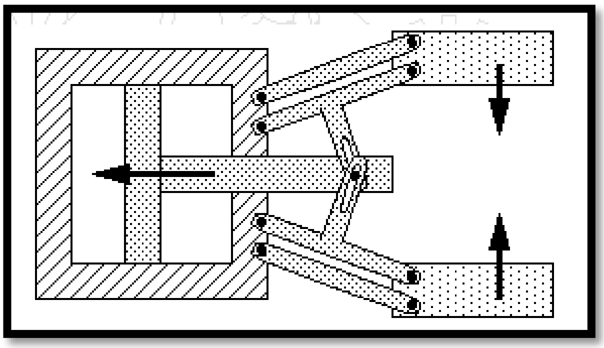
The next step was to select the type of movement that we want for our gripper. I had two type of gripper according to its movement:

1. **Rotation movement:** As we can see in the following picture [3], the gripper is based on a rotation movement to take the objects.



[3] – Example of gripper with rotation movement

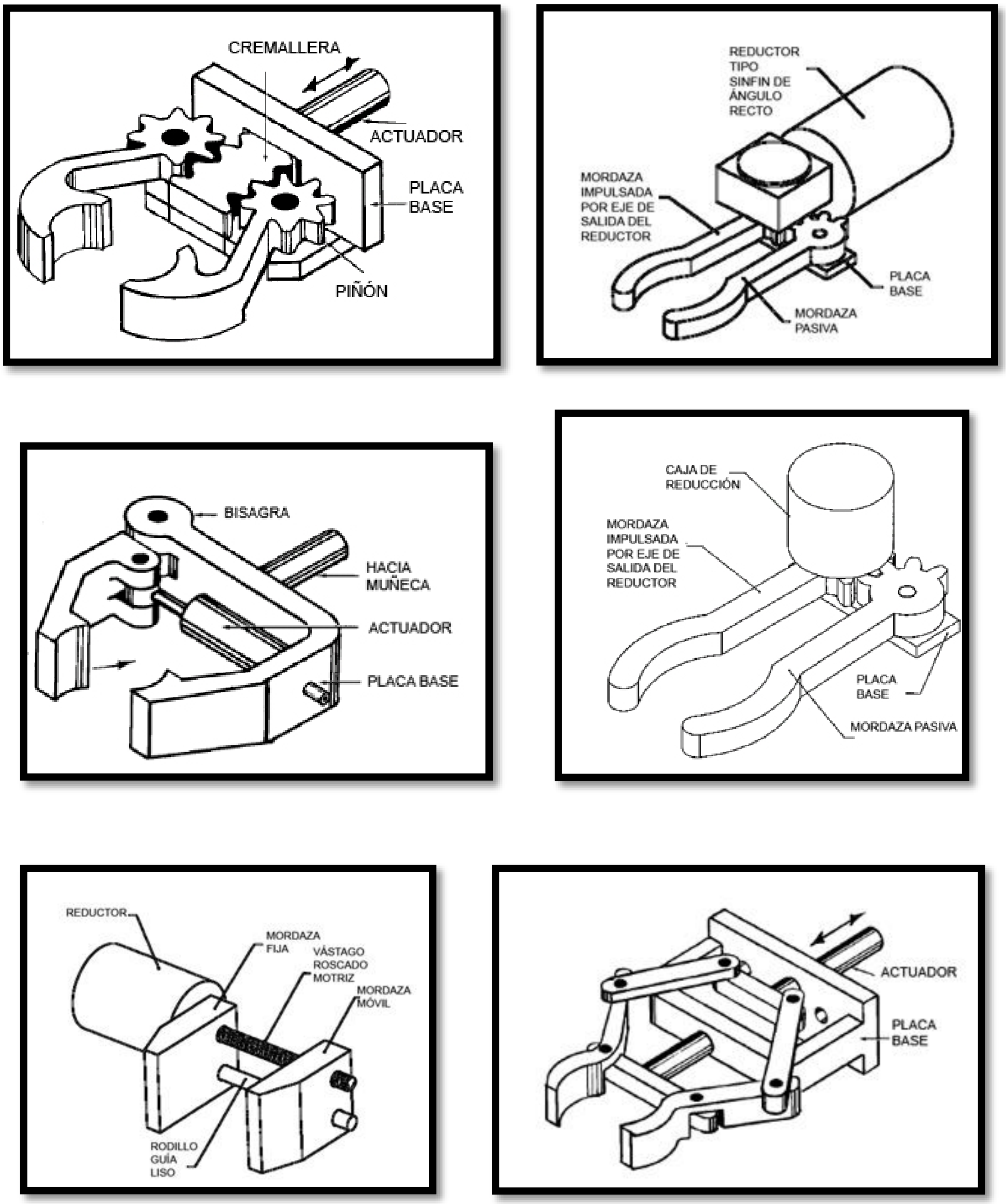
2. **Translation movement:** As we can see in the following picture [4], the gripper is based on a translation movement to take the objects.



[4] – Example of gripper with translation movement

In my opinion, the best gripper's choice was **the translation movement**, because is easier to calculate the distance where we have to put the gripper to take the object and I thought that it was the best way to grab strongly the objects.

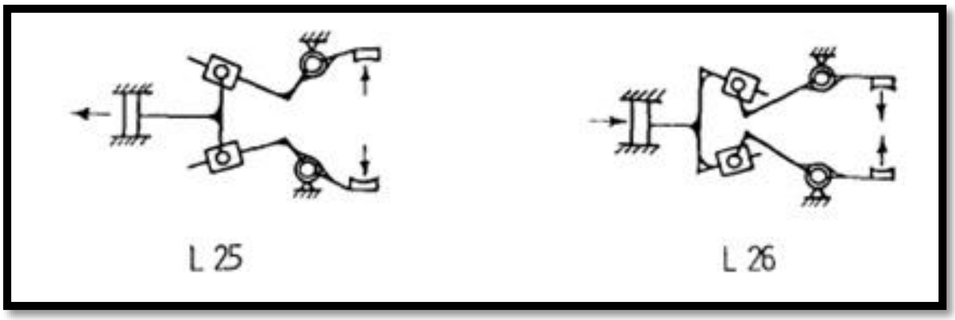
Finally, I needed to design my pressure gripper with a translation movement and I had a lot of possibilities and designs to do, so I selected some of the designs that I saw and I use as prototypes for my gripper's design. These are some of these designs:



[5] – Six different gripper with translation movement.

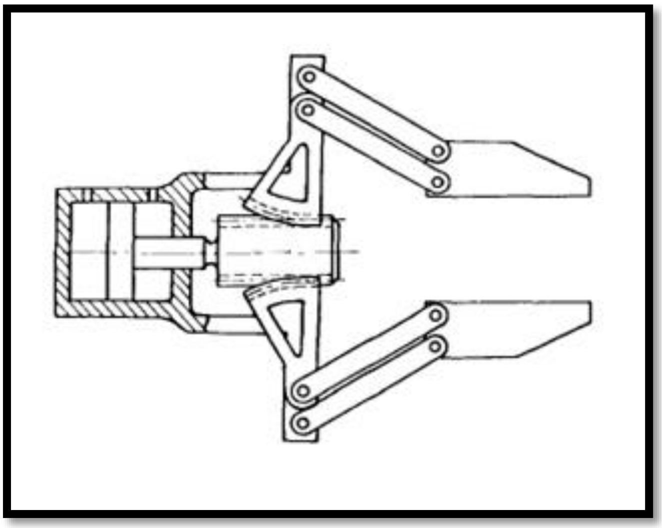
As you can see [5] there are a lot of types of grippers. In addition, the translation movement grippers are classified in other groups according to the mechanism used to move the gripper:

1. **Linkage Grippers:** there is no cam, screw, gear. There is movement only because of links attached to input and output. There must be perfect design of mechanism such that input actuator's motion is transformed into the gripping action at the output.



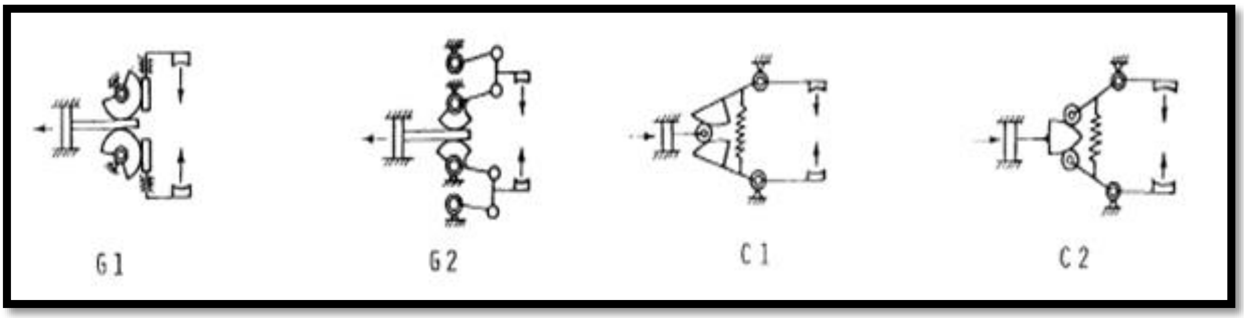
[6] – Examples of two linkage grippers

2. **Gear and Rack Grippers:** movement of input due to gear motion which makes connecting links to go in motion to make gripping action at the output link.



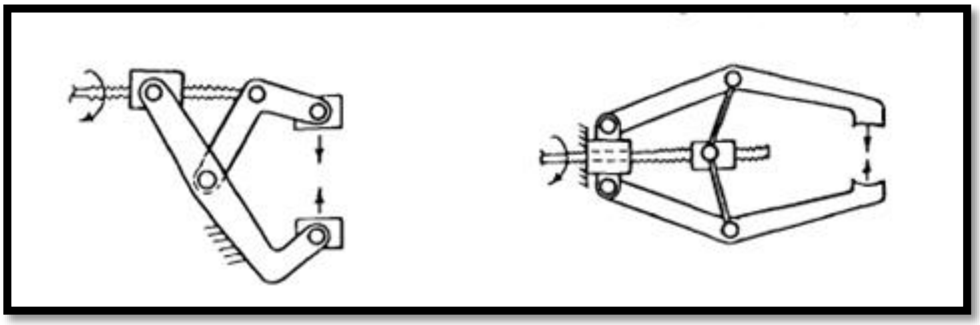
[7] – Gear gripper with the motion in the middle

3. **Cam-actuated Grippers:** reciprocating motion of the cam imparts motion to the follower, thus causing fingers to produce a grabbing action. A variety of cam profiles can be employed- constant velocity, circular arcs, harmonic curves etc. This mechanism is similar that the linkage gripper but in this intervene the cams.



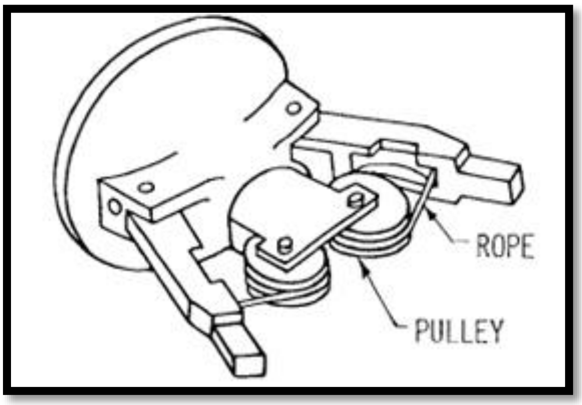
[8] – Four different examples of cam-actuated grippers

4. **Screw-driven Grippers:** operated by turning screw, in turn giving motion to connecting links and thus giving griping motion to output. Screw motion can be controlled by motor attached.



[9] – Examples of screw-driven grippers

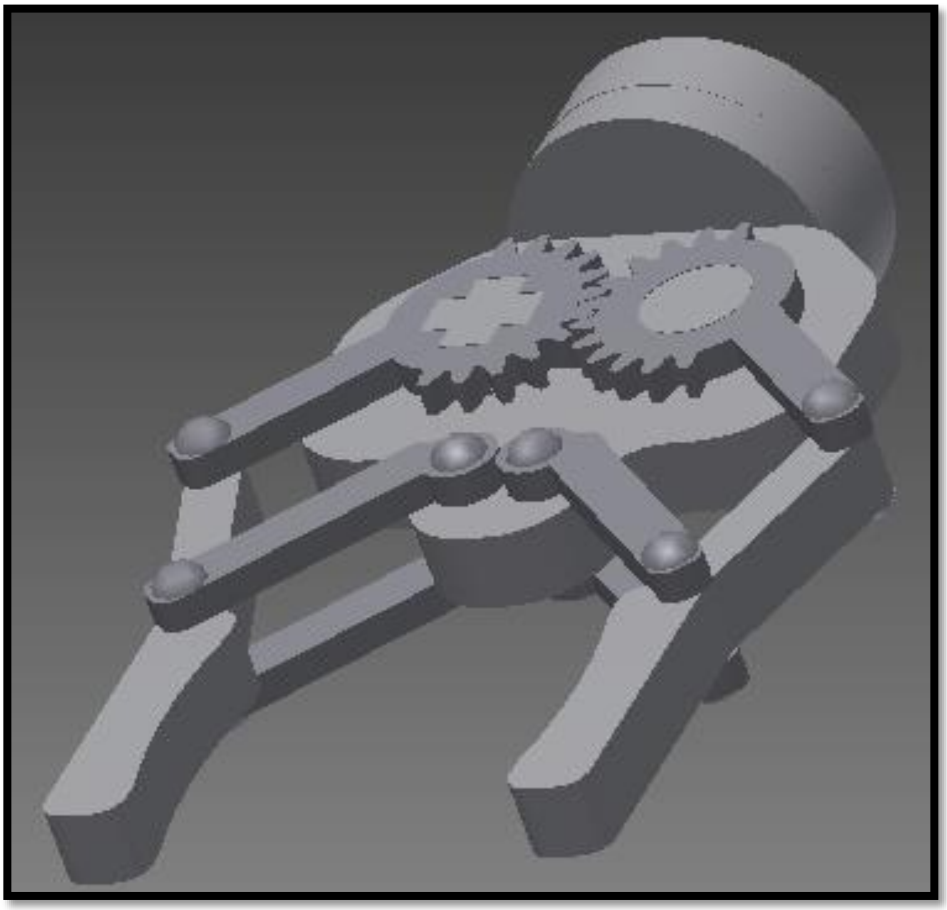
5. **Rope & Pulley Grippers:** motor attached to the pulley makes the winding and unwinding motion of rope in turn it set gripper action into motion via connecting link.



[10] – Rope and pulley gripper

I selected the **gear gripper** because I thought that it was the cheapest way and it was very practical and easy to build.

After all of these choices, my final design of the gripper was the next:



[11] – Robot's gripper design with Autodesk Inventor Professional 2012

I had to take another decision before finishing my design. I decided to use only **one gripper ("one finger")** instead of two or more fingers with the goal of saving material and doing the robot's gripper as cheap as possible.

1.5 Preliminary description

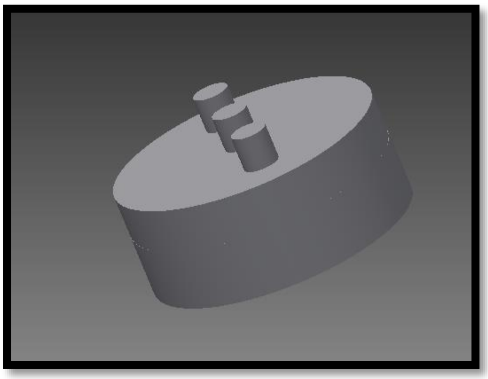
The robot's gripper has two degrees of freedom and it consists in four main pieces:

1. The wrist
2. The base
3. The grippers or fingers
4. The piece that connects the robot's gripper with the arm of the robot. I will call this piece the earth.

1. The wrist

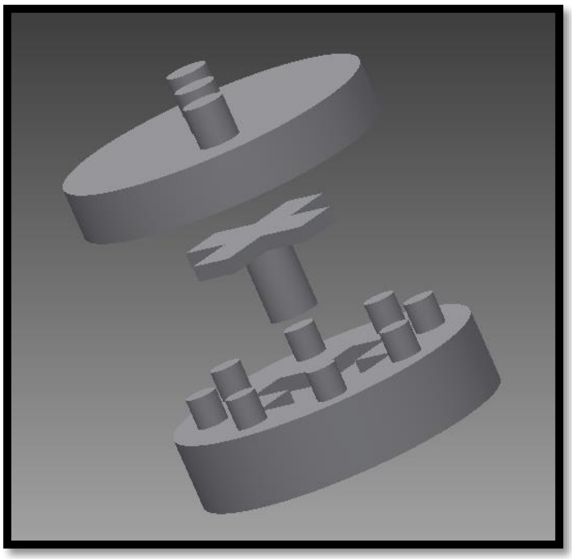
The wrist is the piece that provides to the gripper the rotational movement. The wrist is made by three pieces: two parts that are joined between them through outgoing parts and holes and one piece with the function of connecting the rotational axis of the servomotor with the wrist. This last piece is the responsible for transmitting the movement to the entire wrist.

The wrist will be connected to the base of the gripper and to the earth.



[12] – Assembly of the wrist

This picture [12] shows the assembly of the wrist. We can see three outgoing parts that allow the connection of the wrist to the base.



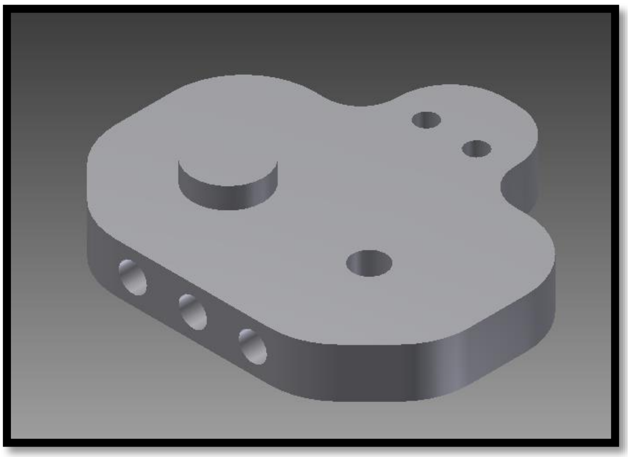
[13] – Exploded view of the wrist

And in the picture [13] we can see all the pieces that form the wrist.

2. The base

The base will be the centre of connections of every pieces of the robot's gripper. To the base will be attached two gears of which one of them will be connected through one connection piece to the other servomotor that provides movement to the gears. These gears will be joined to the grippers and will give movement to them.

In addition, we will use another connection piece that will join the base and the grippers keeping the grippers with an angle of 90º with respect to the horizontal axis every time.

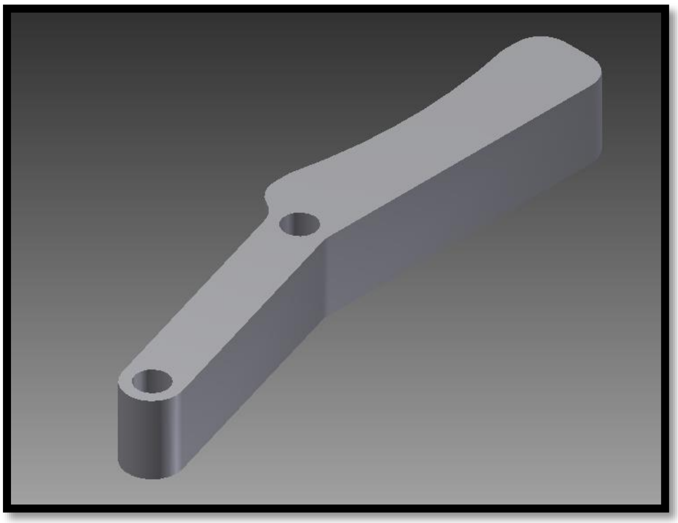


[14] – Picture of the gripper's base

We can see in the picture [14] the three holes to connect the wrist, the outgoing part to insert the gear and other three holes with the function of connect other pieces.

3. The gripper

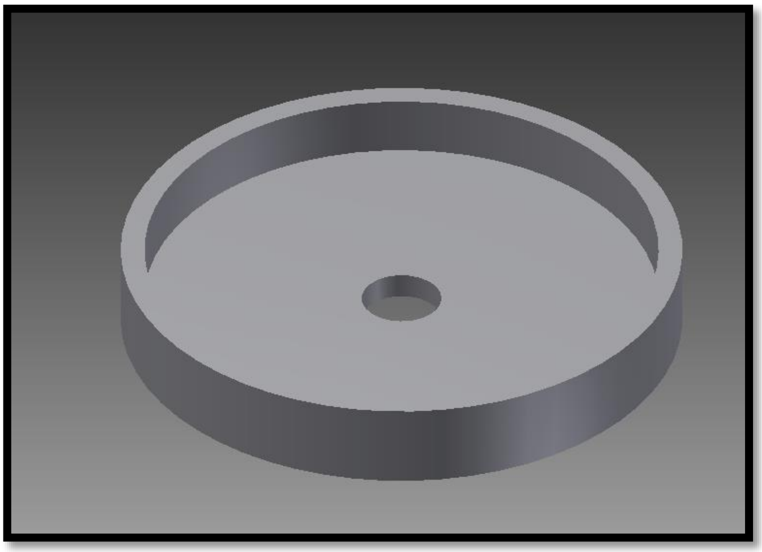
The gripper will have the best possible shape and material with the goal of take a lot of objects with different contours and weights. As I say before, it will have a translation movement.



[15] – View of the "finger" of the robot's gripper

4. The earth

This piece is very important because it must keep the servomotor that gives movement to the wrist fixed. If this piece doesn't fulfill that function, the movement of the gripper will be strange. The other function of this piece is to give the possibility of connecting the entire robot's gripper to a existing robotic arm.

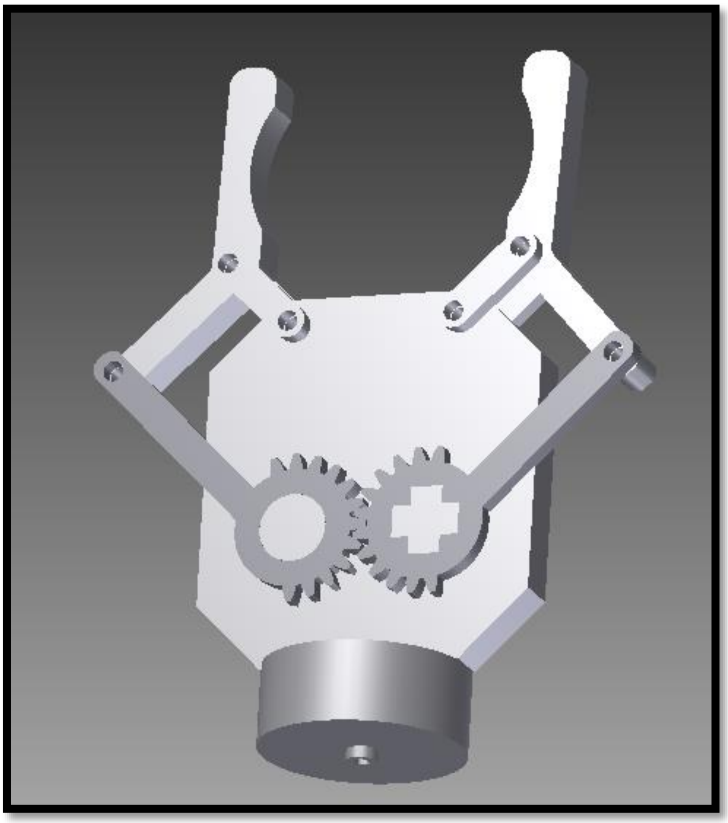


[16] – Perspective view of the earth.

1.6 Possible solutions and justification of chosen solution

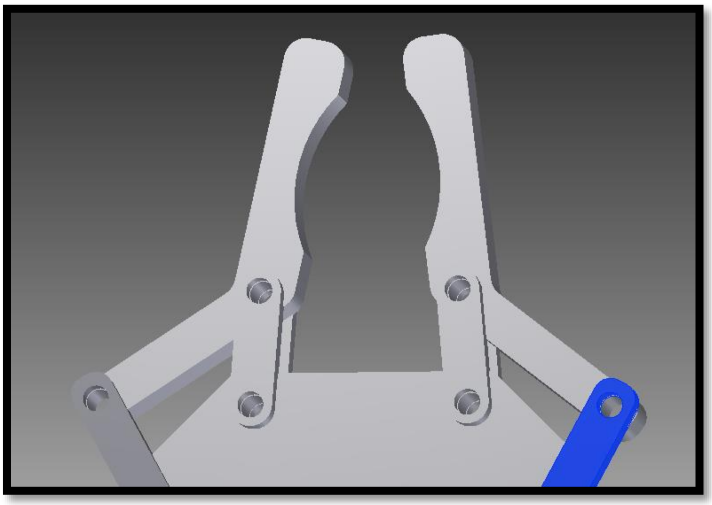
Throughout the development of my project I have being trying with different designs to finally obtain the most effective gripper that I have found. I'm going to show all the designs that I have done:

First design:



[17] – Perspective view of the first design of the gripper

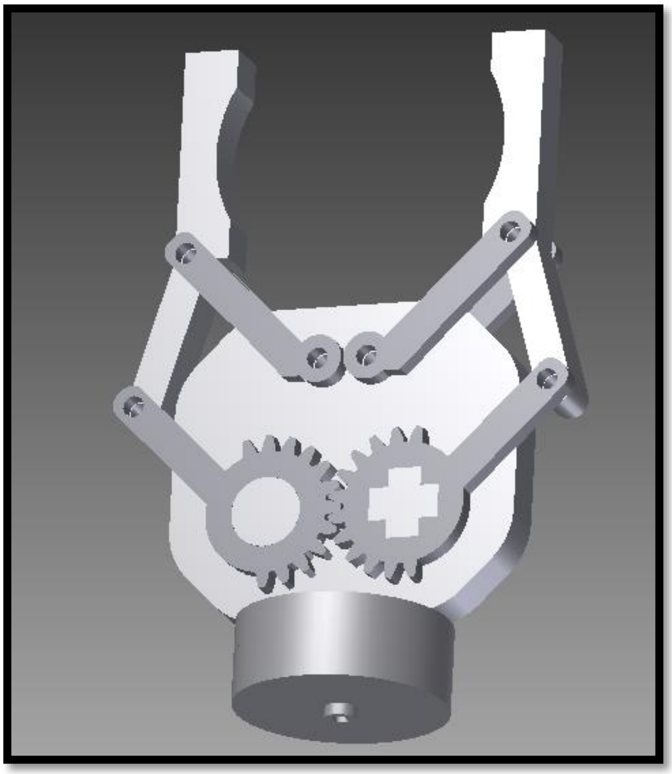
This design was discarded due to the overuse of the material and because the movement of the gripper wasn't only translation and it had a slight rotation.



[18] – Picture to appreciate the rotation's problem

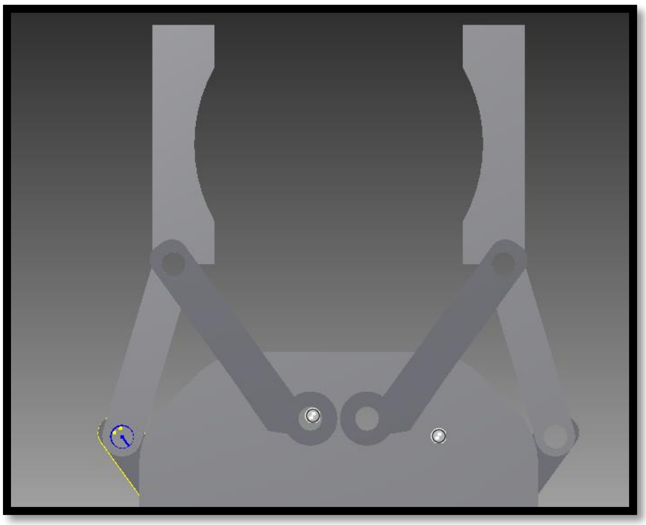
We can observe in the picture [18] that the grippers are not straight. They have rotated due to the radius of rotation of the gears was different than the radius of rotation of the connection piece of the base with the gripper. Because I wanted a robot's gripper with translation movement, I needed to modify it inserting one connection piece with the same radius than the gear.

Second design:



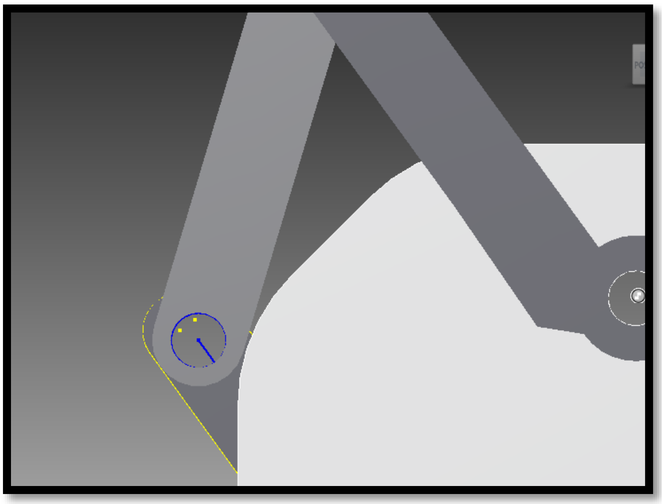
[19] – Perspective view of the second design of the gripper

Once I managed to fix the rotation's problem, I designed a robot's gripper more effective and with less quantity of material used. However, due to the top of the base was very wide, the grippers collided very early with this part and the minimum aperture of the robot's gripper was very big.



[20] – View of the width of the base

As we can see, this gripper was very bad because it could take only very big objects.



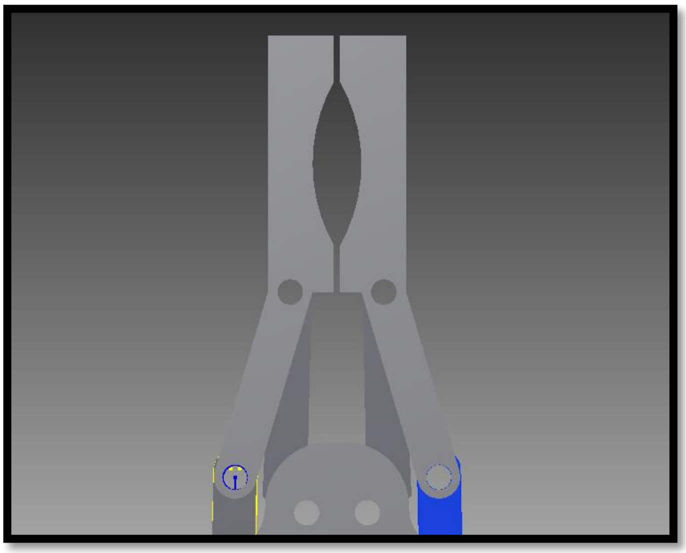
[21] –Collision of the gripper and the base

We can check with the picture [21] the collision between the gripper and the base. To improve it I needed to cut part of the base, this change was very good because we could get a minimum aperture very of the gripper very small and we could save more quantity of material.

Third design:

[22] – Perspective view of the third design of the gripper

The next step was to fix the problem with the minimum aperture of the gripper cutting the gripper's base. On this way, we achieved a total closing of the gripper without interferences with any piece.



[23] – Minimum aperture of the gripper.

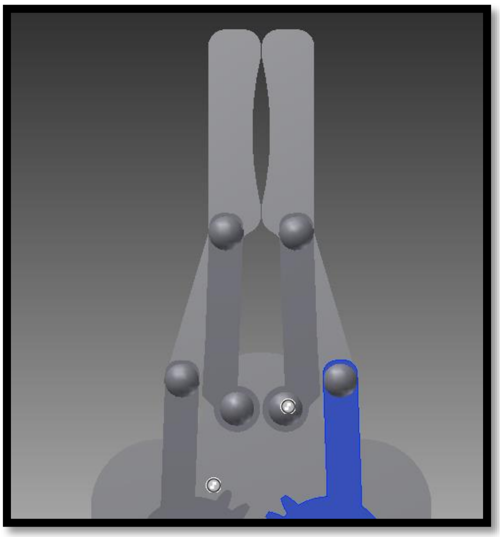
We can check [23] that all the problems have been fixed and the minimum aperture is small, so this design is a good design.

After this design I started to think in some esthetic improvements and I found my last design.

Last design:

[24] – Perspective view of the last design of the gripper

Finally, I have improved the grippers with the goal that the minimum distance between them was much smaller and I have added rivets to join all the pieces between them. In addition, I have rounded the gripper and the 3d printing is easier on this way.



[25] – Minimum aperture of the last design of the gripper

We can observe [25] that this design is perfect because the distance between the grippers is very small. After four designs I have found the best possible. The rivets are only used for the simulation because we are going to use rods when we are ready to build the gripper.

1.7 Previous basics

1.7.1 Program used

The program used for the design of the robot's gripper in the computer is "Autodesk Inventor Professional 2012". I couldn`t use the next versions of this program because of the characteristics of my computer. Autodesk Inventor, developed by U.S., based software company Autodesk, is a computer-aided design application for creating 3D digital prototypes used in the design, visualization and simulation of products.

Inventor includes an integrated motion simulation and assembly stress analysis environment. Users can input driving loads, friction characteristics, and dynamic components, then run dynamic simulation tests to see how a product will work under real-world conditions. The simulation tools can help users optimize strength and weight, identify high-stress areas, identify and reduce unwanted vibrations, and size motors and actuators to reduce energy consumption.

1.7.2 Servomotor

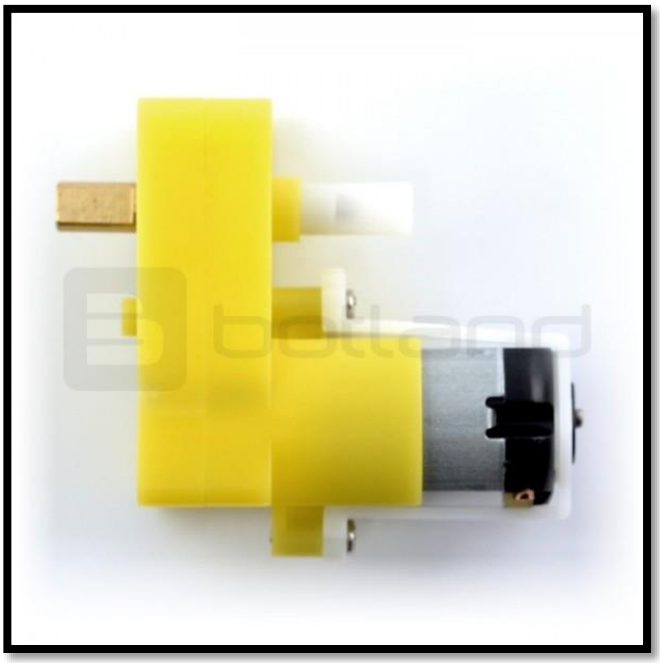
About servomotors, we can see all the information of them and we can buy it in this web page:

http://botland.com.pl/silniki-dc-z-przekladnia-dagu/2166-silnik-dc-dagu-dg02s-2m-481-3v-katowy-z-podwojnym-walem-2-szt.html

The name of the servomotor is Silnik DC Dagu DG02S-2M 48:1 3V and the characteristics of it are the next:

- **Power supply: 3 V**
- **Current consumption: 125 mA (max. 170 mA)**
- **Transmission: 48:1**
- **Speed: 65 ± 10 rev / min**
- **Torque: 0.8 kg *cm (0.078 Nm)**
- **Connect the red wire and black**
- **Shaft diameter: 5.4 mm**
- **Shaft Type: Metal**
- **The shaft is tapered on both sides**
- **The shaft has a threaded hole adapted to the M3 screws (not included)**

- **The engine has dual shaft, which allows the encoder assembly**
- **Engine weight: 35 g**



[26] – Image of Silnik DC Dagu DG02S-2M servomotor

Here, we can observe a picture [26] of one servomotor. In the section of planes and pieces, I will add a plane of the servomotor with all the measures of them necessaries for the design of the robot's gripper.

The price of a couple of servomotors is of 29 zloty.

1.7.3 3D printer

1.7.3.1 What is 3D printing?

It is strongly believed that 3D printing is going to be a very important technology in the future in the world. The scientists think that this technology is going to replace the traditional manufacturing and is going to revolutionize the form of doing new designs of products.

The most important thing of this technology is that is an additive process, it means that the method build the pieces layer by layer, one above the others. This fact is very important because is the first technology that acts on this way. Before of this new technology, the other technologies use subtracting processes, that means that the method builds pieces subtracting material of a big block. In many of these processes the 90% of the material is wasted. In contrast, in 3D printing we use the exact material that we need so we can earn a lot of money using this technology. In addition, 3D printing offers the advantage of a better calculation of the times for building the pieces.

Because of all this reasons, this technology is increasing hugely in the last years.

1.7.3.2 History of 3D printer

The first time the layer by layer manufacturing was used was during the late 1980s and early 1990s, as rapid prototyping (RP). Prototypes allowed to examine the physical design of the object and test it before you start massively produce the product. The RP allowed to obtain prototypes much faster than what had been used until then, usually within a range of days or even hours after conceiving the design. The designers created the model in a CAD software and machines that were following code to determine how to build the object. As "printed" the different layers crossing each other, was born the concept of 3D printing.

According to the years passed, the details of 3D printing were sophisticated, improving printing times, the time required to complete the piece, precision... The processes are now faster, the materials and equipment needed is much cheaper and more and more materials are being adapted for printing.

While evolving the printing technique for layers, important advances were also emerging in different 3D printing machines. The origin of such printers is the RepRap project initiated by Adrian Bowyer in 2004 with the aim of developing a self-replicating machine open source. In May 2007 the first prototype, called Darwin was completed and later the first replication was achieved. Since then, the RepRap community (machines reprap original designs and derivatives) has grown exponentially with a current estimated population of around 4,500 machines. The second generation RepRap, called Mendel, was completed in September 2009. Some of the main advantages of Mendel printers, that Darwin printers didn't have, are mostly print area, greater efficiency of the axes, more simple and easy to install, cheaper and lighter and portability.

Initially, Darwin and Mendel were not designed for the general public, but for people with some technical knowledge. As the RepRap project was acquired character OpenSource, small companies were appearing to begin marketing these 3D printers as well as their derivatives designs. The first company was MakerBot Industries, manufacturing a first batch of Cupcake CNC in April 2009. However, there was still a long way to give and would increase greatly the spread of this technology. The goal was to find a balance between quality and price, so any user could have their own printer at home at an affordable price without having to resort to high investment in a professional machine.

For this reason, our printer Velleman K8200 was created with a price around 600 euros, which allows to be purchased by every professional that need it in his work.

In the next sections we are going to talk about the characteristics of this 3D printer.

1.7.3.3 How it works?

The initial point for every 3D printing process is a 3D digital model, which can be created by a lot of software programs (in my case Autodesk Professional Inventor 2012) or scanned with a 3D scanner. The model is read by the printer in layers and when the material is ready to be processed the 3D printer build the piece layer by layer according to the digital design.

The most common materials used for 3D printing now are ABS and PLA but the use of Nylon is increasing considerably.

There are a lot of 3D processes to build the pieces using different mechanisms and different forms of the material. However, if the pieces are very complex, sometimes is impossible to build them with this technology.

However, this technology is not only to press the button "Print", it requires a very good preparation and design of the pieces by computer's software and a lot of time and patience to print every piece.

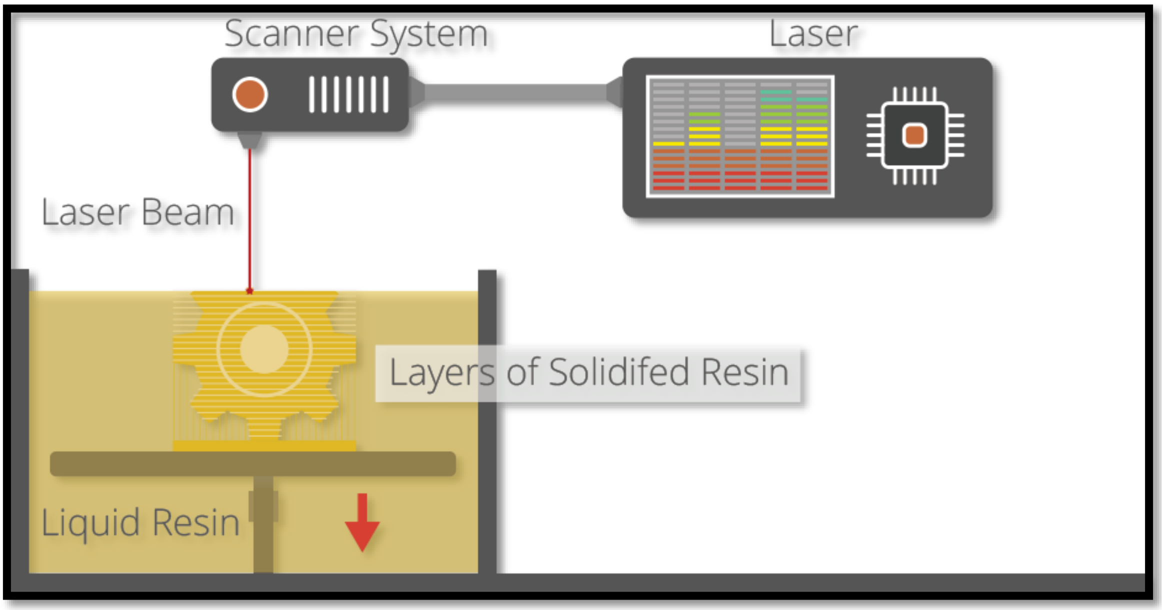
1.7.3.4 3D printing processes

There are a lot of different processes. I'm going to explain briefly some of them and which is the process of our 3D printer.

I. Stereolithography

It was the first 3D printing process, it's a laser-based process that works with photopolymer resins that react with the laser and cure forming a very accurate solid.

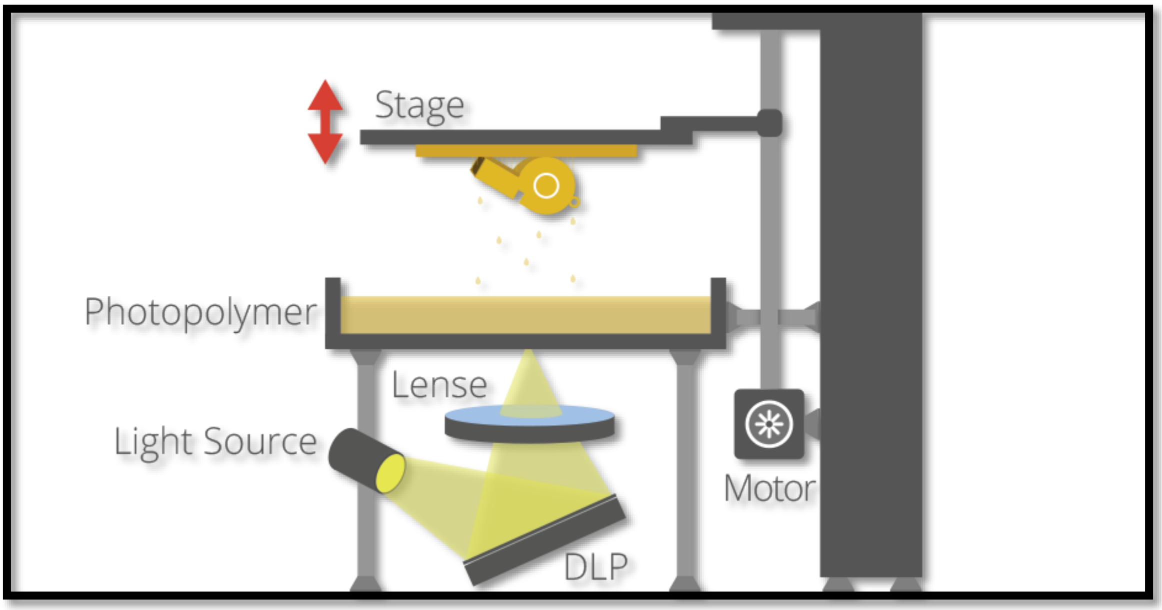
The process is a bit complex but I'm going to summarize this. The photopolymer resin is inside of a vat with a platform in movement inside of the vat. A laser beam cross the surface of the resin and with the laser beam the resin becomes hard according to the 3D data supplied to the printer. When the layer is done, the part of the resin which the laser beam hasn´t hit goes down and another layer starts to be created by the laser beam. This process continues creating layers and it stops when the piece is made and can be removed from the vat.



[27] – Stereolithography diagram process

II. Digital light processing (DLP)

DLP is a similar process to stereolithography because it also works with photopolymers. However, in this case the source for hard the material is the light. DLP uses a conventional light source such an arc lamp with a liquid crystal display panel or a deformable mirror device, which is applied to the complete surface of the vat of photopolymer resin in only a pass. This process is also very precise and is generally faster than stereolithography. We must know that in this process is important to uses a vat not very deep to help the process.

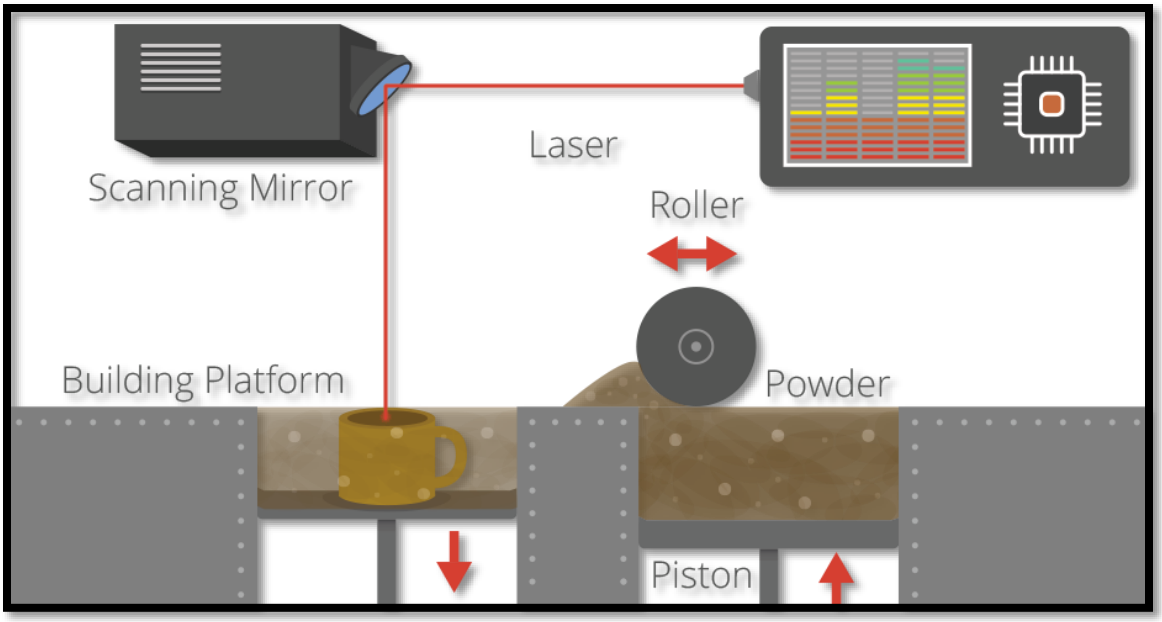


[28] – Digital light processing diagram

III. Laser sintering/Laser melting

These terms are used to refer to a process that uses the laser beam but, in this case, the material is powdered. The laser hits the material according to the 3D data and the material is sintered forming a solid piece. When the laser finish the layer, the powdered material goes down and a roller smoothes the surface before the laser beam starts again with the next layer. This last step is important for the compaction of the piece.

This process is very good in the aspect of the building of strange geometries that can't be built with another process. However, because of the high temperatures of sintering the time that we have to wait to have the pieces finished is significant. The pieces made by this process are stronger that the pieces of the processes that we have seen before.

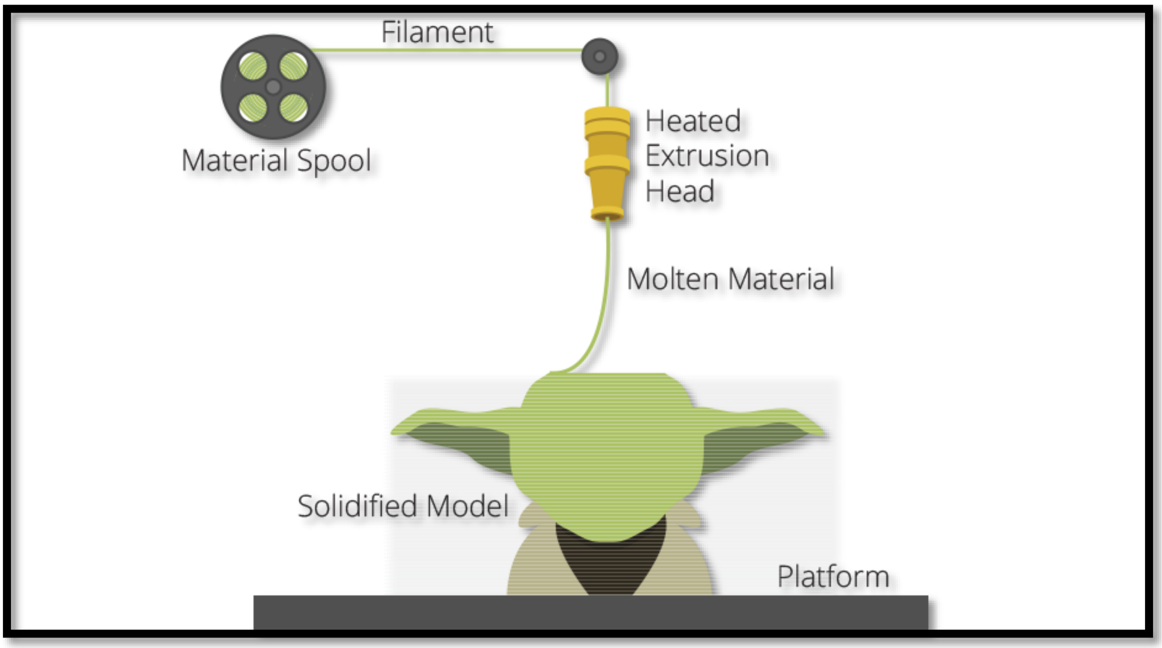


[29] – Laser sintering diagram process

IV. Fused Deposition Modeling (FDM)

This process is probably the most common for 3D printing. The process consists in the deposit of melting plastic filaments through a heated extruder doing a layer. This process continues doing layers above the previous one in function of the data supplied to the printer. Each layer becomes hard as it is deposited on the other layers.

This process could be slow for some pieces and geometries and layer-to-layer adhesion could be a problem, so we can insert these pieces in water. But we can solve this problem using acetone.



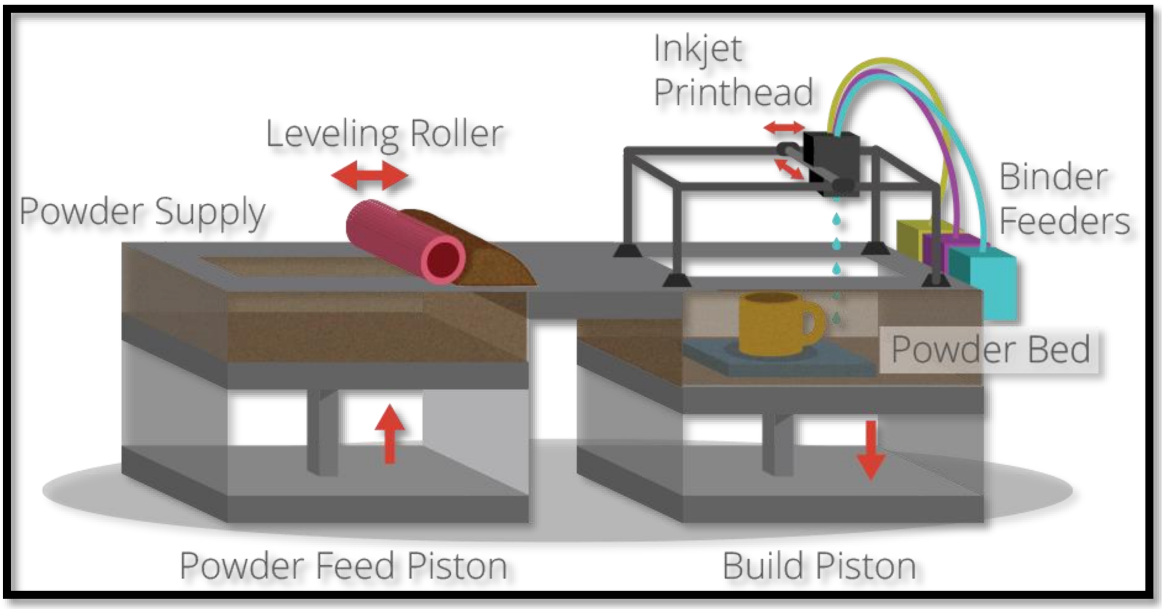
[30] –Fused deposition modeling diagram process

This is the process that we are going to use with our 3D printer Velleman K8200.

V. Inkjet: Binder jetting

This process used a binder which is jetted and sprayed according to the 3D model into a powder bed of the piece material to fuse it a layer at a time until the pieces is created. Like in the laser sintering we use a roller in this procedure to consolidate the piece.

With this process we can use a lot of colors which can be added to the binder.

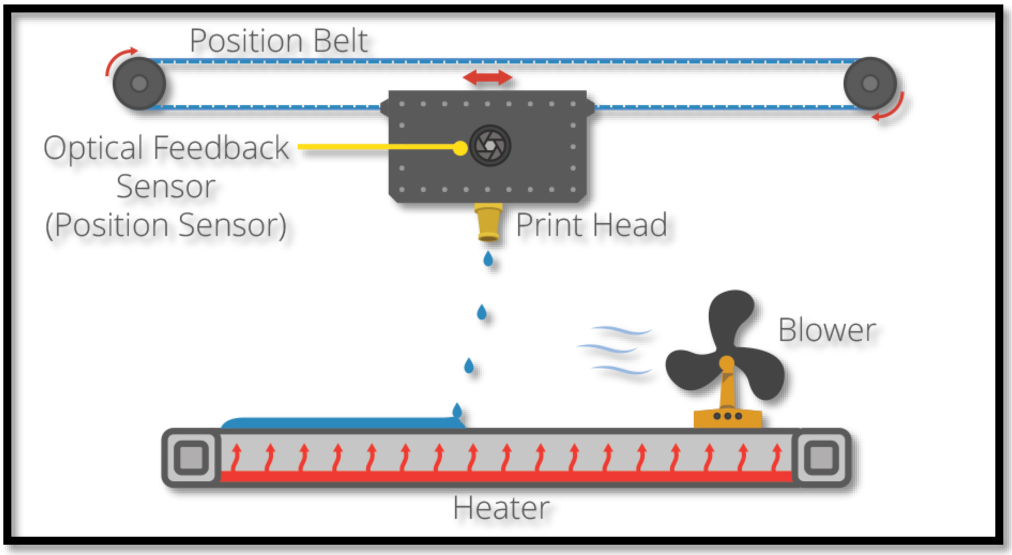


[31] –Binder jetting diagram process

VI. Inkjet: Material jetting

Material jetting is a 3D printing process that allows creating the pieces with the material in liquid or molten state. However, the materials tend to be liquid photopolymers that are cured with the ultraviolet light, forming the layers.

With this process we can use a lot of different materials and the result is very accurate.

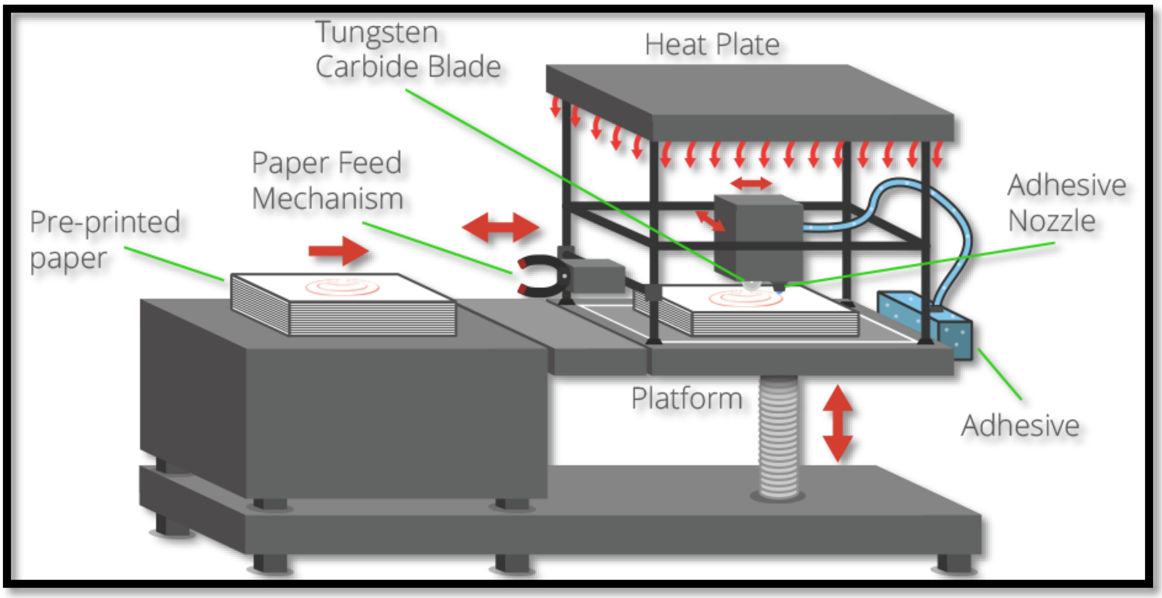


[32] – Material jetting diagram process

VII. Selective Deposition Lamination (SDL)

The SDL process builds pieces layer by layer using standard copier paper. Each new layer is fixed to the other layers by an adhesive according to the 3D model. It means that the wider adhesive will be in the part of the piece model and the narrower will be in the surrounding area.

A lot of pieces of paper are glued between them and then they are cut. When all the pieces of paper are treated we will have the piece ready.



[33] – Selective deposition lamination diagram process

1.7.3.5 3D printing materials

There are a lot of materials used for 3D printing nowadays. The most important are the next:

- **Plastics:** The most common plastics in the world of 3D printing are nylon, polyamide, **ABS, PLA**… Nylon and Polyamide are normally used in powder form with the laser sintering process or in filaments used for the fused deposition modeling (FDM) process. ABS and PLA are also in form of filaments so the main process used for these materials is FDM. In my project I'm going to work with PLA because is a cheap material and it offers a lot of colors to choose. It isn't as strong and flexible as ABS but I think is a very good choice to print my robot's gripper with this material.

- **Metals:** These materials are used commonly for big pieces in industries. The most famous materials for this work are aluminium and cobalt. Other material very important in this area is the stainless steel in powder form. For the jewellery we use silver and gold.

- **Ceramics:** These materials are relatively new for the 3D printing. They are not very useful because they have to be treated by a lot of processes to be used correctly.

- **Paper:** As I explain before, in some 3D printing processes is necessary the standard copier papers. This method is good for the environment and doesn't require another treatment when the print is finished.

- **Bio materials:** There are a lot of investigations about these materials because medicals think that is possible to print organs for transplant. It will be a success for the medicine.

1.7.3.6 3D printing applications

The first applications of the 3D printing were the design of industrial prototypes and this was the only application during the first years.

However, a lot of sectors of the industry have adopted this way of manufacturing and nowadays in almost all major companies exist the use of the 3D printing. Some of these sectors are the next:

- **Medical and dental**

This sector was one of the first using 3D printing technologies and the growth of this knowledge in the medical sector has being huge.

This technology has a lot of applications in medical and dental sector. As it regards the dental sector, it is used in the manufacture of tools intended to create dental aligners or to make patterns for the downstream metal casting of dental crowns. As it regards to medical sector, the technologies are utilized to build, for example, hip and knee implants and nowadays is increasing the use of these with the skin, the organs, the bones…

However, all of these applications are not in the market, they are for exclusive use of the companies.

- **Aerospace**

This sector was also one of the first using this technology producing prototypes for the aircraft development.

Because of the critical nature of aircraft development, the R&D is demanding and strenuous, standards are critical and industrial grade 3D printing systems are put through their paces. Process and materials development have seen a number of key applications developed for the aerospace sector.

However, the specialists in this sector are not very optimistic in the use of these technologies in aerospace sector.

- **Automotive**

This sector use at first time 3D printing, specifically, in the Formula 1 where this kind of technology is used with the goal of selling some pieces or building replacement parts.

- **Jewellery**

Traditionally, the processes of design and manufacturing of jewellery required of a lot of experience and preparation in every different discipline to build this kind of materials.

In the first years, 3D printing hadn't got to find a good technique to satisfy these disciplines but in the last years 3D printing has impacted in this sector because with this technology, the specialists can avoid some of the complicated processes to manufacture jewellery.

- **Art**

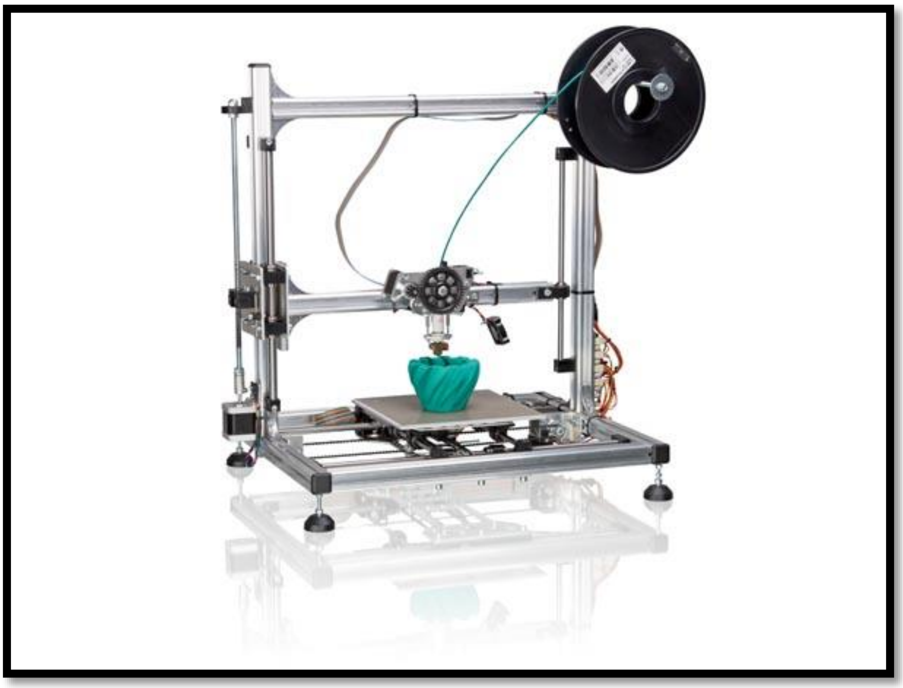
In the art, 3D printing is being a revolution, a lot of artists are using this technology in their techniques of art and many people are getting fame because of using of 3D printing.

- **Architecture**

This is the closest field to my project, because in this sector the professionals use software like CAD to design models and then they can print these models with 3D printing.

1.7.3.7 Our 3D printer

The printer that I have used to print my design is the model "Velleman K8200".



[34] – Image of printer Velleman K8200

It's a build it yourself 3D printer kit to print objects of maximum 20 x 20 x 20 cm using PLA or ABS filament (3 mm plastic wire). It is an extremely fast, reliable and precise printer even when printing at higher speeds. The K8200 is compatible with all free RepRap software and firmware. It is made out of aluminium profiles and is easy to assemble, it leaves room to the user to freely alter the machine and modify it to their liking. The print bed is heated.

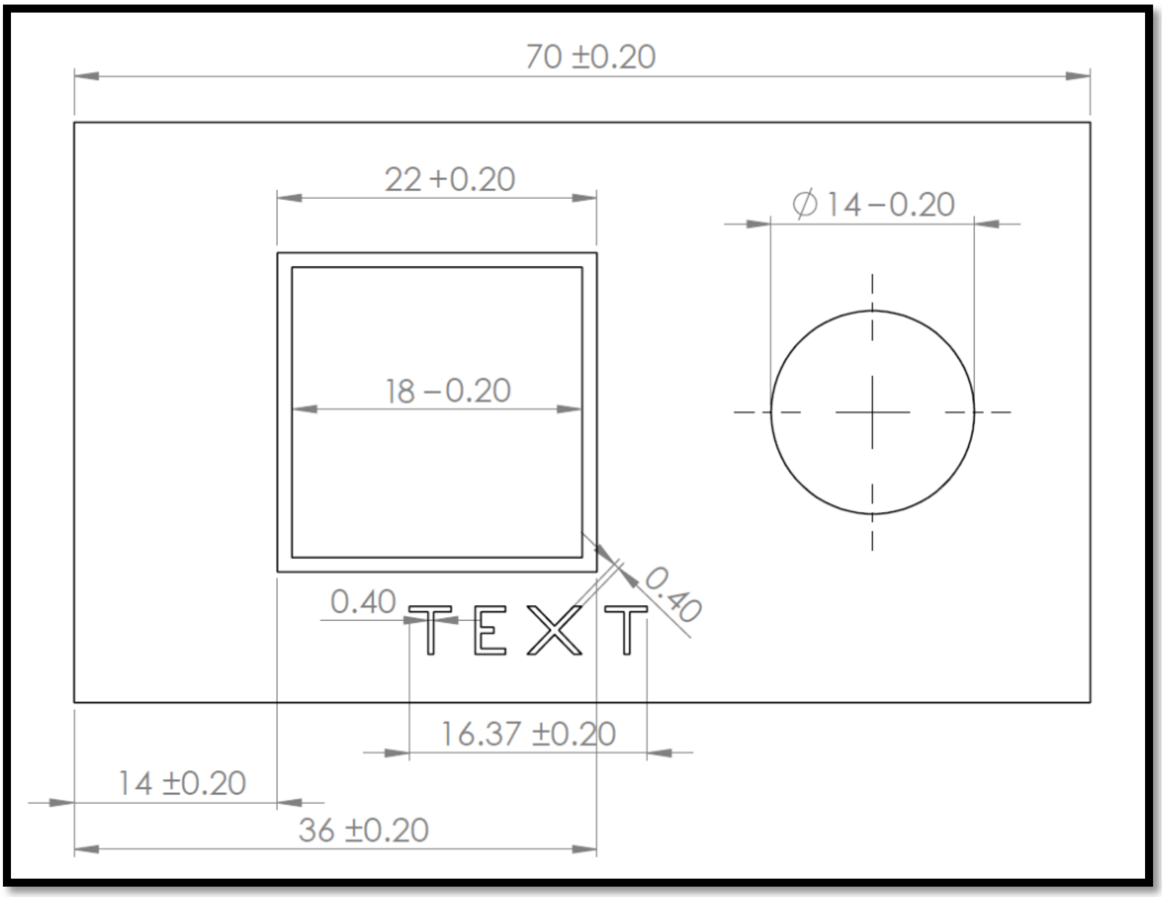
The characteristics of the printer are the next:

- **Linear ball bearings: 8 and 10 mm (0.314" and 0.393")**
- **Technology: FFF (Fused Filament Fabrication) for PLA and ABS**
- **Power supply: 15 Vdc / 6,6A max.**
- **FTDI USB 2.0 to Serial**
- **Dimensions of printable area: 20 x 20 x 20cm / 7.87 x 7.87 x 7.87"**
- **Typical printing speed: 120 mm/s**

- **Maximum print speed: 150 to 300 mm/s (depending on the object to be printed)**
- **Extrusion nozzle: 0.5 mm**
- **Extrusion thermistor: NTC 100K**
- **Extruded aluminum profiles: 27.5 mm / 1.08" wide**
- **Movement: 4 NEMA 17 stepper motors**
- **Resolution:**
  - **Nominal mechanical resolution:**
    - **X and Y: 0.015 mm / 590.55 µin (smallest step the printing plate can move in the X and Y direction)**
    - **Z: 0.781 µm / 30.74 µin(smallest step the printing plate can move in the Z direction)**
  - **Nominal printing resolution:**
    - **Wall thickness (X,Y): 0.5 mm / 0.019"**
    - **Layer thickness (Z): 0.20 - 0.25 mm / 0.0078 - 0.0098"**
- **Dimensions:**
  - **Width: 50cm / 19.7"**
  - **Depth: 42cm / 16.5"**
  - **Height: 62cm / 24.4"**
  - **Weight: 9Kg / 19.84lbs**
- **Software: Repetier version 0.84**
- **included: 5m PLA black simple**

Our 3D printer has a standard nozzle diameter of 0.4mm which common among all 3D printers. This means that each and every line of plastic drawn out to create an outline is 0.4mm thick. For ultra-fine detail of surfaces, this represents our absolute minimum feature size. Whilst we can print at layers of 0.05mm, if we were to print for example embossed lettering, the thickness of each line that forms the individual letters must be 0.4mm for the best finish. This is usually never an issue however for ultra-fine detail that is the limit.

With tolerances, the printer typically has an accuracy of +/- 0.2mm. This tolerance is a factor of the plastic cooling and expanding slightly along the walls of parts, resulting in solid sections tending towards the +0.2mm tolerance while holes tend towards the -0.2mm tolerance. Tolerances do not build up over the length of a piece. It is critical to understand that these tolerances result in overall a +0.4mm for any interferance or tolerance fits. For a 10mm rod to fit into a 10mm hole, they must be altered to 9.8mm for the rod and 10.2mm for the hole in order to print with a tolerance fit.



[35] – Picture about the tolerances of a standard 3D printer.

The tolerances do not build up and are all independent of each other, prints are dimensionally stable to a large degree. Parts that expand by 0.2mm must have 0.4mm cut off them to fit inside a hole that has contracted by 0.2mm.

1.7.4 Material used

Polylactic acid or polylactide (PLA, Poly) is a biodegradable thermoplastic aliphatic polyester derived from renewable resources, such as corn starch (in the United States), tapioca roots, chips or starch (mostly in Asia), or sugarcane (in the rest of the world). In 2010, PLA had the second highest consumption volume of any bioplastic of the world.

The name "polylactic acid" does not comply with IUPAC standard nomenclature, and is potentially ambiguous or confusing, because PLA is not a polyacid (polyelectrolyte), but rather a polyester.

Properties:

Due to the chiral nature of lactic acid, several distinct forms of polylactide exist: poly-L-lactide (PLLA) is the product resulting from polymerization of L,L-lactide (also known as L-lactide). PLLA has a crystallinity of around 37%, a glass transition temperature 60–65 °C, a melting temperature 173–178 °C and a tensile modulus 2.7–16 GPa. Heat-resistant PLA can withstand temperatures of 110 °C. PLA is soluble in chlorinated solvents, hot benzene, tetrahydrofuran, and dioxane.

PLA has similar mechanical properties to PETE polymer, but has a significantly lower maximum continuous use temperature

Polylactic acid can be processed like most thermoplastics into fiber (for example, using conventional melt spinning processes) and film. The melting temperature of PLLA can be increased by 40–50 °C and its heat deflection temperature can be increased from approximately 60 °C to up to 190 °C by physically blending the polymer with PDLA (poly-D-lactide). PDLA and PLLA form a highly regular stereocomplex with increased crystallinity. The temperature stability is maximised when a 1:1 blend is used, but even at lower concentrations of 3–10% of PDLA, there is still a substantial improvement. In the latter case, PDLA acts as a nucleating agent, thereby increasing the crystallization rate. Biodegradation of PDLA is slower than for PLA due to the higher crystallinity of PDLA.

1.8 Stages of development

Once we have understood what is and how works the 3D printer and the program "Autodesk Inventor Professional 2012", I can explain the steps that I have done during the design of my robot's gripper:

1. **Initial study**

Before of starting the 3D model in the software, we must do an initial study of the grippers in the market, the possibilities for the gripper, the advantages and disadvantages…

2. **Design of the model in Autodesk Inventor Professional 2012.**

First of all and after all the decisions that we have to take to get the best design of the gripper, we must create our gripper's 3D model in my computer.

3. **Possibilities of improvements for the gripper.**

Once we have our possible final design, we must think about all the improvements that we can introduce in our model with the goal of getting a perfect gripper.

4. **Calculate all the forces generated in the gripper.**

When we have the final model we need to calculate the forces exerted by the gripper, to know the kind of objects that we are ready to take.

5. **Save all the pieces in STL format.**

For doing possible the 3D printing, we have to save in the computer all the pieces in STL format.

6. Send the pieces in STL format to the 3D printer.

Once we have saved the pieces in the correct format we can send them to the printer and we can start to print them. We have to connect the computer with the printer and select the size and the orientation of each piece.

7. Preparation of the printer.

We have to add the plastic material or other material (in our case PLA) to the printer.

8. Printing.

We start to print all the pieces we need. It's not a fast process so we have to wait and be patient. The thickness of each layer is between 0.1 and 0.2 mm.

9. Take the pieces.

When the piece is ready we can take it. Please be sure that the machine is not hot and you have wait the necessary time.

10. Retouch of the pieces.

As I have explained before, the printer has a good accuracy but the pieces are not perfect for the assembly of the gripper. We need to retouch all the pieces until they are perfect (sanding, wetting…).

11. Build the assembly.

Once we have all the pieces in perfect conditions, we can build the assembly. But we must be careful if we don't want to mess up all the work we have done.

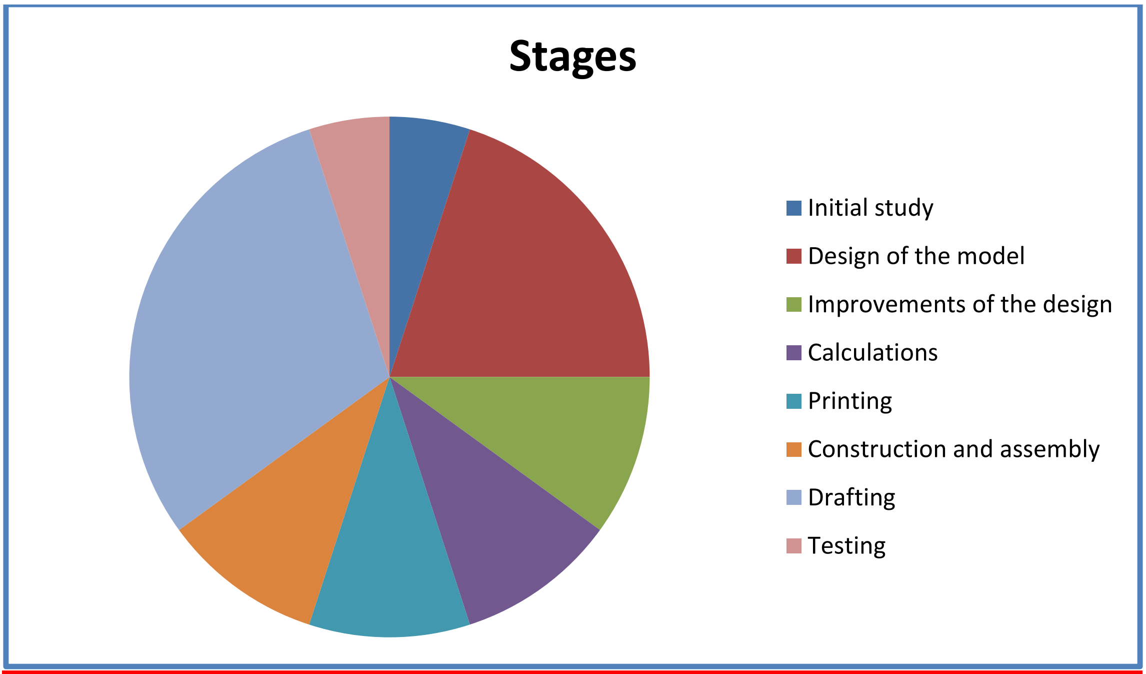
12. Testing the gripper.

Finally, we can check if the gripper works correctly and we have the option of test it in a robot's arm.

13. Checking of the forces.

Now we can check if the real forces are similar to the theoretical forces. It's difficult to obtain similar forces because it depends on a lot of parameters that affect to the gripper.

1.8.1 Diagram of the stages



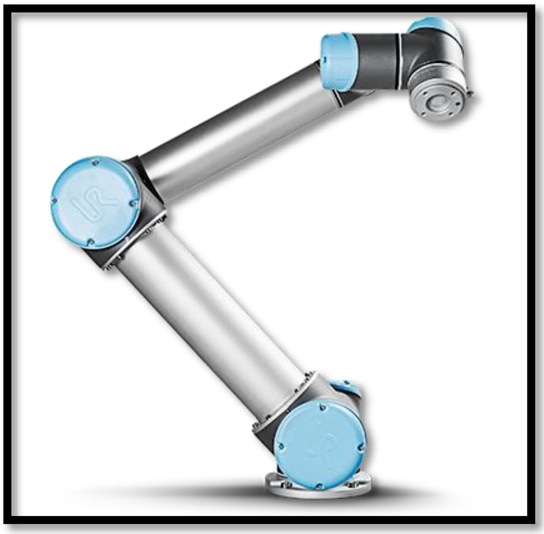
[36] – Diagram of the most important stages to get the gripper

As we can observe in the diagram the largest processes are the design of the model because it requires a lot of time thinking about the shape, the thickness, the movement… and the drafting because it is, maybe, the most important part of the project. All your work is summarize in these pages so you must do your best.

1.9 Applications and examples of real grippers.

Nowadays, the robots and the robotic grippers have a lot of applications, especially in the world of the industry. I'm going to explain some of the applications and to show some real examples that we can use in these applications:

- **Collaborative robots:** A lot of grippers are used in this kind of robots. Collaborative robotic arms are easily integrated into existing production environments. With six articulation points, and a wide scope of flexibility, they are designed to mimic the range of motion of a human arm. Robotic grippers share the same values as collaborative robotics by being human scale, flexible and easy to use.



[37] – Image of a collaborative robot where you can insert some grippers.

We can observe in the picture one collaborative robotic arm, and in the end of the arm we can insert a lot of kind of grippers like the following ones:

[38] – Possible grippers to insert in the collaborative robots

- **Assembly robots:** This kind of robots streamlines the processes and improves its accuracy and efficiency. These robots can perform tasks tedious and boring assembly to leave the factory staff to other jobs, while at the same time improving quality. Robots work 24 hours a day all year without a break. Downtime is eliminated, reducing labor costs and provides a high return on investment.

[39] – Example of an assembly robot

We can insert in this robots grippers like this one that provides the flexibility to handle various operations with a wide range of parts:

[40] – Possible gripper to insert in assembly robot

- **Advanced manufacturing:** A flexible robotic hand or gripper and a force torque sensor create a perfect combo that can be used on your platform for a wide range of Advanced Manufacturing and R&D projects.

[41] – Example of robotic hand in Advanced Manufacturing

- **Machine tending:** We can use a **single, programmable, flexible robot gripper** to handle a wide variety of parts in your machine tending applications.

[42] – Example of gripper used in machine tending

- **Robot welding:** Is the use of mechanized programmable robots, which completely automate a welding process by both performing the weld and handling the part.

[43] – Example of gripper of a robot welding

We can observe that the gripper is not the same design that our gripper but is interesting to see the quantity of different grippers that you can discover in the market.

We can find more and more applications for robot's grippers but these are the most interesting that I have found. However, I would like to name some of the other applications:

- Part location
- Part identification
- Bowl Feeding
- Conveyance
- End-Effectors
- Tool Changing
- Force Sensing
- Part Fastening or Joining
- Error Proofing
- Visual Inspection
- Foundry Work
- Application of materials
- Application of sealants and adhesives
- Court
- Mount
- Palletizing
- Quality control

1.10 Possible Improvements

I have designed a structure easy to include improvements for future project. We can highlight the next possible improvements:

- **Design of the gripper:** I have designed the simplest gripper because of my budget but in future projects with a bigger budget it's possible to include a magnetic gripper, a gripper with more than one finger… There are a lot of changes and improvements that we can do in our gripper, it only depends on the budget we have.
- **Design of an arm:** It's possible to use this robot's gripper to include it in a robotic arm. We can design that arm according with the wrist of the gripper that we have done.
- **Inclusion of more degrees of freedom**: Because this project is the design of only the gripper is difficult to include a lot of degrees of freedom but there is the possibility if you continue designing the arm of include more degrees of freedom that allow taking objects in a lot of different positions.
- **Electrical and digital design:** My goal of this project was the mechanical design of the gripper but once we have this design, we have the possibility to improve the design including a digital and electrical design, controlling the gripper with a joystick, controlling the angle and the force that we need to exert… We can introduce also a system to control the gripper with the computer. There are a lot of possibilities but it requires a lot of time.

- **Adding elements:** We can add a lot of elements with the goal of improve the gripper. I have think in some things that we can add:
    - A sensor to detect when an object is between the grippers.
    - A small drill to provide to the gripper of other functions.
    - A small laser apparatus.
    - An automatic screwdriver.

1.11 Conclusions

At the beginning of this project some main goals and secondary goals were settled. All of those goals have been fulfilled:

- We have achieved the main goal that is the design and manufacturing and construction of a robot's gripper.
- We have designed one robot's gripper with a good structure to insert improvements and changes and it's a good chance for other people who like this kind of projects to start a new design with this one as base.
- Personally, I have learnt a lot with this project, especially, about the robotics and printing 3D world. I have discovered that the robotics world is going to be, probably, a very important area in the future and it can help in a lot of industrial processes.

As final conclusion, I would like to say that all the process of the project has been a success so I'm very satisfied with this.

PIECES AND PLANES

2.1 The base

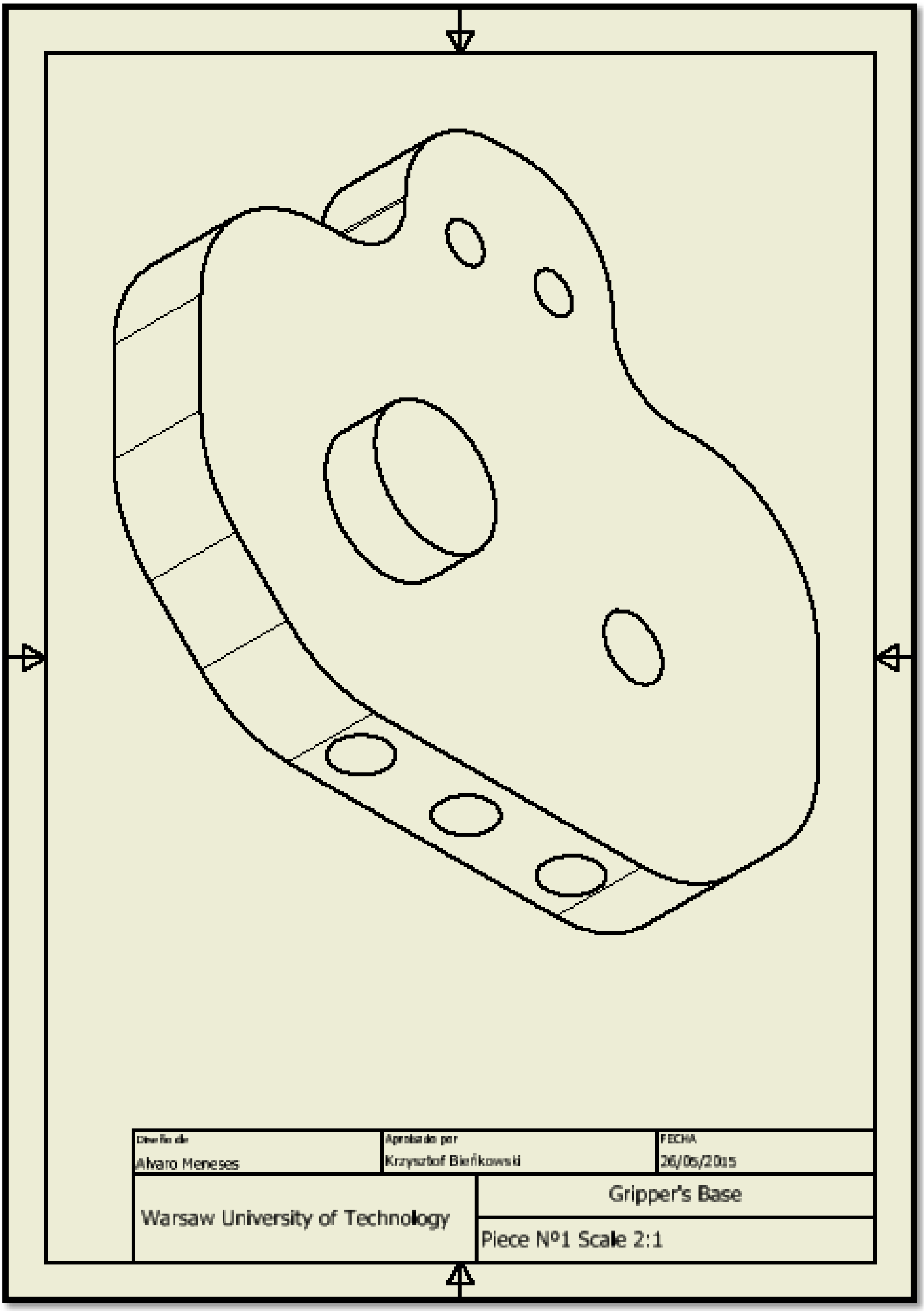
This is the most complex piece because every piece is connected to this one. The distances of this element must be perfectly calculated to get a good working of the entire mechanism. We have to take into account some critical aspects when we are designing this piece:

- **The rotation elements:** This aspect is one of the most importants aspects to take into account because if we want to get a translation movement avoiding the rotation of the gripper the length of the radius of rotation of the elements must be the same. To get this goal, we must calculate with a lot of precision where can we connect in the base all the rotation elements and the correct distance between them.

- **Gears:** Other important aspect is the placement of the gears. They should be rightly located in the base to get a perfect movement of the gripper. It's very important when we are designing the base to think that one gear y connected to the servomotor that must be fixed to the base and the other gear has to be hooked to the base but allowing its movement.

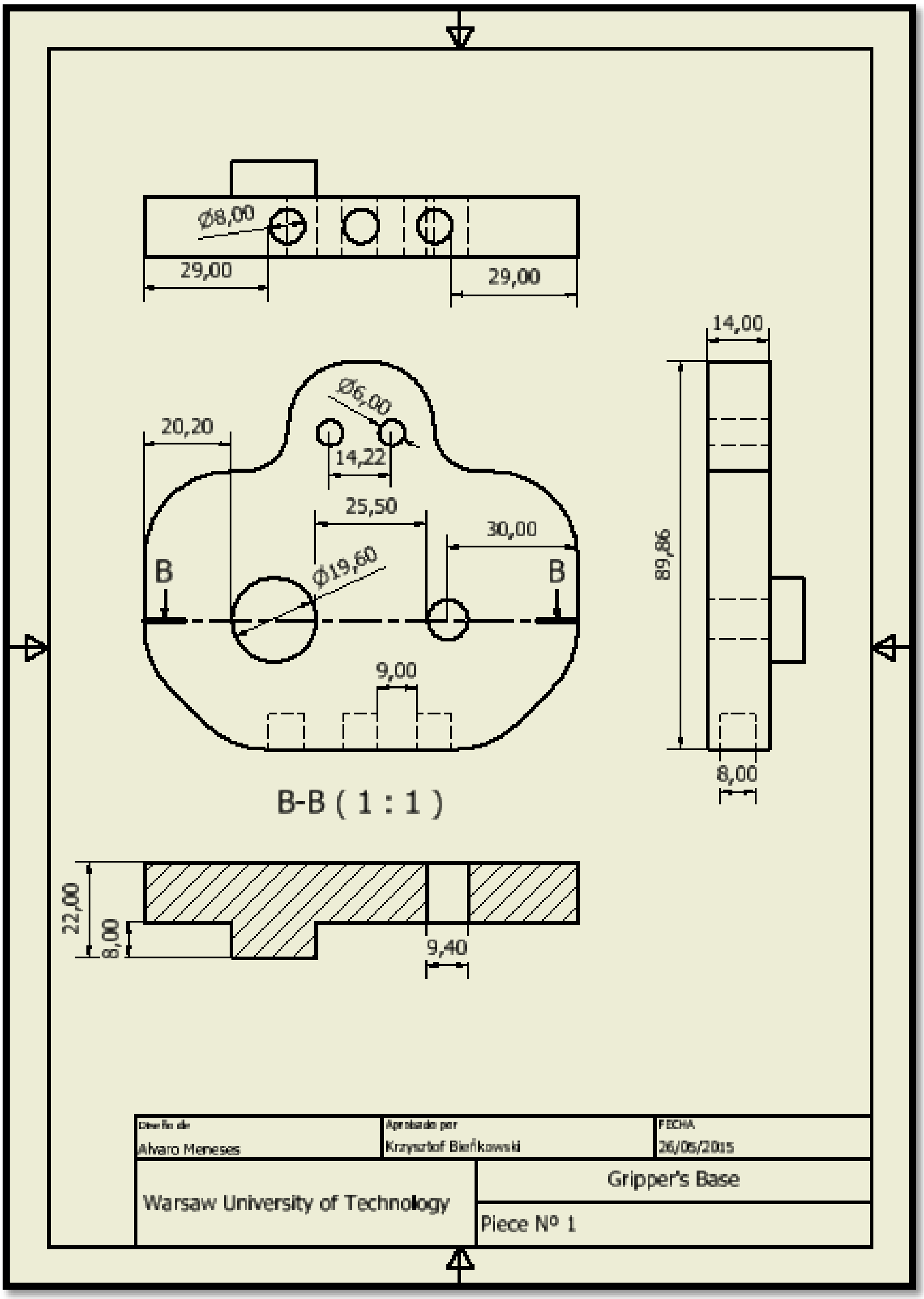
- **Servomotor:** The servomotor provides the movement to the gripper through the connection of this with the gears. This servomotor is fixed to the base.

In this first plane [44] we can see the perspective view of the base. We can appreciate in the middle of the base one outgoing part and one hole. The outgoing part is to fit the left gear and the hole is to connect the right gear to the servomotor through a link-up. In the bottom of the base, we can observe three holes, these holes are used to link the base with the wrist. In the top of the base, there are two holes used to connect the link-up between the base and the gripper.



[44] – Isometric view of the base

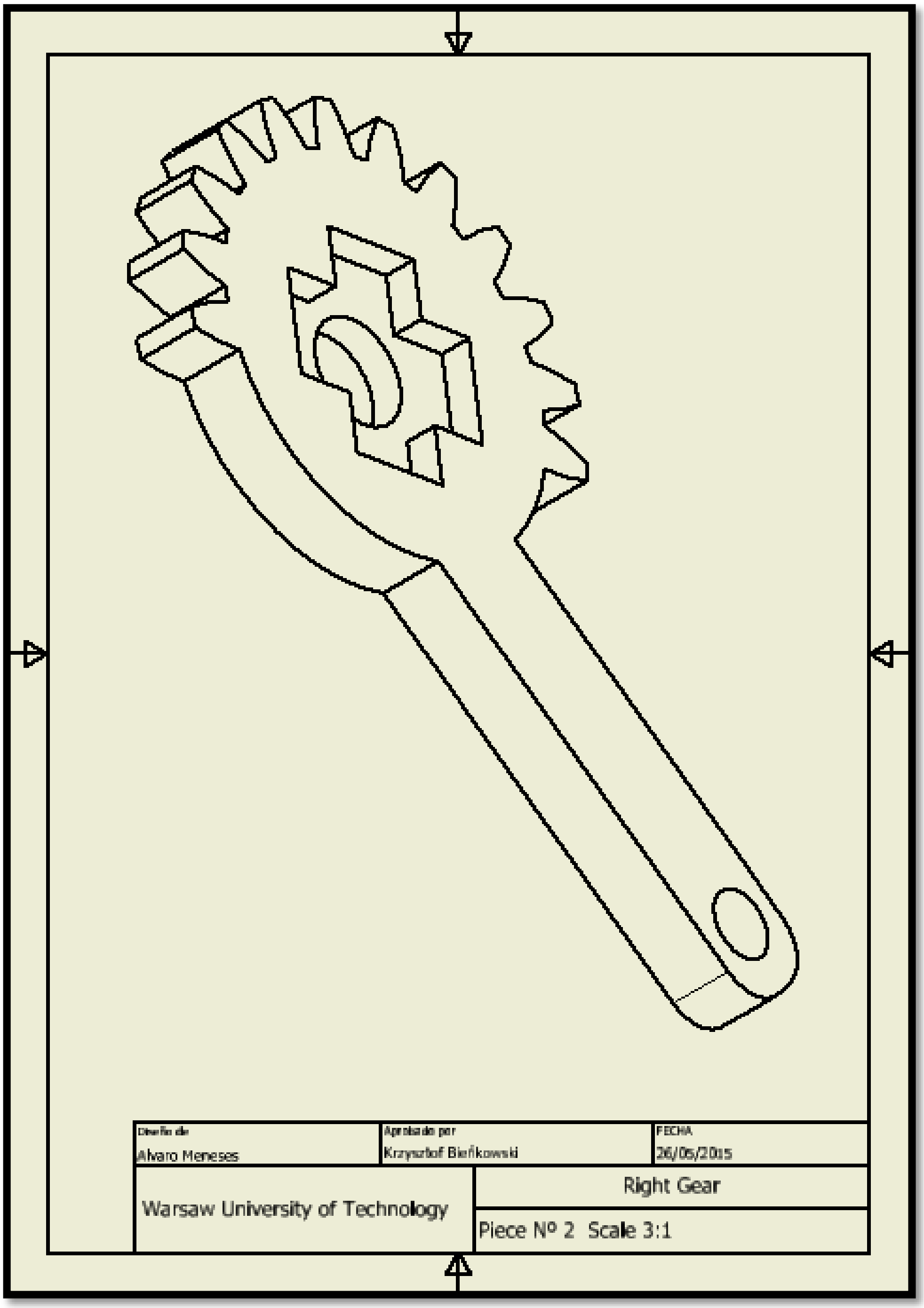
In this plane [45], we can appreciate the views of the base with some of the measures. During the project I'm going to include the planes of every piece with the goal of being a reference to other future projects. However, in some pieces there aren't all the neccesary distances because it could mess up the planes, but the most important measures to build the pieces are marked. We can observe the three important views to determine a piece and a sectioned view in order to get a better view of the piece. The scale of the plane is 1:1.



[45] – Plane with views and measures of the base

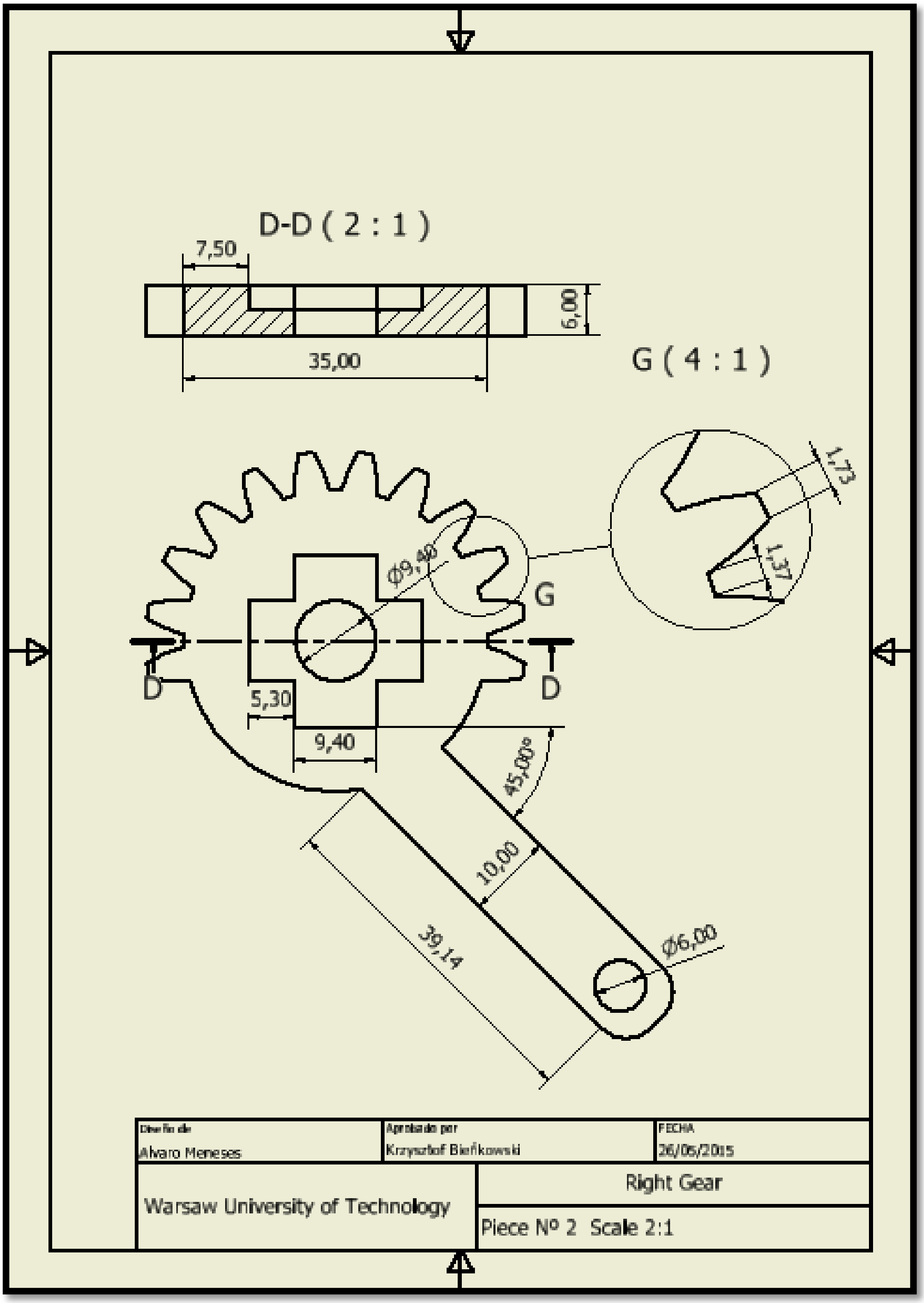
2.2 Right gear

This gear consists in a cogwheel but not all around but in more than a half of its contour. It is connected to the servomotor through a link-up with cross shape as we can see in the perspective plane [46] and it is supported on the base. The outgoing part is used to connect the gear with the gripper. This gear is the responsible for transmitting the rotation to the other gear, it is called drive wheel.



[46] – Isometric view of the right gear

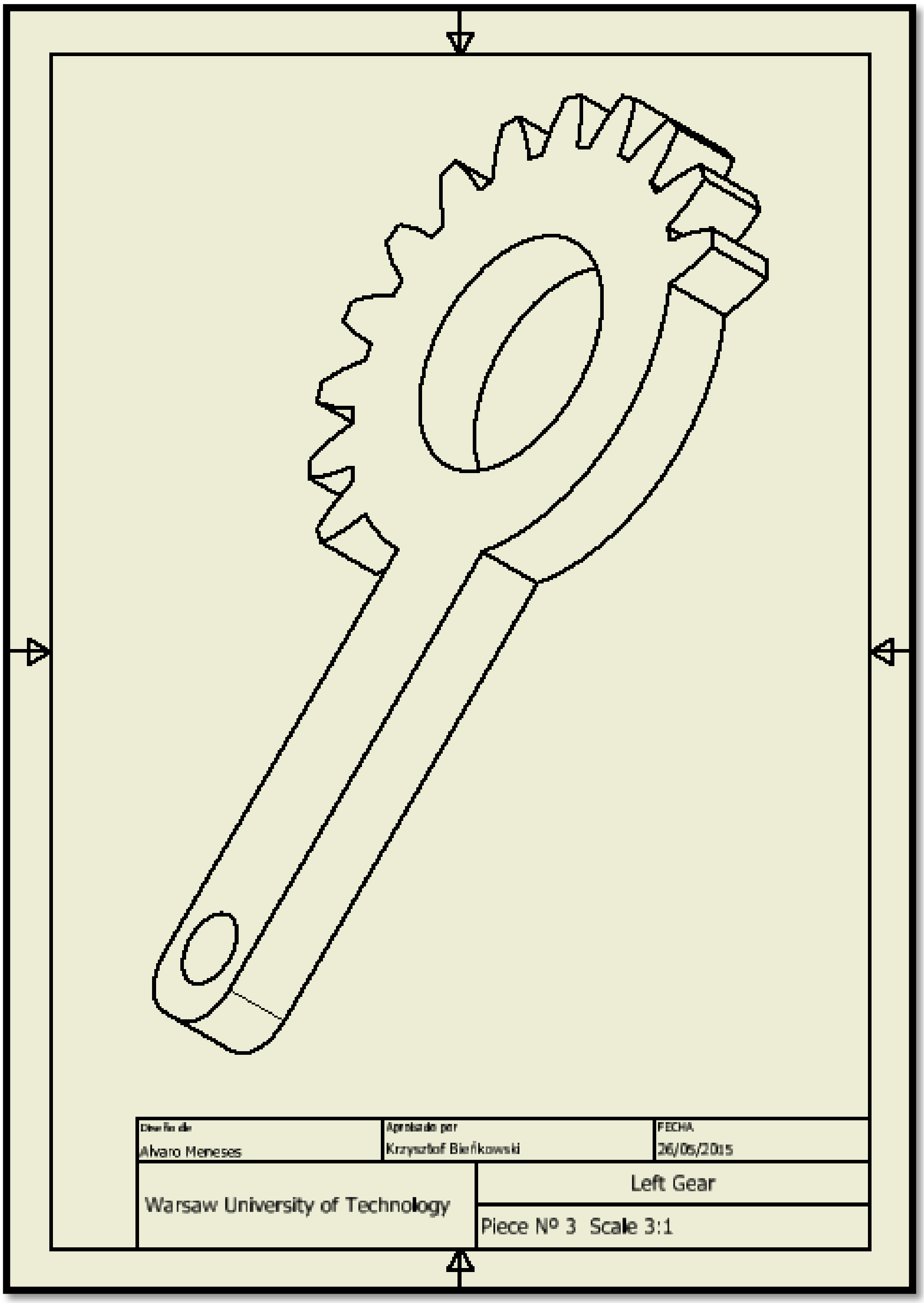
In this plane [47] we can see three different views: the frontal view, the top view sectioned and a detailed view to notice with total clarity the measures of the teeth of the gear. The scale of the plane is 2:1.



[47] – Plane with views and measures of the right gear

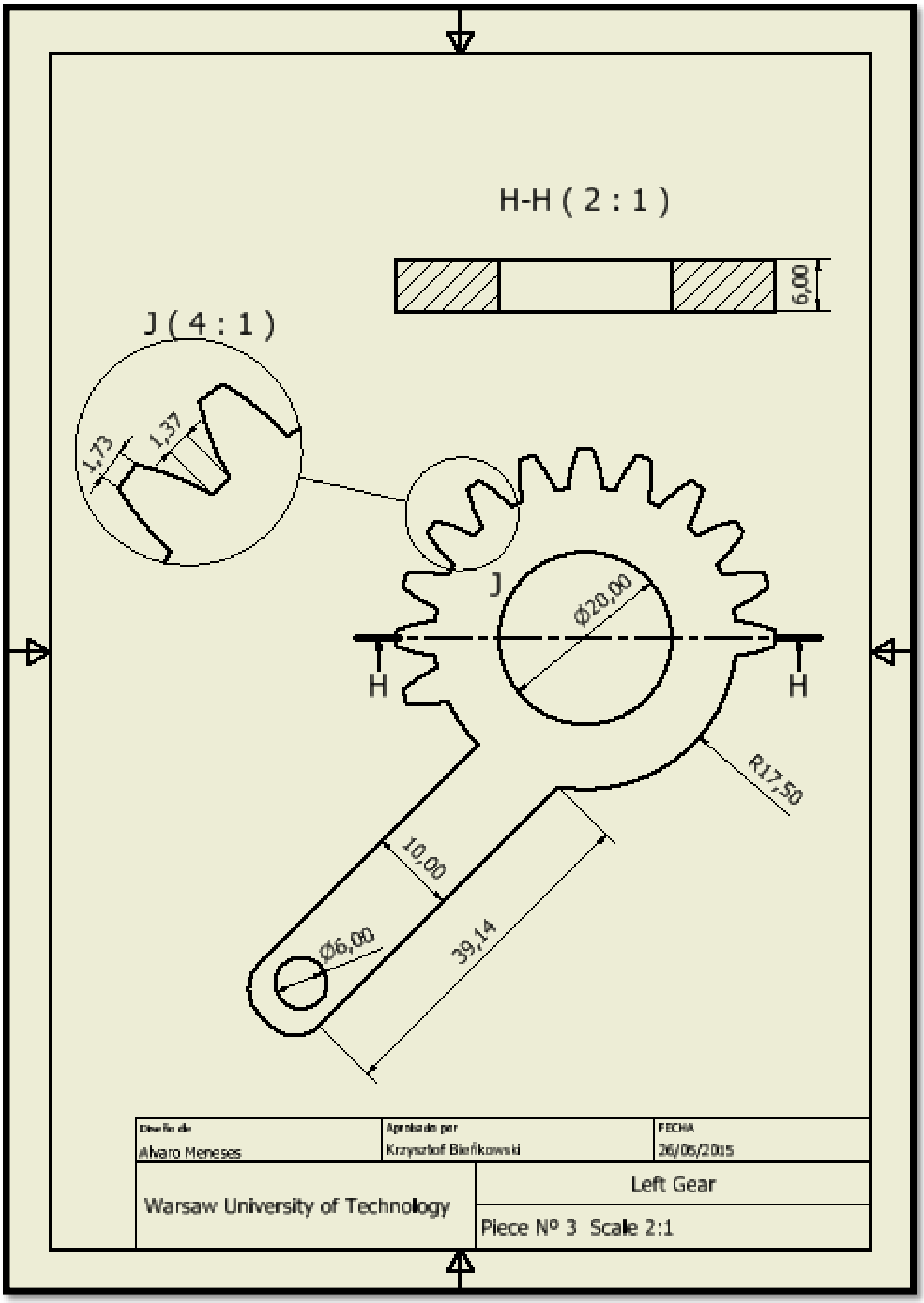
2.3 Left Gear

This gear is a cogwheel like the other but this is connected to the base through the big hole that we can see in the plane [48]. It's also supported on the base. The rotation of this gear is due to the other gear, so this gear is called driven wheel.



[48] – Isometric view of the left view

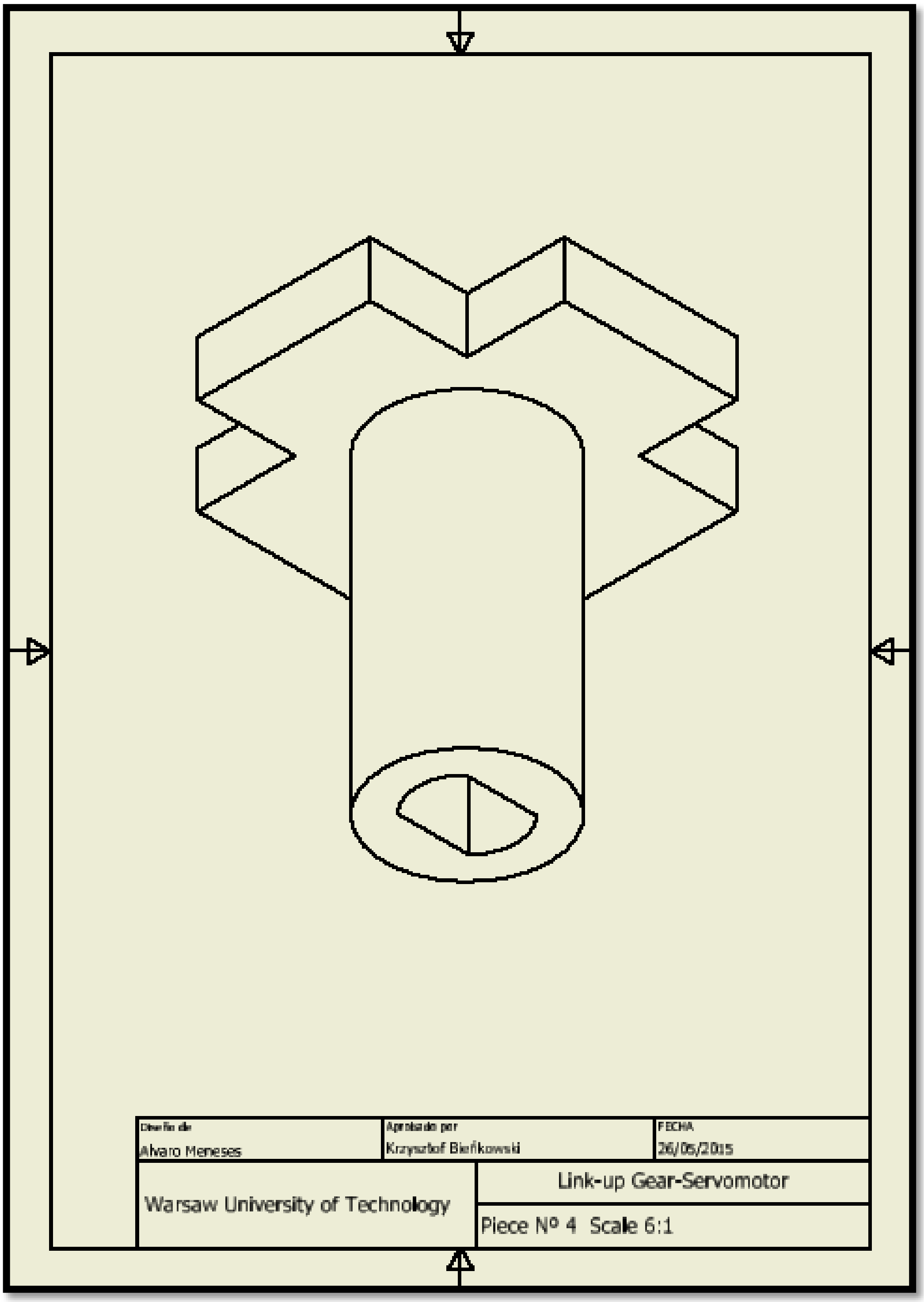
We can observe in the plane [49] the same views like the other gear, and I think is perfectly defined on this way. We can check that the measures of the teeth in the right and left gears are the same so this is very important to the working of the mechanism.



[49] – Plane with views and measures of the left gear

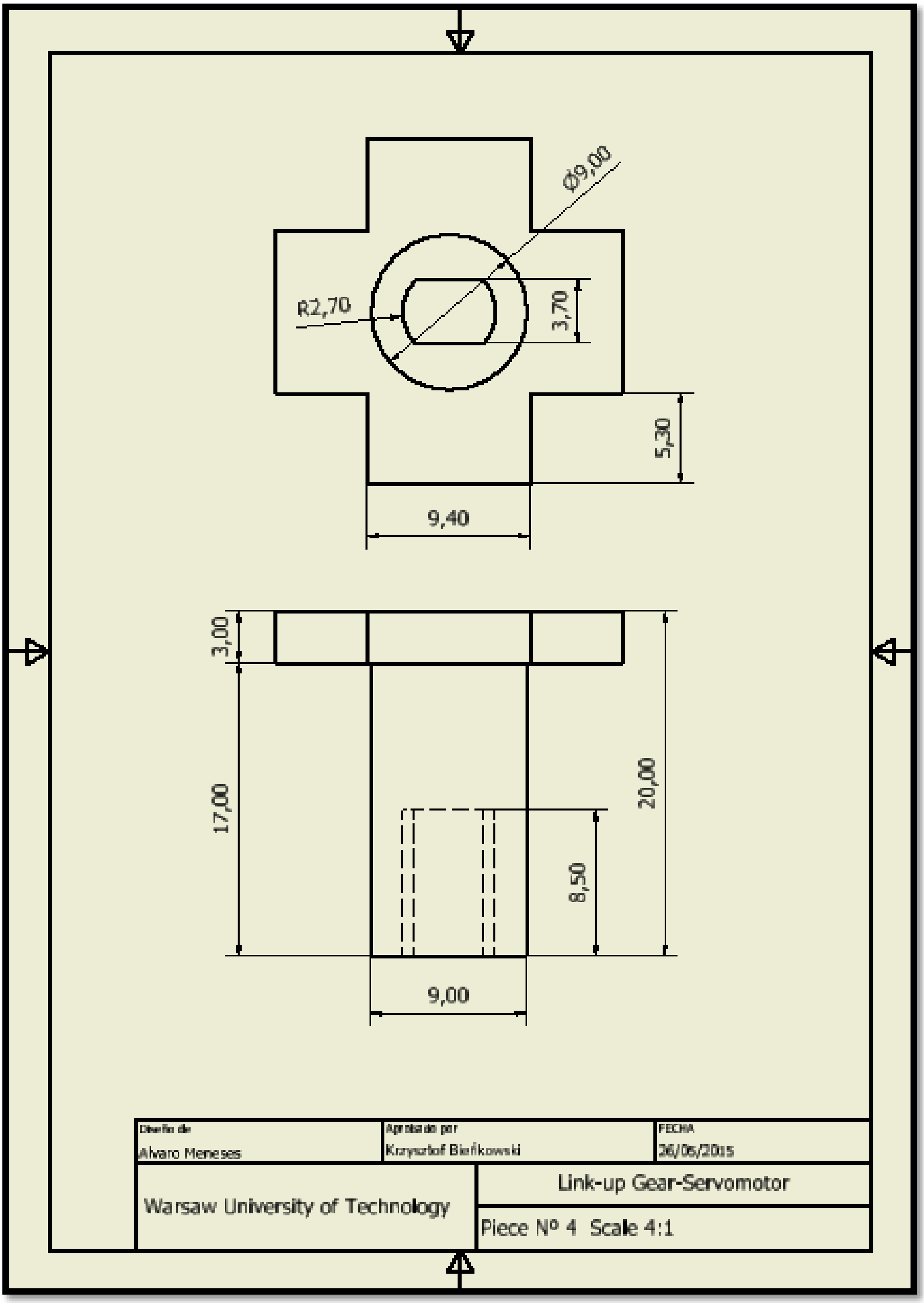
2.4 Link-up Gear-Servomotor

This element is very important because is the responsible for the movement of the gear and, of course, of the gripper. It's the link between the servomotor and the gear. The shape of a cross is because is more efficient than another shape and with this shape the movement is transmitted very well.



[50] – Isometric view of the link-up Gear-Servomotor

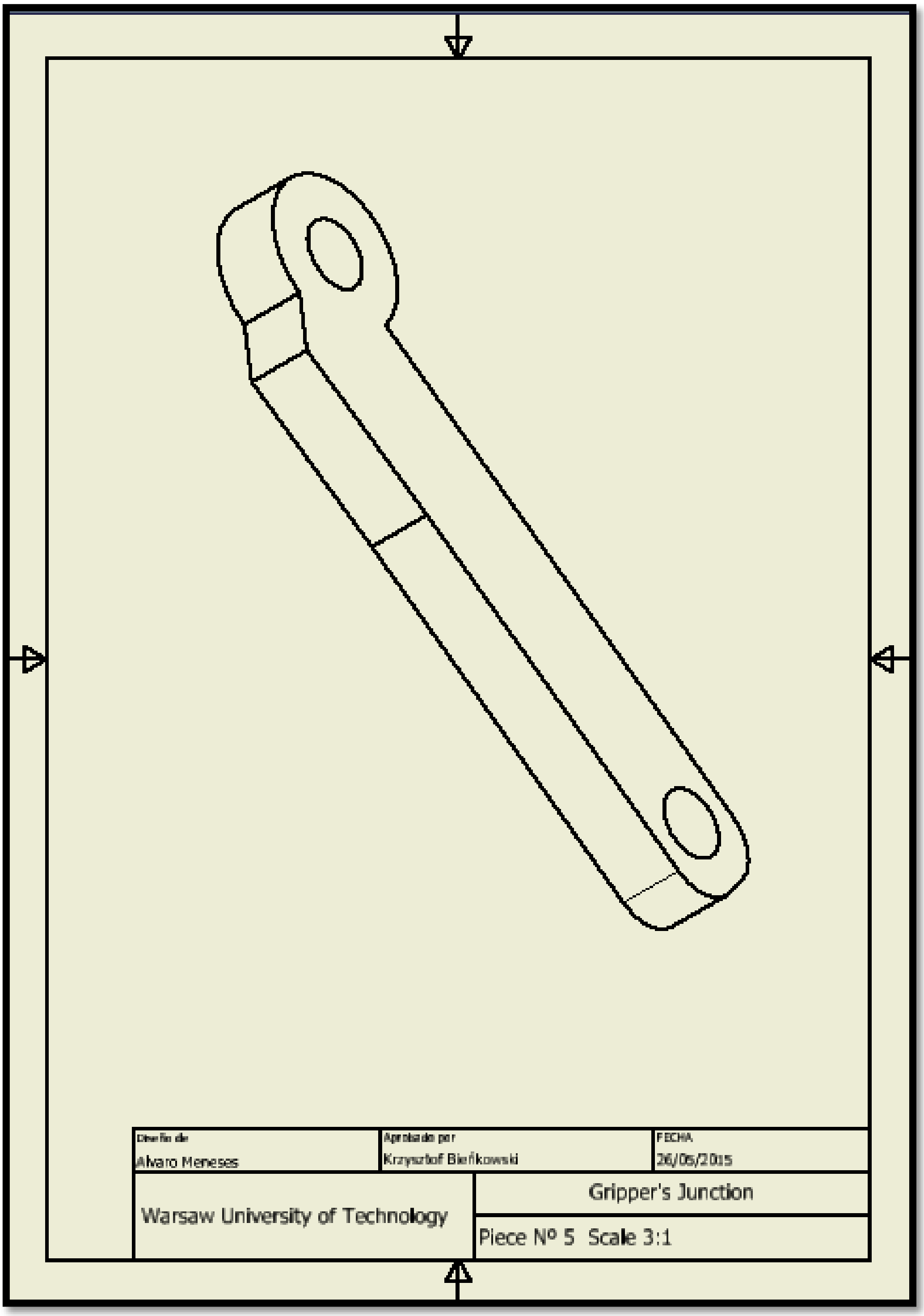
The plane [51] is done with a scale of 4:1. We can see that in the bottom of the piece there is a hole to introduce the axis of servomotor and transmit its movement to the piece.



[51] – Plane with views and measures of the link-up gear-servomotor

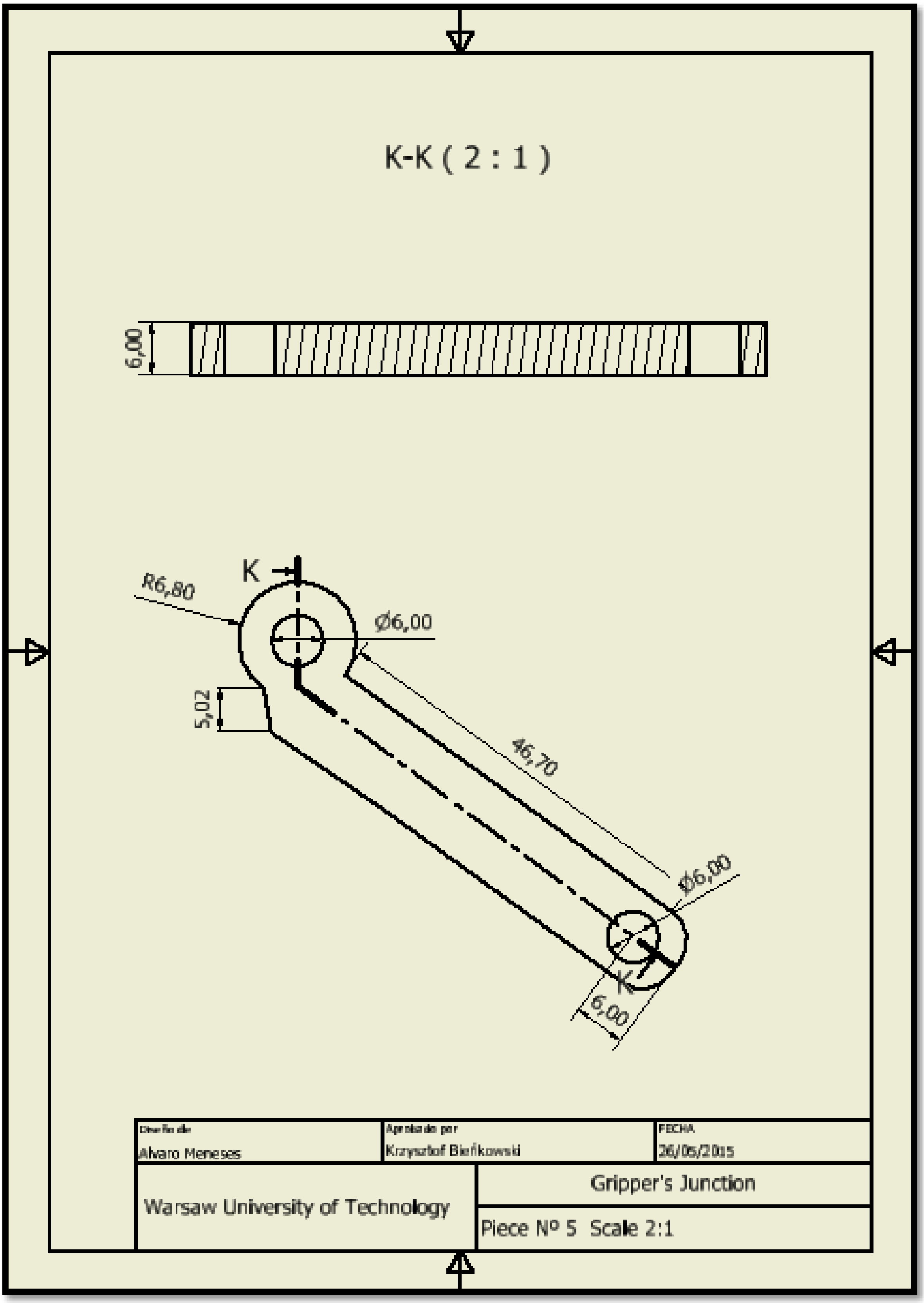
2.5 Gripper's Junction

This piece works as the connection between the base and the gripper. It has the same radius of rotation than the gear and it has also the same thickness to get good aesthetics. The holes of the piece are used to connect the element to the base and to the gripper.



[52] – Isometric view of the gripper's junction

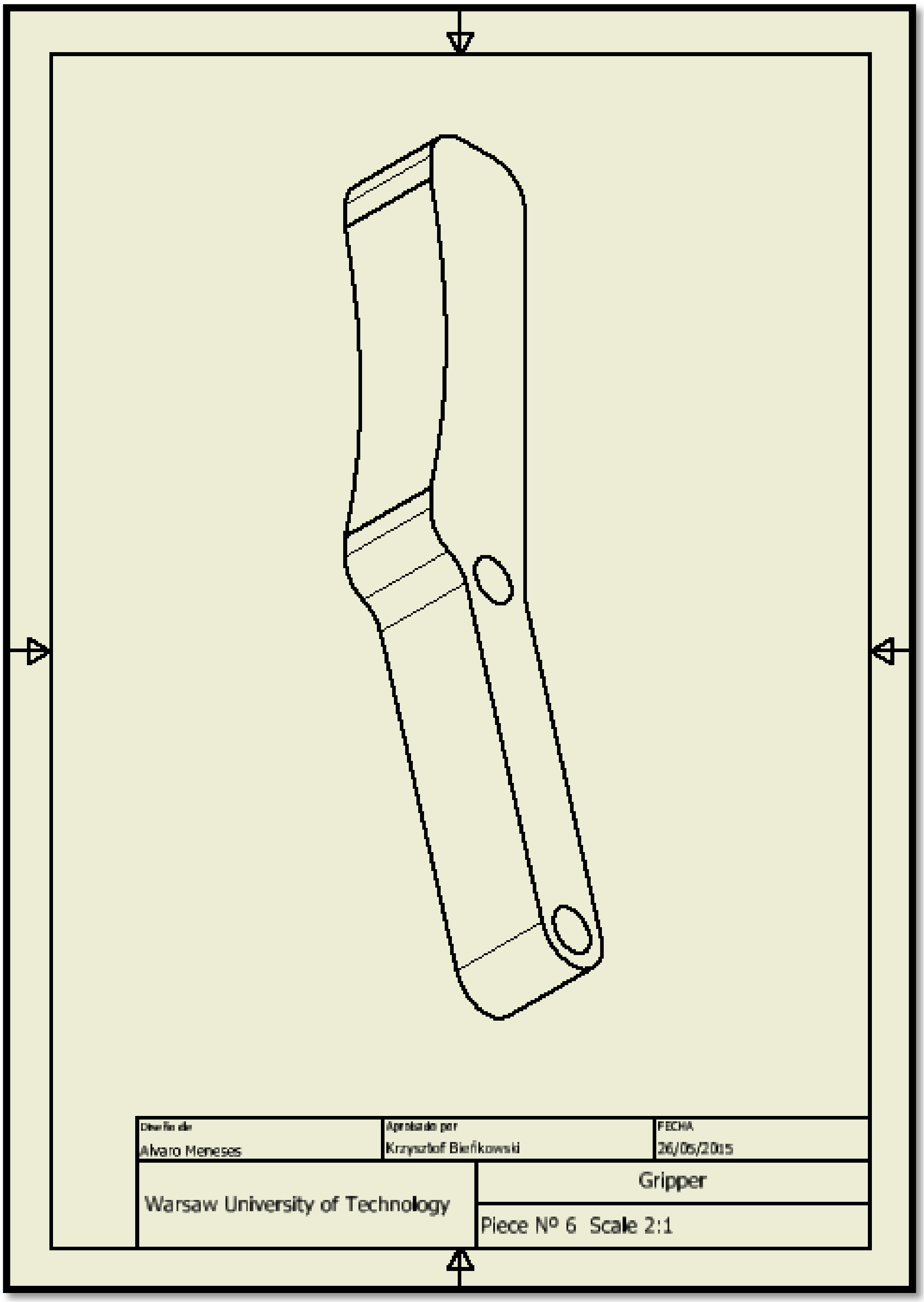
In this plane [53] I have done a different cut K-K with the goal of appreciating the two holes of the piece. The scale of the plane is 2:1.



[53] – Plane with views and measures of the gripper's junction

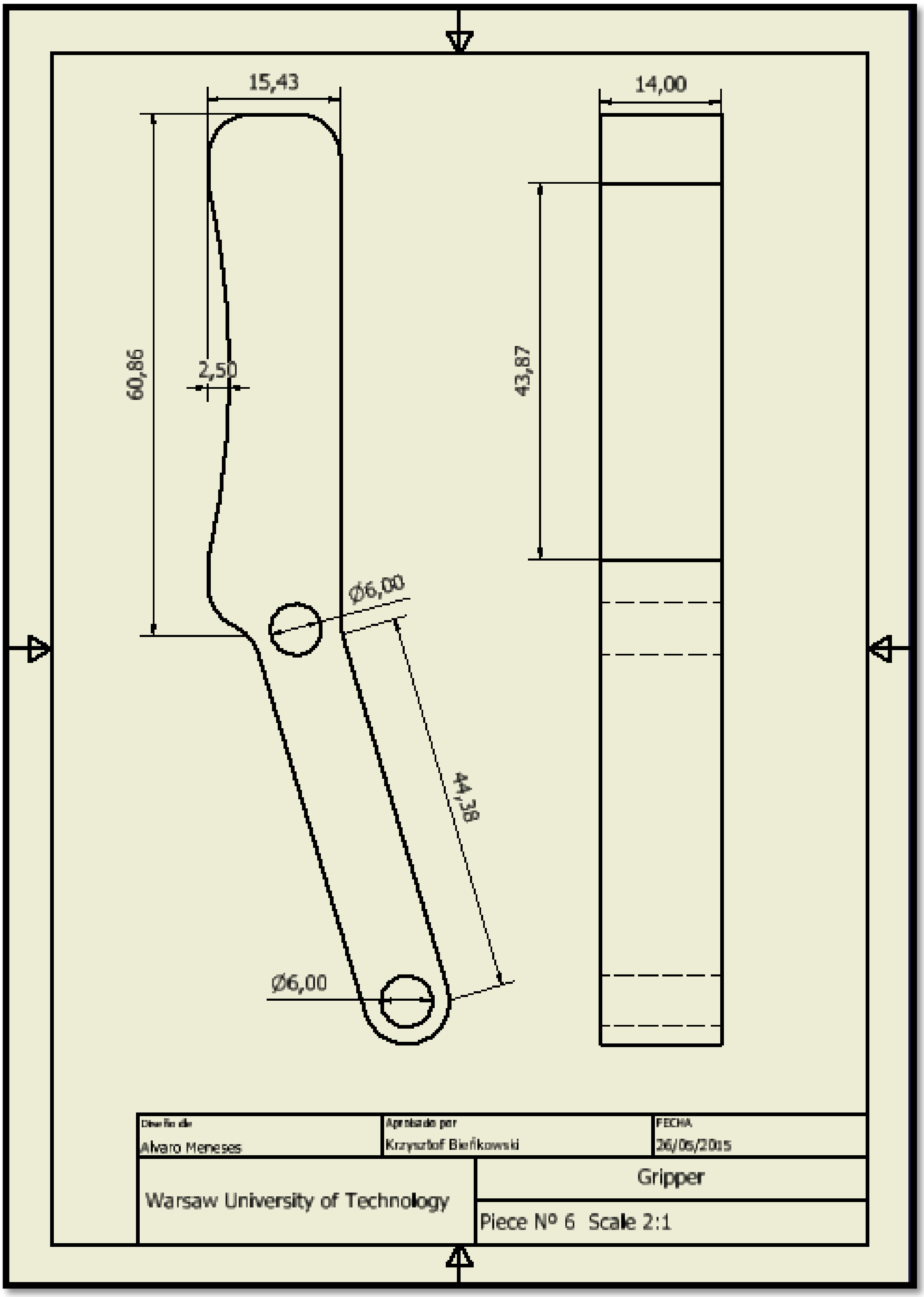
2.6 Gripper

The gripper is the final element, the working of every piece (servomotor, link-up, gear…) ends in the movement of this piece. The design of the gripper is the best possible to take the thinnest objects. The holes that we can see in the plane [54] are used to connect the gear and the junction gripper with the gripper.



[54] – Isometric view of the gripper

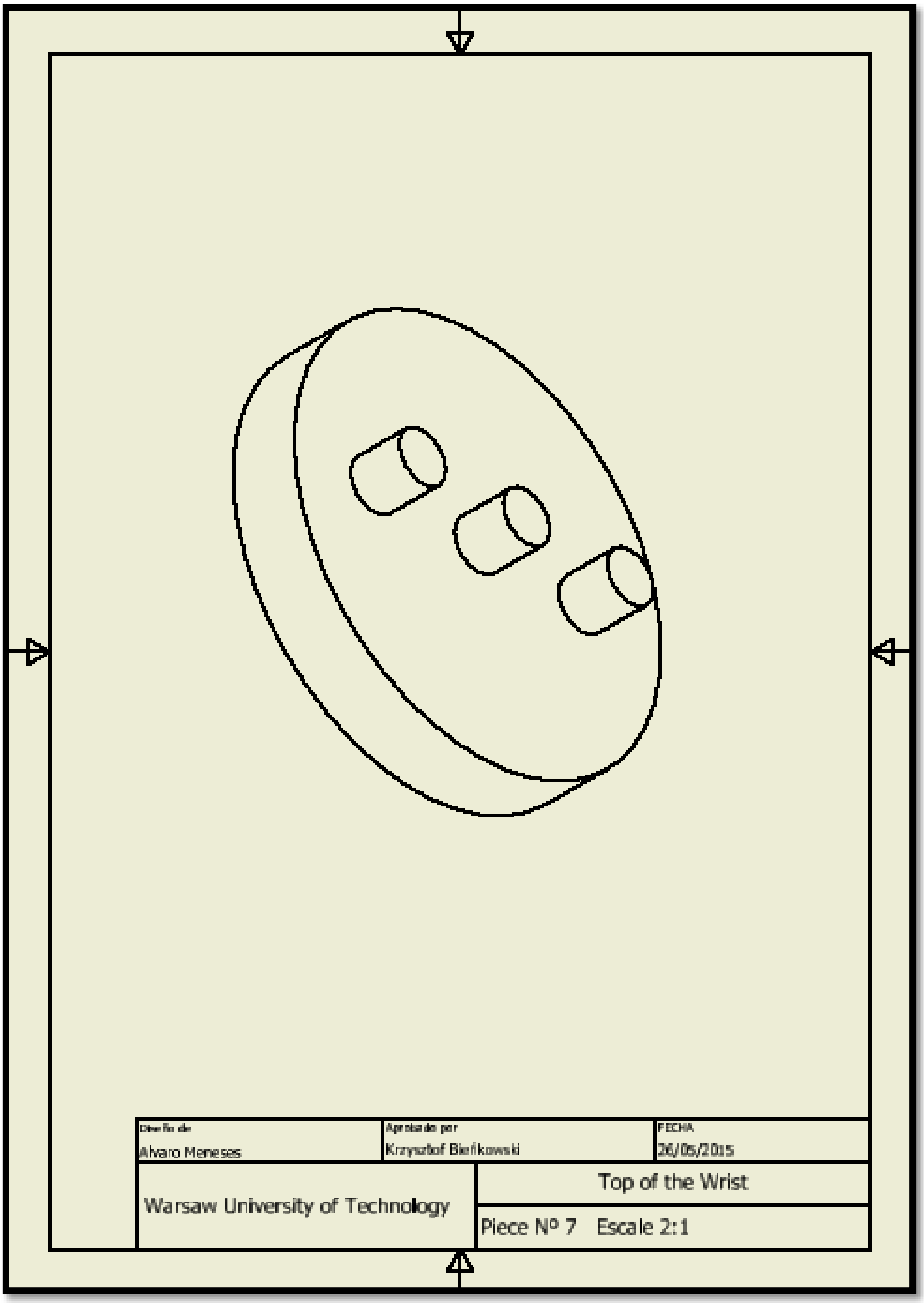
We only need two views to determine the measures of the gripper. We can observe is the plane [55] that the distance of the curve of the gripper with respect to the vertical axis is only of 2.5 mm so is really small. The scale of the plane is 2:1.



[55] – Plane with views and measures of the gripper

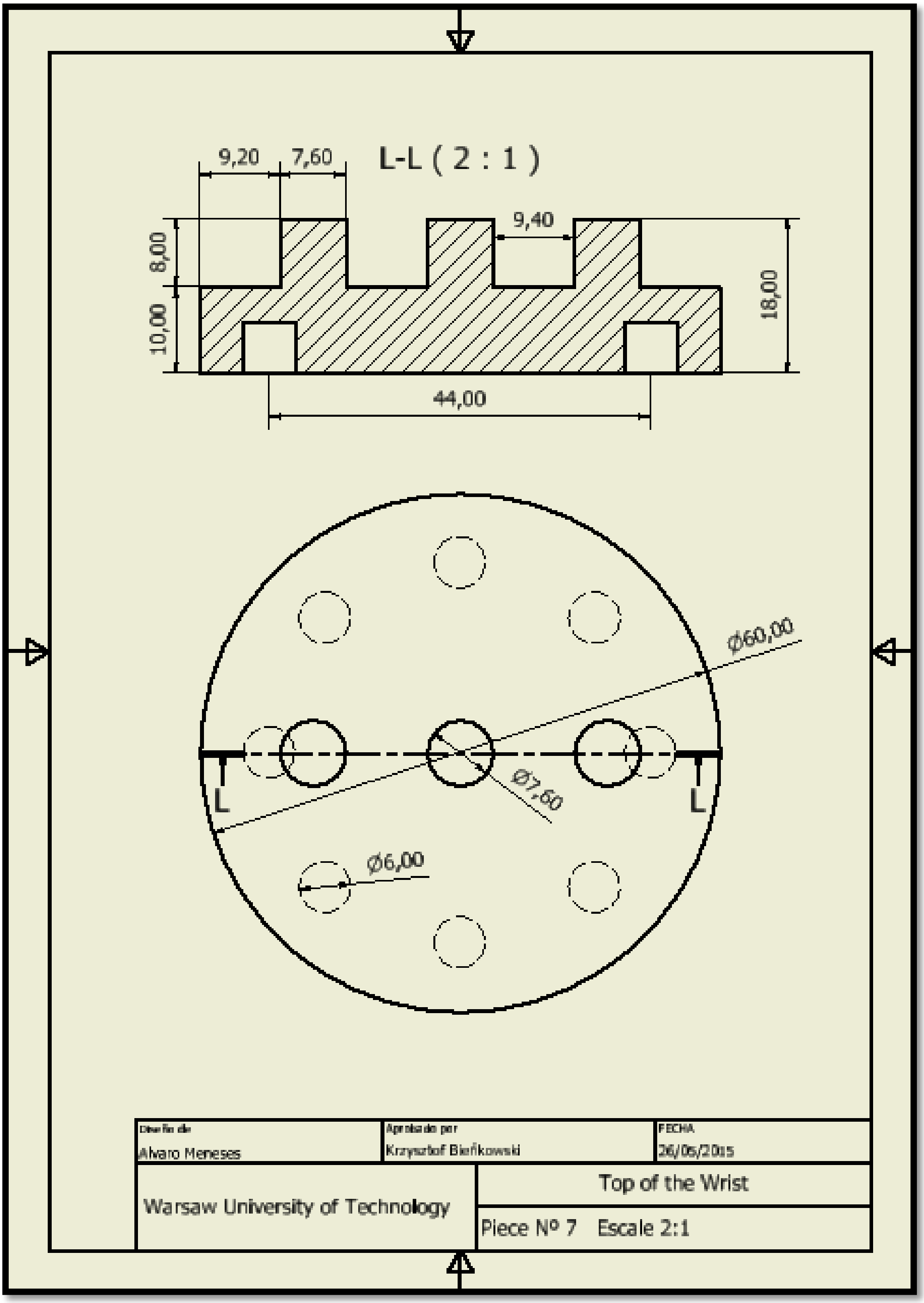
2.7 Top of the wrist

This element is the part of the wrist that connects the base to the wrist. The connection is through the three outgoing parts that we can distinguish in the plane [56].



[56] – Isometric view of the top of the wrist

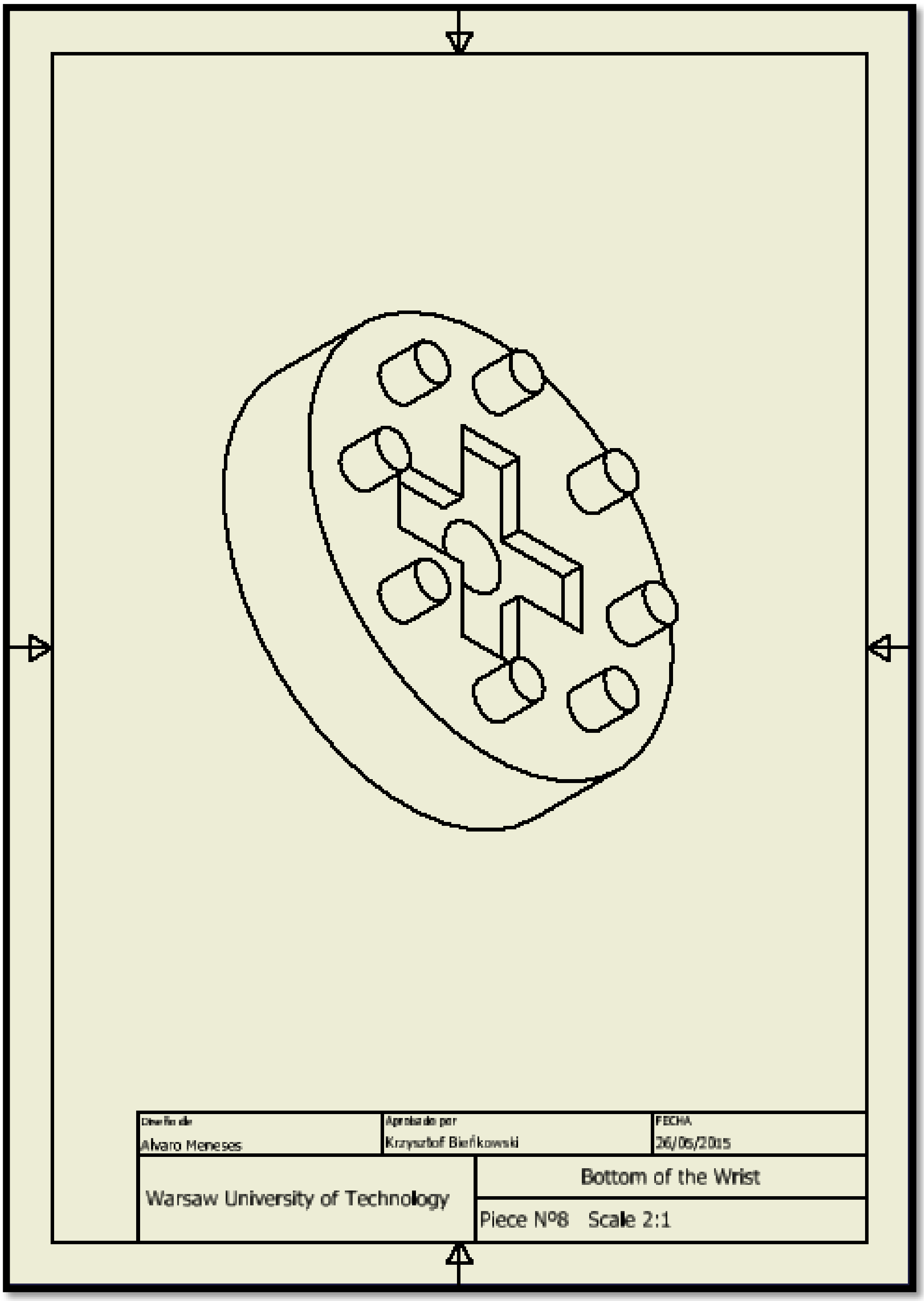
In this plane [57] we can perceive eight holes in the bottom of the piece that join the top of the wrist with the bottom of the wrist. I have use a cut to see the internal aspect of the piece. The scale of the plane is 2:1.



[57] – Plane with views and measures of the top of the wrist

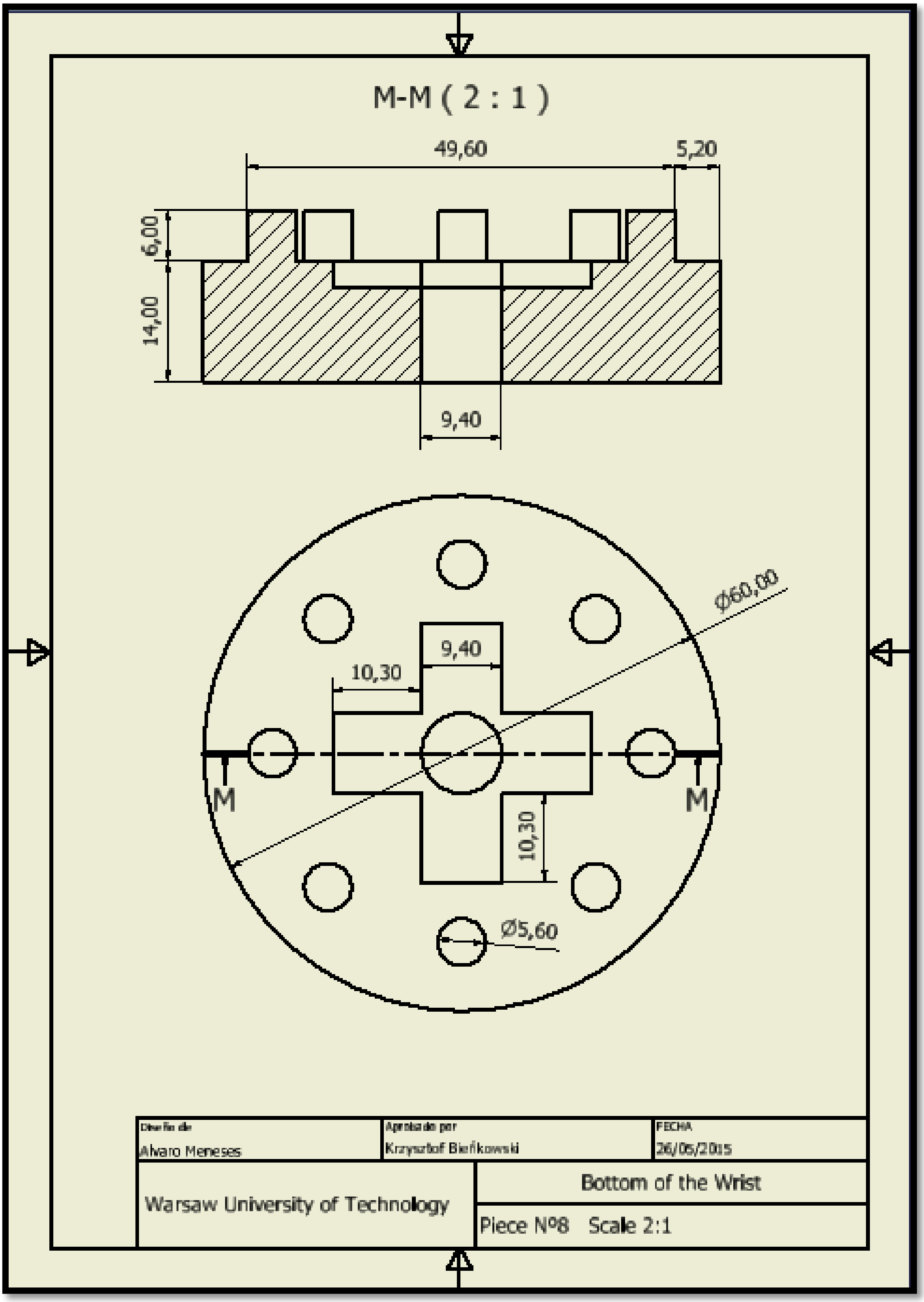
2.8 Bottom of the Wrist

The bottom of the wrist has two important functions: the joint between the top and the bottom of the wrist and the connection with the servomotor that gives the movement to the wrist. The first function is satisfied with the outgoing parts of the piece and the second function with the hole and the cross.



[58] – Isometric view of the bottom of the wrist

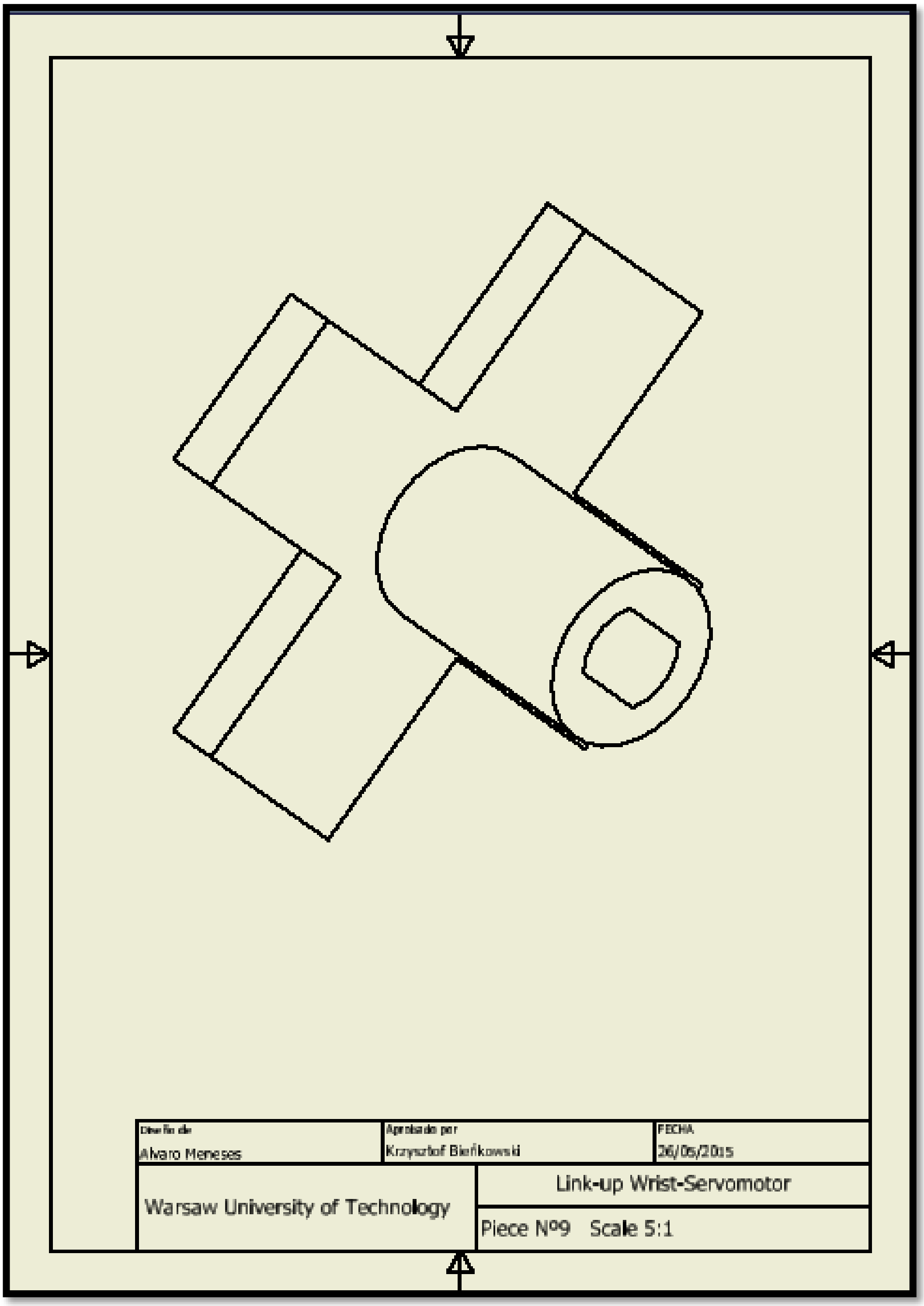
In this plane [59] we can appreciate perfectly the structure of the piece with the two parts to satisfy the functions that I mentioned before. The best way to observe inside the piece is doing the cut M-M. The scale is 2:1.



[59] – Plane with views and measures of the bottom of the wrist

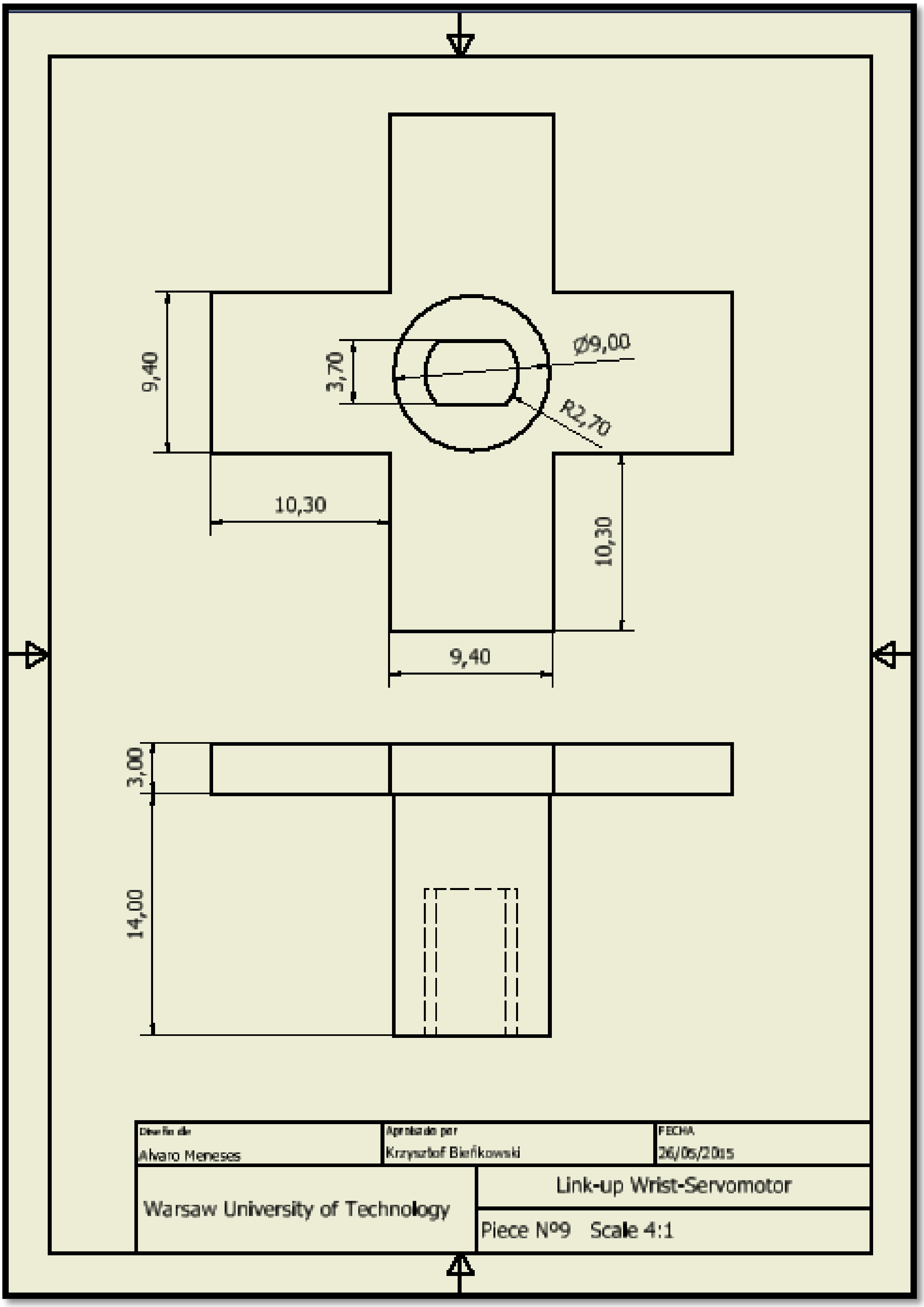
2.9 Link-up Wrist-Servomotor

This element is the responsible for the movement of the wrist, and with the wrist, the rest of the robot's gripper. It's the link between the servomotor and the wrist. Like in the other link-up the shape is a cross because is the most efficient possible to transmit the movement.



[60] – Isometric view of the link-up wrist-servomotor

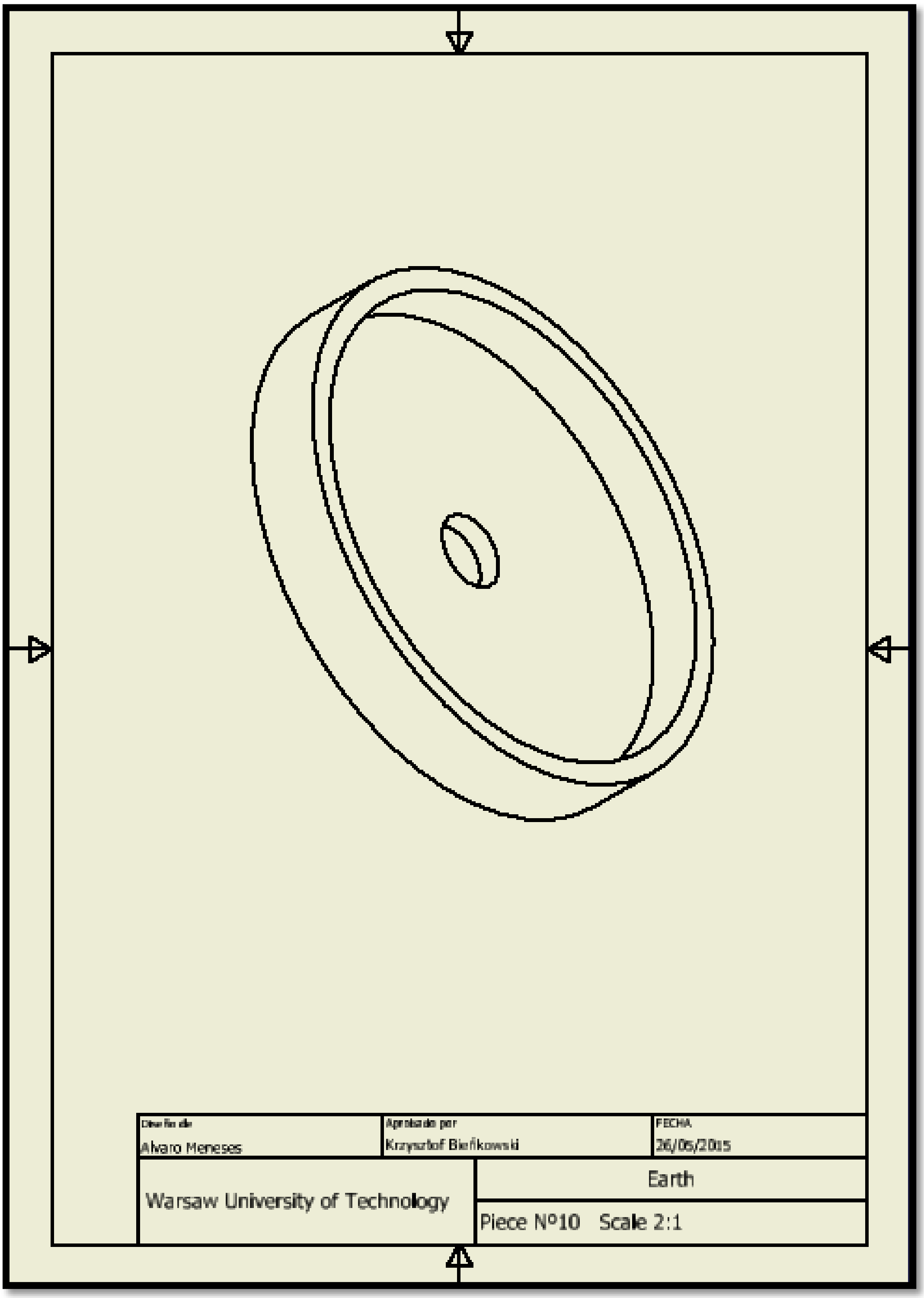
We can see like in the other link-up the hole in the bottom of the piece to insert the servomotor axis and transmit the movement to the wrist. The scale is 4:1.



[61] – Plane with views and measures of the link-up wrist-servomotor

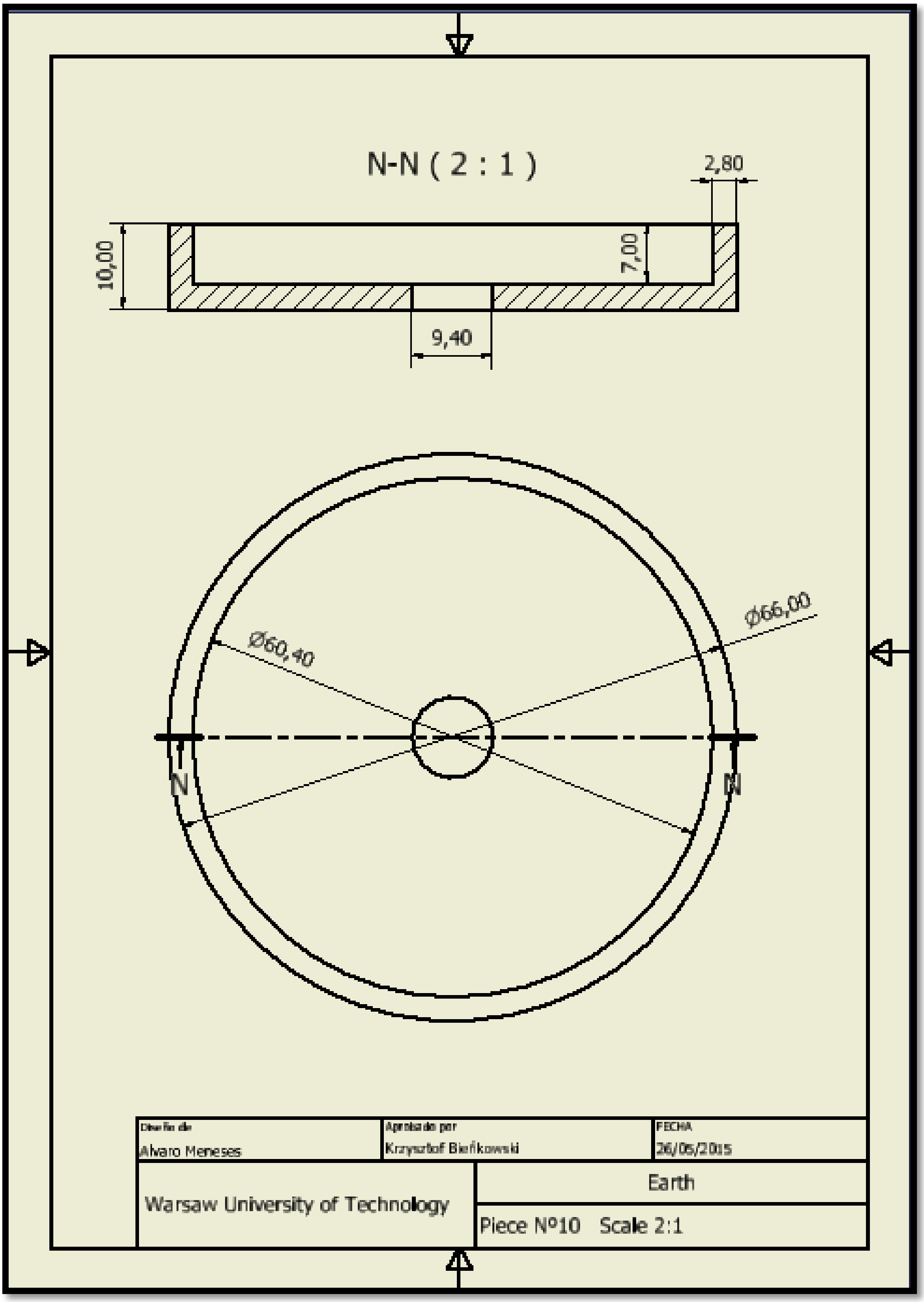
2.10 Earth

This piece is very important because is the responsible for the supporting of the servomotor. We will fix it to this piece with the goal of getting a perfect rotation.



[62] – Isometric view of the earth

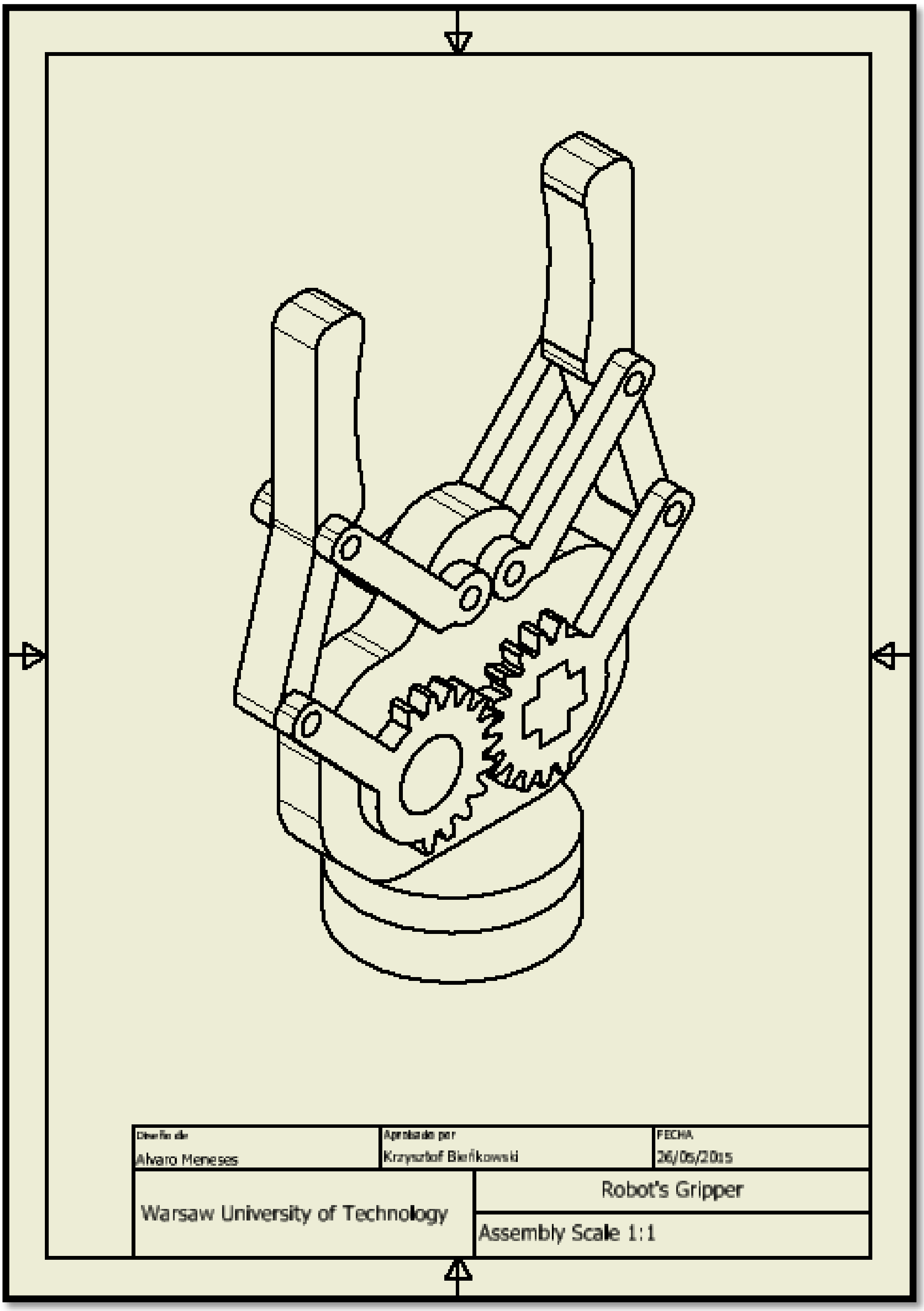
We can observe the piece [63] in a scale 2:1. I have made a cut to see the inner part of the piece.



[63] – Plane with views and measures of the earth

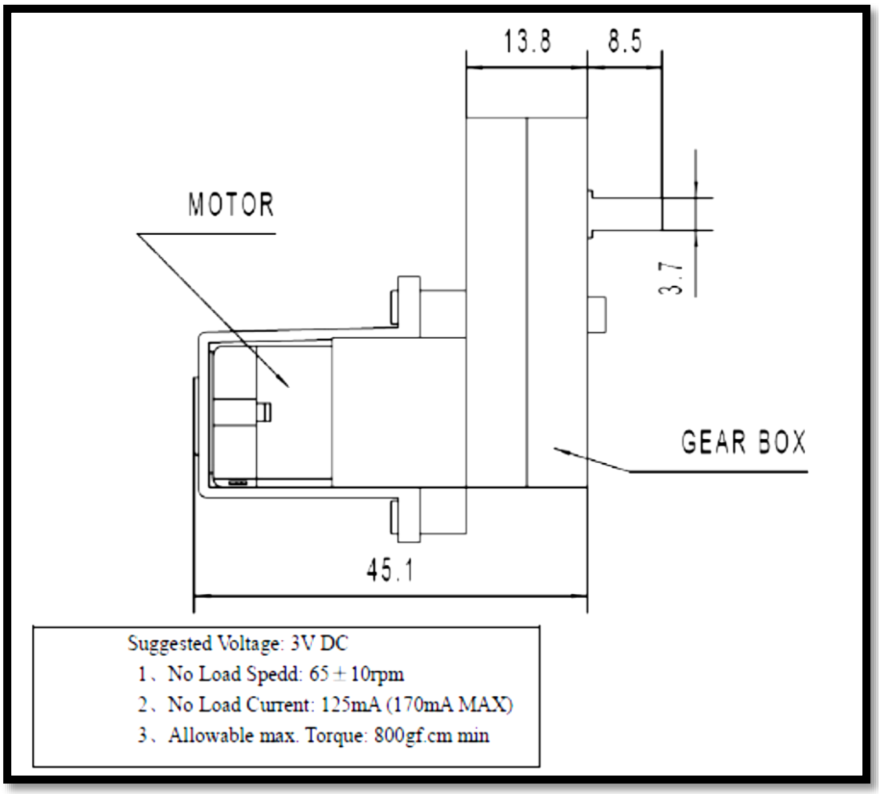
2.11 Assembly

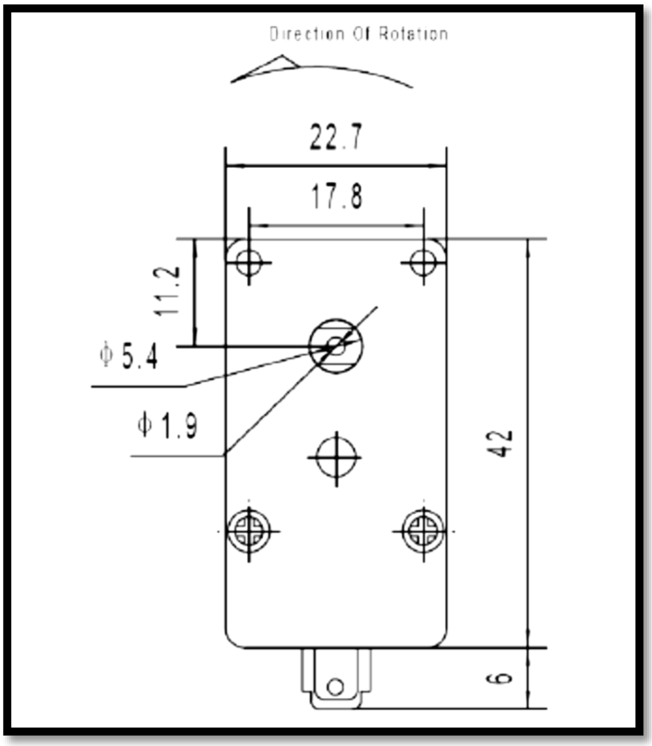
And this is the assembly of all the pieces that i have mentioned before. I think that the aesthetic aspect is very nice for the gripper, so I'm really satisfied with the result.



[64] – Isometric view of the gripper's assembly

2.12 Servomotor





[65] – Plane with views and measures of the servomotor

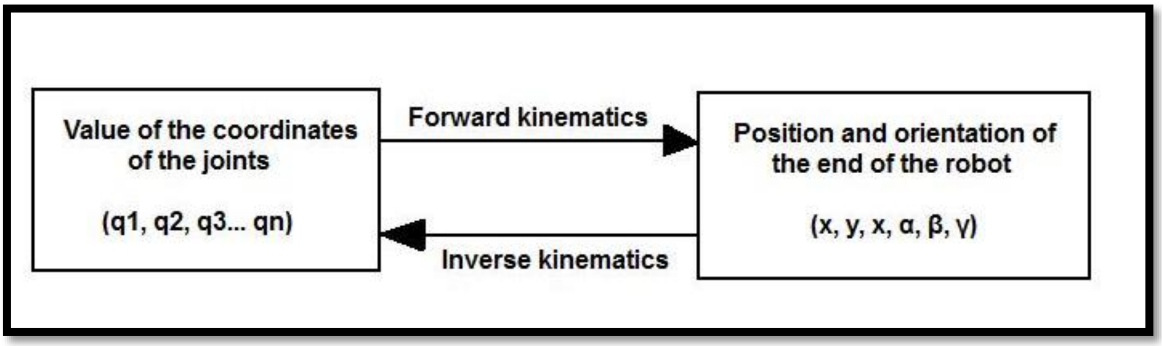
CALCULATIONS AND FINAL RESULT

3.1 Kinematics

In this section I'm going to explain the movement of a robot in function of the reference system fixed to the base.

We have two problems to solve in terms of robotic arm kinematics:

- **Forward Kinematics:** determining the position and orientation of the final end of the robot, with respect to a reference coordinate system, known values joints.
- **Inverse Kinematics:** determine the configuration to be taken by the robot to a position and orientation of the end known.



[66] – Diagram of the relationship between forward and inverse kinematics

3.1.1 Forward kinematics

In my project this is not very important because my robot's gripper consists only in the wrist and in the gripper but for the people, who wants to continue with this project designing an arm for this gripper, is very important to understand the forward kinematics.

We use the forwards kinematics to determine the position and orientation of the end of the robotic arm with respect to a coordinate system that is the reference once you know the values of the joints and the geometric parameters of the elements of the robot.

$$x = f_x(q_1, q_2, q_3, \ldots, q_n)$$
$$y = f_y(q_1, q_2, q_3, \ldots, q_n)$$
$$z = f_z(q_1, q_2, q_3, \ldots, q_n)$$
$$\alpha = f_\alpha(q_1, q_2, q_3, \ldots, q_n)$$
$$\beta = f_\beta(q_1, q_2, q_3, \ldots, q_n)$$
$$\gamma = f_\gamma(q_1, q_2, q_3, \ldots, q_n)$$

Generally, a robot of n degrees of freedom has n links connected by n joints, so each pair link-joint is a degree of freedom. We can assign a system of reference to every link and if we used the homogeneous transformations we can obtain the relative rotations and translations of the robot. With all the transformations we must create a matrix that is called homogeneous transformation matrix. The matrix that represents the relative position and orientation between two consecutive links is denominated ${}^{i-1}A_i$. In this way, the matrix ${}^{0}A_k$ is the matrix that represents the powertrain of the robot with respect to the references system of its base. When every degree of freedom is considered, the matrix is called T. For example, for a system of six degrees of freedom the powertrain is represented with the next matrix:

$$T = {}^{0}A_6 = {}^{0}A_1 \cdot {}^{1}A_2 \cdot {}^{2}A_3 \cdot {}^{3}A_4 \cdot {}^{4}A_5 \cdot {}^{5}A_6$$

To describe the relationship between two references systems of two links we use the representation Denavit - Hartenberg (D-H). Denavit and Hartenberg proposed in 1955 a matrix method to systematically establish a coordinate system {Si} i linked to each link of an articulated chain. This representation allows passing of one reference system to other doing four basic transformations that depends only on the characteristics of the link.

The transformations are some translations and rotations that relate the element I with the element i-1. The transformations are the following:

- ✓ Rotation around z_{i-1} axis with an angle θ_i.
- ✓ Translation along z_{i-1} at a distance d_i.
- ✓ Translation along x_i at a distance a_i.
- ✓ Rotation around x_i axis with an angle α_i.

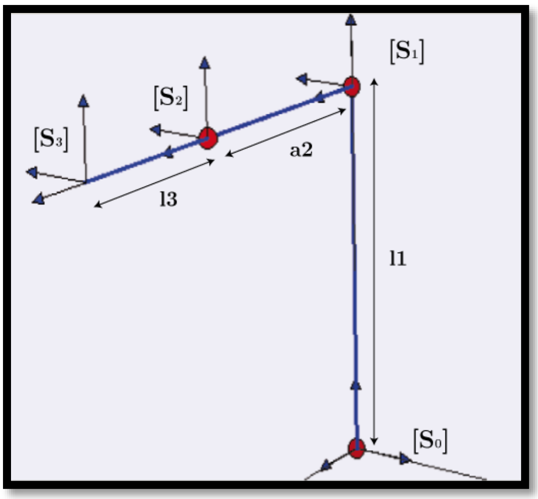
Once we have the values of θ_i, d_i, a_i and α_i that are called D-H parameters of the link I, the transformation matrix that relates the system i and i-1 is:

$$^{i-1}A_i = T(z,\theta_i)\cdot T(0,0,d_i)\cdot T(a_i,0,0)\cdot T(x,\alpha_i)$$

If we develop this expression with the D-H parameters the result is the next:

$$^{i-1}A_i = \begin{pmatrix} \cos\theta_i & -\cos\alpha_i\cdot\sin\theta_i & \sin\alpha_i\cdot\sin\theta_i & a_i\cdot\cos\theta_i \\ \sin\theta_i & \cos\alpha_i\cdot\cos\theta_i & -\sin\alpha_i\cdot\cos\theta_i & a_i\cdot\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

I'm going to show a example of resolution of a robot with 3 R pairs. The first step that we have to do is to insert the reference systems D-H. We can see in the following picture [67] the procedure:



[67] – References systems in a 3 R pairs robot

The next step is to calculate the D-H parameters with the goal of calculate the matrix $^{i-1}A_i$.

In this case we have three joints so we need to create a table with the four transformations for each joint:

Joint	θ	d	a	α
1	q1	l1	0	90º
2	q2	0	a2	0
3	q3	0	l3	0

The calculation of the rotation matrices is in the next way:

$$^{0}A_1 = \begin{pmatrix} \cos(q_1) & 0 & \sin(q_1) & 0 \\ \sin(q_1) & 0 & -\cos(q_1) & 0 \\ 0 & 1 & 0 & l1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$^{1}A_2 = \begin{pmatrix} \cos(q_2) & -\sin(q_2) & 0 & a2\cdot\cos(q_2) \\ \sin(q_2) & \cos(q_2) & 0 & a2\cdot\sin(q_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$^{2}A_3 = \begin{pmatrix} \cos(q_3) & -\sin(q_3) & 0 & l3\cdot\cos(q_3) \\ \sin(q_3) & \cos(q_3) & 0 & l3\cdot\sin(q_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Finally, the transformation matrix that provides us the position and orientation of the end part of the robot from the coordinates q1, q2 and q3 is the product of the three previous matrices:

$$T = {}^{0}A_1 \cdot {}^{1}A_2 \cdot {}^{2}A_3 = {}^{0}A_3$$

3.1.2 Inverse kinematics

The inverse kinematics problems are used to find the values to be taken by the coordinates of the robot's joints q = [q1, q2, q3…qn] for the collocation of the end of the robot's arm (orientation and position) in function of a localization. This process is not as easy as the forward kinematics because it is solved using very complicated equations and sometimes there is more than one solution for the same problem.

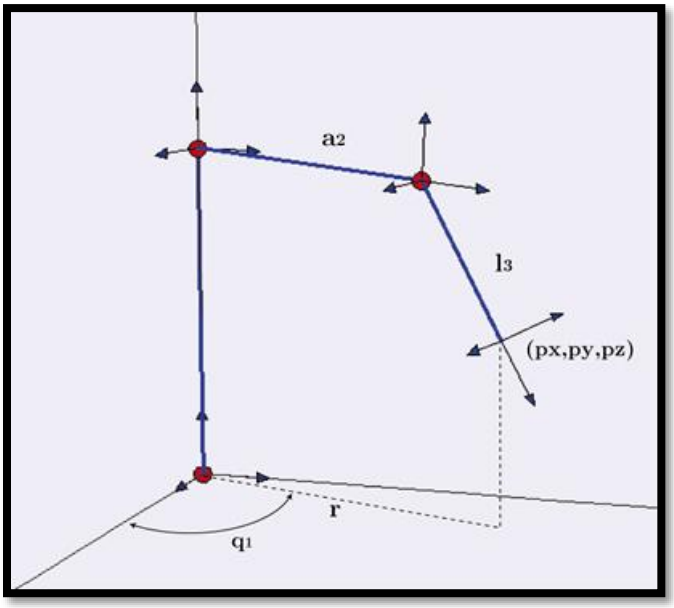
At present, there are procedures that solve this kind of problems giving the solution of the values of the joints that place and guide the end of the arm. However, these procedures are iterative, so they don't guarantee to have the solution in the correct time. In this way, it's better to find a close solution. It is, to find an explicit mathematical relationship of the form:

$$q_k = f_k(x, y, z, \alpha, \beta, \gamma)$$
$$k = 1 \ldots n$$

In order to achieve this relationship it is usual to employ geometric methods, consisting in using trigonometric relationships and the resolution of the triangles formed by the elements and the robot joints. Most robots have usually relatively simply kinematic chains and the three first degrees of freedom usually have a planar structure. It helps to calculate the correct values of the joints. In addition, the last three degrees of freedom are usually used for the orientation of the tool, allowing the uncoupled resolution (kinematic decoupling) of the robot end position and orientation of the tool. As an alternative to solve the same problem you can use to directly manipulate equations for the direct kinematic problem. That is, from the relation between the transformation matrix and the equations based on the joint coordinates q = [q1, q2,. . . , Qn], you can clear the variables n joint qi in terms of the components of the vectors n, o, and p:

$$\begin{bmatrix} n & o & a & p \\ 0 & 0 & 0 & 1 \end{bmatrix} = \left[tij(q_i \ldots q_n) \right]$$

I'm going to solve the inverse kinematics of a robot with geometric method. The starting data are the coordinates (px, py, pz) related to the system [S0] where it wants to position its end.



[68] – Picture of the starting situation of the robot

The value of q1 is easy to calculate:

$$q_1 = arctg\left(\frac{p_y}{p_x}\right)$$

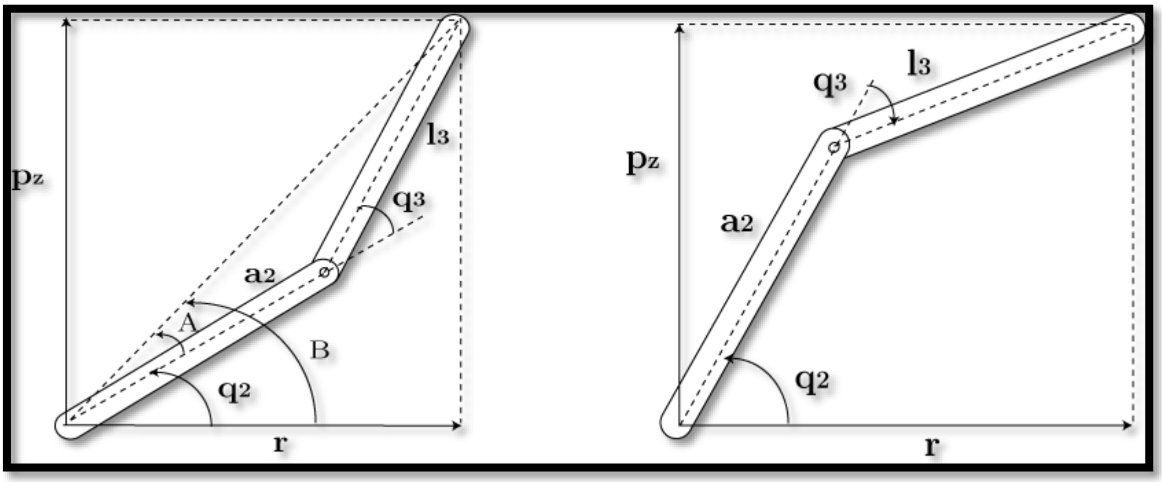
Considering that the links are in the same plane and using cosine theorem:

$$\left.\begin{aligned} r^2 &= p_x^2 + p_y^2 \\ r^2 + p_z^2 &= a_2^2 + l_3^2 + 2 \cdot a_2 \cdot l_3 \cdot \cos(q_3) \end{aligned}\right\} \rightarrow \cos(q_3) = \frac{p_x^2 + p_y^2 + p_z^2 - a_2^2 - l_3^2}{2 \cdot l_2 \cdot l_3}$$

Using this expression we can solve q3:

$$q_3 = arctg\left(\frac{\pm\sqrt{1-\cos(q_3)^2}}{\cos(q_3)}\right)$$

We can observe [69] we have two possible solutions of q3 in function of the sign of the root, these two solutions correspond to two possible positions:



[69] – Picture of the possible positions of the robot

The calculation of q2 is done through the difference between A and b, being q2= B-A:

$$B = arctg\left(\frac{p_z}{r}\right) = arctg\left(\frac{p_z}{\pm\sqrt{p_x^2 + p_y^2}}\right)$$

$$A = arctg\left(\frac{l_3 \cdot \sin(q_3)}{l_2 + l_3 \cdot \cos(q_3)}\right)$$

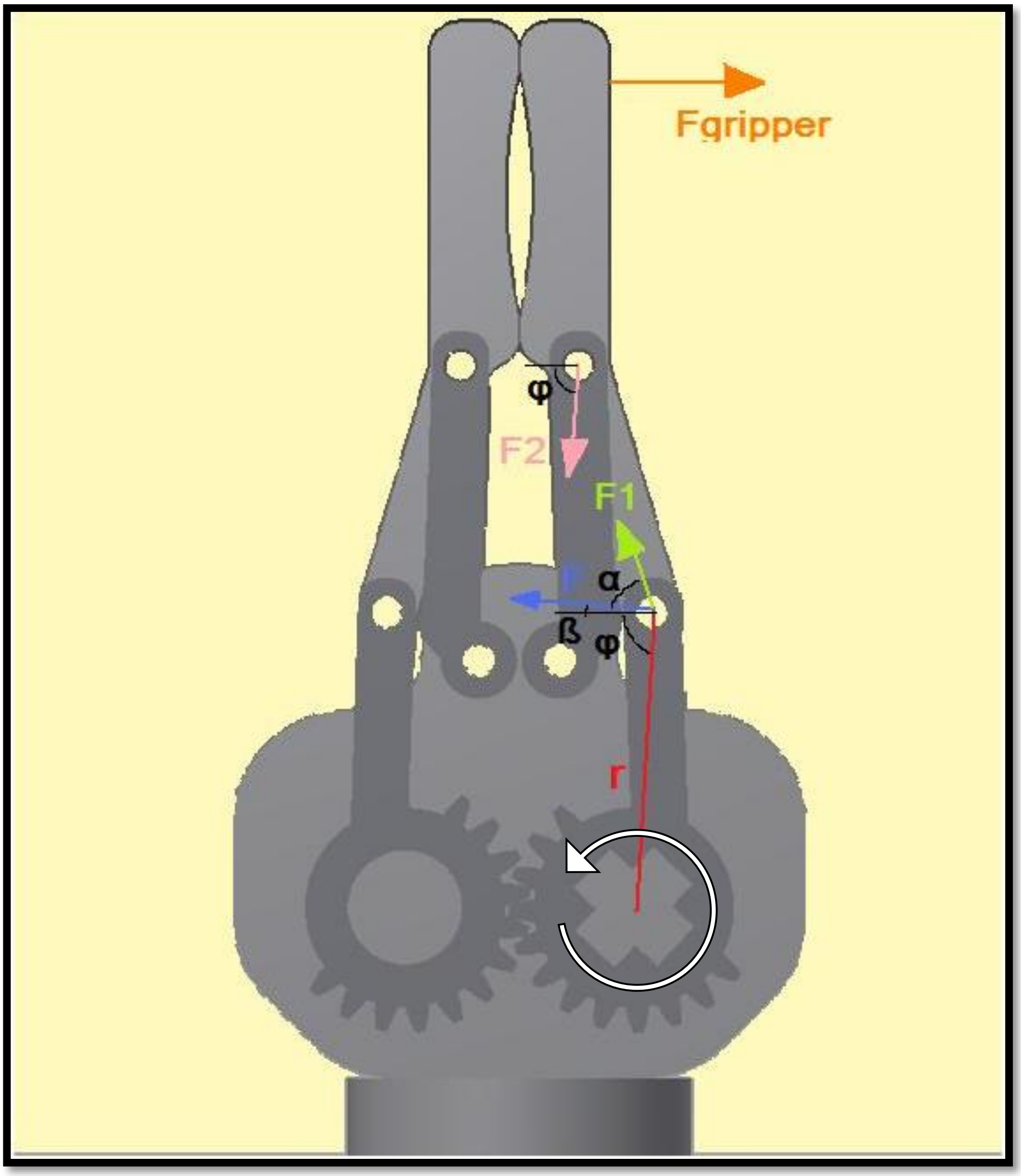
And finally:

$$q_2 = arctg\left(\frac{p_z}{\pm\sqrt{p_x^2 + p_y^2}}\right) - arctg\left(\frac{l_3 \cdot \sin(q_3)}{l_2 + l_3 \cdot \cos(q_3)}\right)$$

3.2 Calculation of the forces exerted in the gripper

In this section we are going to calculate the forces exerted in the robot's gripper by the torque. For this, we are going to take three situations of the gripper: when the gripper is in the minimum aperture, when the gripper is in a medium aperture and when the gripper is in the maximum aperture.

3.2.1 Minimum aperture



[70] – Picture with the forces exerted in the gripper with the minimum aperture

First, we have to calculate the force exerted by the torque, this force must be perpendicular to the radius of rotation and this force is called F. The formula of the torque is the next:

$$\mathbf{T = F \cdot r}$$

So,

$$\mathbf{F = \frac{T}{r}}$$

We have the information about servomotor so we know that the torque is equal to 0.078 N·m that is the same to 78 N·mm. Then we have to calculate the radius of rotation but this is easy because with "Autodesk Inventor Professional 2012" you can measure the distance between every points and the distance of the radius is r = 51.742 mm. Now, we can use the formula to calculate the force:

$$\mathbf{F = \frac{T}{r} = \frac{78\ N{\cdot}mm}{51.742\ mm} = 1.5075\ N}$$

However, this force is not in the direction of the gripper so we have to calculate the component of this force that is in the direction of the gripper, F1. For this, we must measure the angle α with "Autodesk Inventor" and calculate the component F1 using the next formula:

$$\mathbf{F1 = F \cdot \cos(\alpha)}$$

Where α is equal to 69.78º, so:

$$\mathbf{F1 = 1.5075 \cdot \cos(69.78) = 0.521\ N}$$

Now we must solve a system with two equations and two unknowns. The first equation is the next:

$$\Sigma Fx = 0 \rightarrow -F1\cdot\cos(\alpha+\beta) - F2\cdot\cos(\varphi) + Fgripper = 0$$

Where β = 3.64º and φ = 86.36º, so:

$$Fgripper = 0.521\cdot\cos(73.42) + F2\cdot\cos(86.36)$$

The second equation is:

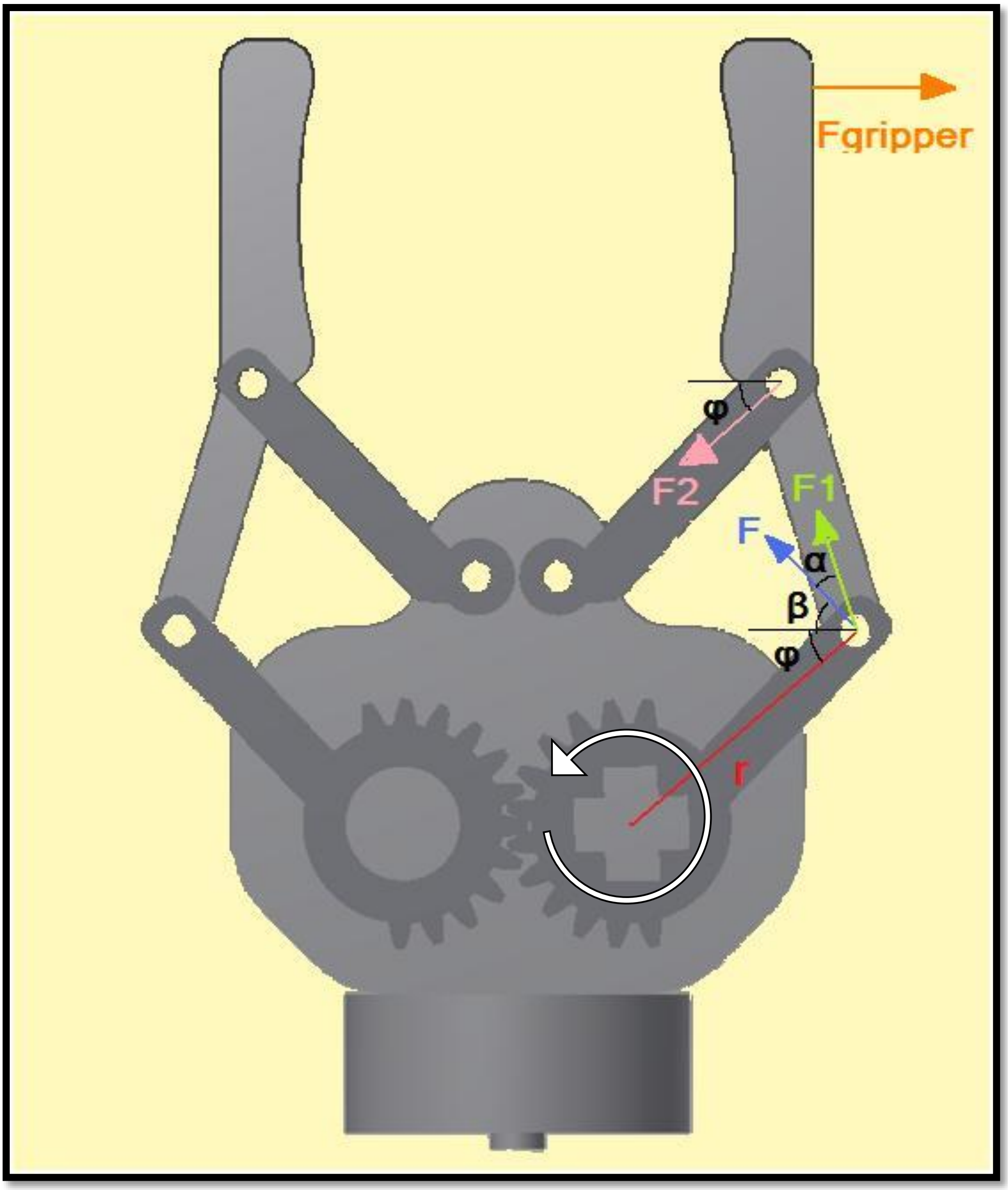
$$\Sigma Fy = 0 \rightarrow F1\cdot\sin(\alpha+\beta) - F2\sin(\varphi) = 0$$

$$F2 = \frac{F1\cdot\sin(\alpha+\beta)}{\sin(\varphi)} = \frac{0.521\cdot\sin(73.42)}{\sin(86.36)} = 0.5003\ N$$

Then:

$$Fgripper = 0.1804\ N$$

3.2.2 Medium aperture



[71] – Picture with the forces exerted in the gripper with a medium aperture

Now we are going to do the same process but the directions of the forces have changed, so the values of the angles are not the same and the value of the forces neither. However, the module of the force F is always the same because it only depends on the value of the torque and the value of the radius of rotation is also constant. So now we are going to start calculating the component of F that is in direction of the gripper. For this, we must measure the angle α with "Autodesk Inventor" and calculate the component F1 using the next formula:

$$F1 = F \cdot \cos(\alpha)$$

Now the value of α is equal to 22.76º, we can see that this value is smaller than the previous one, so the force is going to be bigger:

$$F1 = 1.5075 \cdot \cos(22.76) = 1.3901\ N$$

Now we must solve a system with two equations and two unknowns. The first equation is the next:

$$\Sigma Fx = 0 \rightarrow -F1\cdot\cos(\alpha+\beta) - F2\cdot\cos(\varphi) + Fgripper = 0$$

In this case, β = 50.55º and φ = 39.45º, so:

$$Fgripper = 1.3901\cdot\cos(73.31) + F2\cdot\cos(39.45)$$

The second equation is:

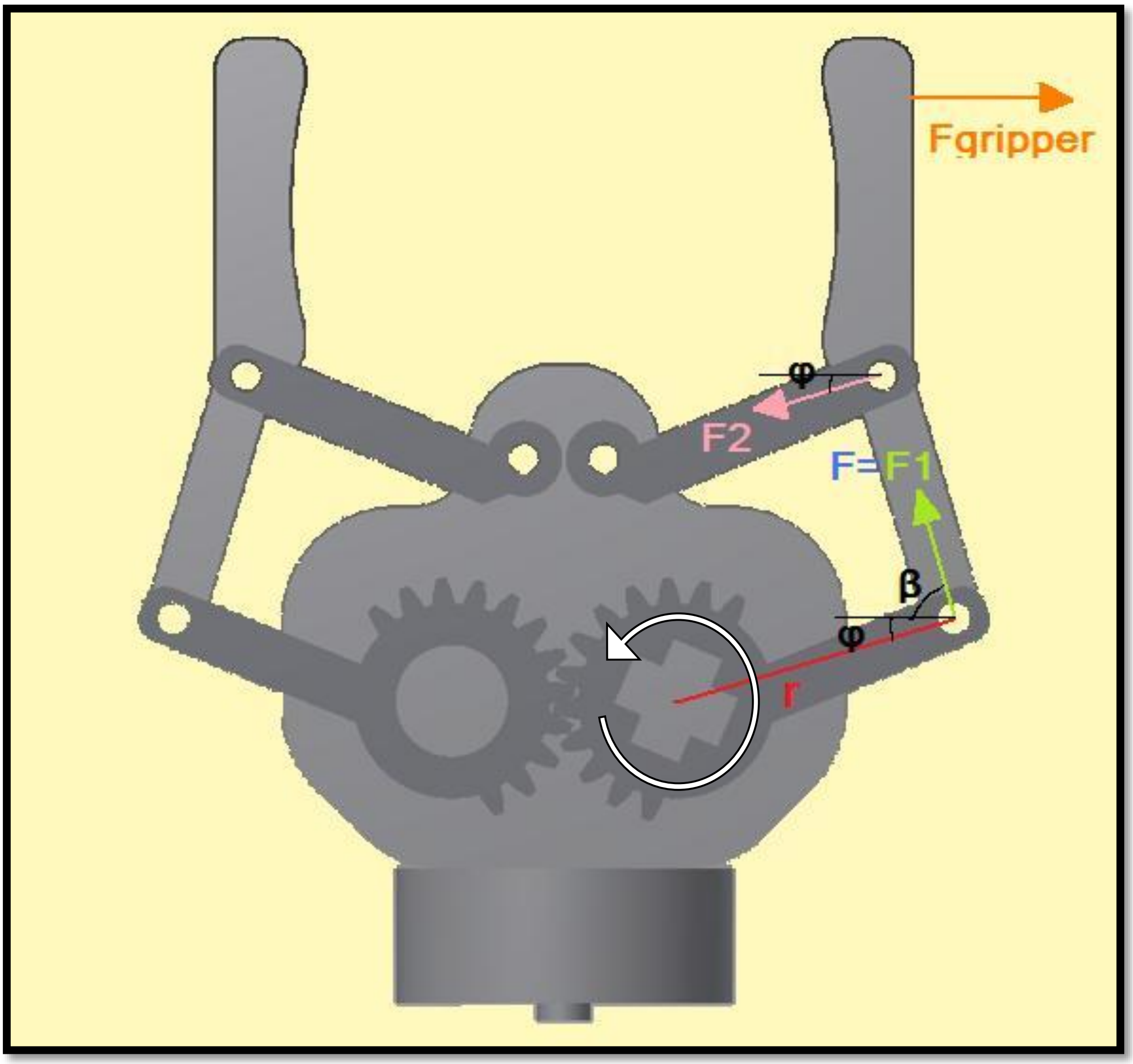
$$\Sigma Fy = 0 \rightarrow F1\cdot\sin(\alpha+\beta) - F2\sin(\varphi) = 0$$

$$F2 = \frac{F1\cdot\sin(\alpha+\beta)}{\sin(\varphi)} = \frac{1.3901\cdot\sin(73.31)}{\sin(39.45)} = 2.0956\ N$$

Then:

$$Fgripper = 2.0174\ N$$

3.2.3 Maximum aperture



[72] – Picture with the forces exerted in the gripper with the maximum aperture

Finally, we are going to do the same process but the directions of the forces have changed again, so the values of the angles are not the same and the value of the forces neither. The value of F continues being the same and we have a particular case here because the force F is in the direction of the gripper so the angle α is now zero and F = F1. We don't need to calculate any component in this case and we can start with the resolution of the equations:

The first equation is the next:

$$\Sigma Fx = 0 \rightarrow -F1\cdot\cos(\beta) - F2\cdot\cos(\varphi) + Fgripper = 0$$

In this case, β = 73.28º and φ = 16.72º, so:

$$Fgripper = 1.5075\cdot\cos(73.28) + F2\cdot\cos(16.72)$$

The second equation is:

$$\Sigma Fy = 0 \rightarrow F1\cdot\sin(\beta) - F2\sin(\varphi) = 0$$

$$F2 = \frac{F1\cdot\sin(\beta)}{\sin(\varphi)} = \frac{1.3901\cdot\sin(73.28)}{\sin(16.72)} = 5.0184\ N$$

Then:

$$Fgripper = 5.2399\ N$$

We can conclude that the force exerted by the gripper must be bigger when is aperture of the gripper is big.

3.3 Final result

In this section we are going to see the final and real result of the gripper. I'm going to add a photo of the real assembly of the gripper and one table with the time of printing of every piece and the number of layers. With this real gripper we are able to calculate the real forces and we can compare it with the theoretical forces calculated in the project.

3.3.1 Real aspect of the gripper

We can observe in the image [73] the final aspect of the gripper. This is very similar to the 3D model so we can say that the project has been very satisfactory.

[73] – Picture of the real aspect of the gripper

- **Minimum aperture:**

[74] – Picture of the real gripper with the minimum aperture

- **Maximum aperture**

[75] – Picture of the real gripper with the maximum aperture

- **Frontal view**

We can observe that the real front view of the robot's gripper is similar to the 3D model front view, so we can conclude that the project is a success.

[76] – Front view of the robot's gripper.

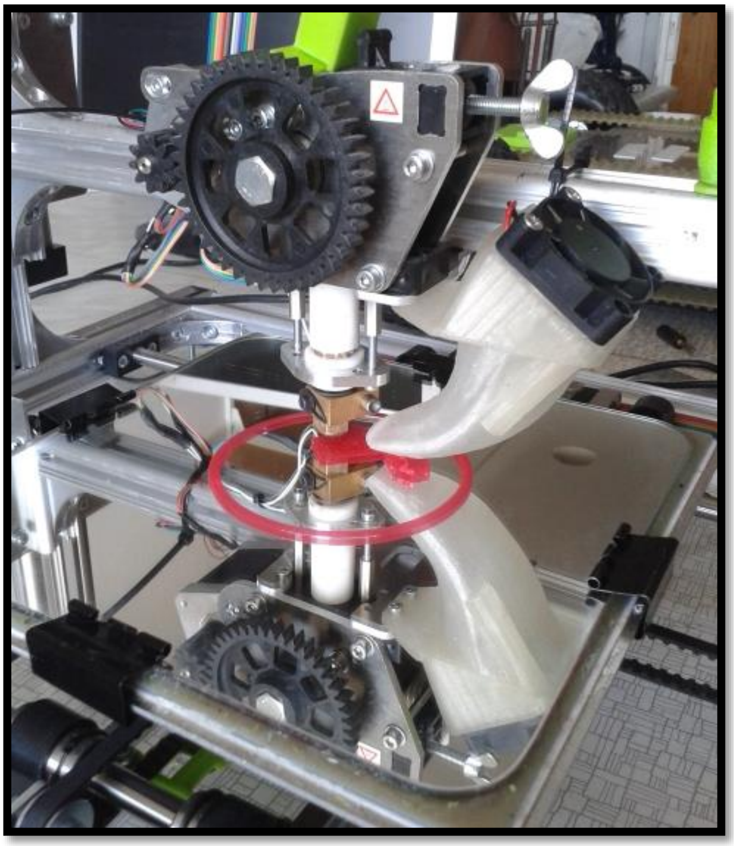
3.3.2 Time of printing

Here we can compare the time required for each piece and the number of layers necessaries to print it:

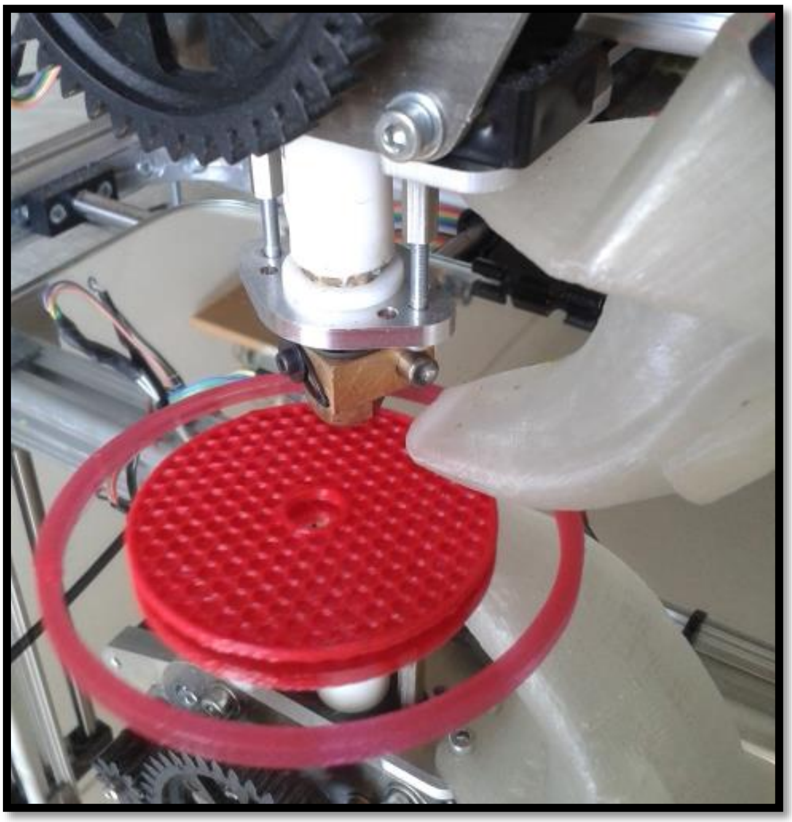
Piece	Printing time	Number of layers
Base	3 hours	73
Right gear	40 minutes	50
Left gear	40 minutes	50
Link up Gear-Servomotor	30 minutes	67
Gripper's junctions	1 hour 20 minutes	20
Grippers	2 hours	47
Top of the wrist	1 hour 30 minutes	60
Bottom of the wrist	1 hour 20 minutes	67
Link-up Wrist-Servomotor	30 minutes	67
Earth	40 minutes	60

3.3.3 Building of the robot's gripper

- **Printing**



[77] – Picture of 3D printing process

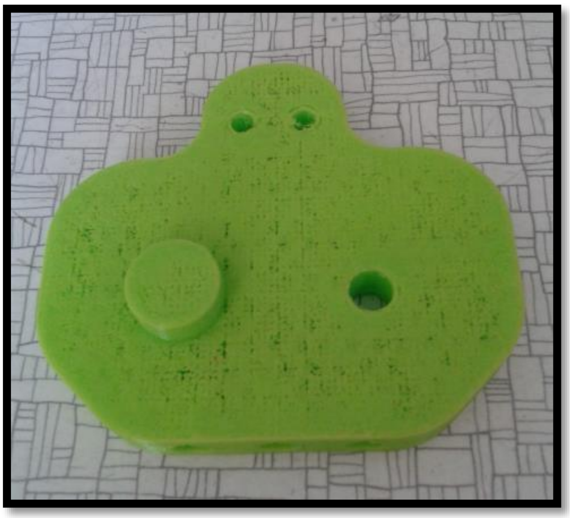


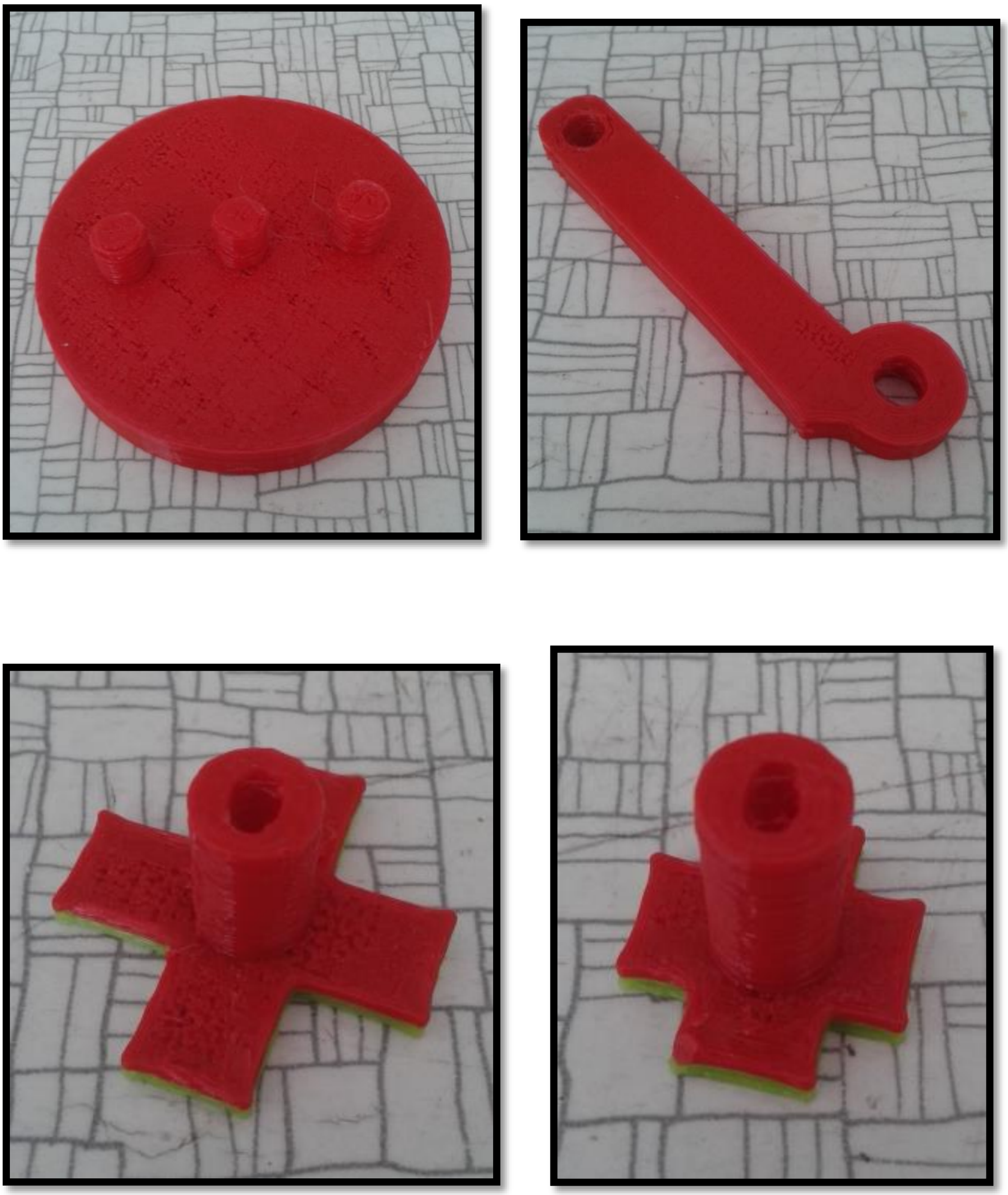
[78] – Structure of the piece during 3D printing process

- **Drilling**

[79] – Drilling of the base

- **Pieces**



[80] – Pictures of the pieces before the assembly

STANDARDS, REGULATIONS AND CONDITIONS

In this part, I'm going to write some international standards of security of the robots and some security measures which everyone have to comply when is designing a robot.

The most important standard are the following:

- **International standard ISO 10218:1992**

It is a standard made by the international agency Standardization [ISO-92]. It is relatively recent, dating from 1992. Roughly contains the following information: a section on safety analysis, the definition of risks and identifying possible sources of hazards or accidents. It also contains a section on design and manufacturing, which devotes a brief analysis to the design of robotic systems, considering mechanical, ergonomic and control aspects.

- **American standard ANSI/RIA R15.06-1992.**

It is a policy conducted by the National Institute of US Standardization (ANSI) [ANSI-92]. Also dating from 1992, and a review of the regulations published in 1986. It is relatively short. But it has some features that deserve stand. For example, the inclusion in the section on the definition of risks of some sections that deal with the probability of occurrence of an accident and the severity of the possible physical harm to a person, dependent on operator experience level and frequency in which it is in the danger zone.

- **European standard EN 775**

The European Committee for Standardization (CEN) approved in 1992 the
Standard EN 775, the intentional adaptation of ISO 10218:1992.

Most important security measures are the following:

- **Limit determination system:** intended use, space and working times, etc.

- **Identification and description of all hazards** that may generate the machine during the working phases. Should be included risks arising from a joint effort between the machine and the Computer and risks arising from misuse of the machine.

- **Defining the risk of accident.** It is defined probabilistically depending on the physical damage that may occur.

- **Check** that **the security measures** are adequate.

BUDGET

The budget of this project is very low. One of the goals of the project was to get a cheap robot's gripper and we have got it. The next table shows the prices and the quantities of the resources that we have needed to design the robot's gripper:

Nº	Product and description	Unit price	Quantity	Price
1	**Autodesk Inventor Professional 2012**. Software for the design of the 3D model. Free with student license.	0,00 €	1	0.00 €
2	**Servomotor Silnik DC Dagu DG02S.** Servomotor with torque = 0.8 kg·cm, mass = 35 g and input voltage = 3 V.	3,47 €	2	6,94 €
3	**PLA plastic.** Filaments of PLA with a section of 3 mm. We have used of three colors: green, white and red.	16,95 €/kg	0,25 kg	4,24 €
	Total price			**11,18 €**

Nº	Product and description	Unit price	Quantity	Price
1	**Autodesk Inventor Professional 2012**. Software for the design of the 3D model. Free with student license.	0,00 PLN	1	0.00 PLN
2	**Servomotor Silnik DC Dagu DG02S.** Servomotor with torque = 0.8 kg·cm, mass = 35 g and input voltage = 3 V.	14,5 PLN	2	29 PLN
3	**PLA plastic.** Filaments of PLA with a section of 3 mm. We have used of three colors: green, white and red.	70 PLN/kg	0.25 kg	17,5 PLN
	Total price			**46,5 PLN**

The change of Euros to Zlotys have been made the day 04/06/2015

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The rest of the images are my own drawings using "Autodesk Inventor Professional 2012", pictures taken with my mobile phone or drawing created with "Paint".

Web pages

- *Web pages about thesis and project related to my project:*

http://www.itson.mx/publicaciones/rieeyc/Documents/v4/art2junio08.pdf

http://revistas.utp.edu.co/index.php/revistaciencia/article/view/3191/1883

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http://www-tc.pbskids.org/designsquad/pdf/parentseducators/DSN_NASA_MissionSolarSystem_RoboArm.pdf

- *Web pages of real robotics arms in the market*

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- *Web pages about 3D printing*

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