DEPARTAMENT OF
MECHANICAL AND INDUSTRIAL ENGINEERING

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BSc in Mechanical Engineering Science

Development, production and performance testing of a three axes CNC router

MASTER IN MECHACNICAL ENGINEERING

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Aos meus Avós.

Acknowledgments

Firstly, I want to thank my supervisor, Professor Alberto Martinho, for the opportunity to carry out this work, as well as freedom given throughout the entire process. When in need, the knowledge and guidance provided, were essential to this work.

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Don't get so hung up on where you'd rather be, that you forget to make the most of where you are... Stop worrying about what you can't control, live a little!

Abstract

Nowadays there are Computer Numerical Control (CNC) machines with up to 9 axes, which allow the fabrication of high complexity parts in a single machining operation. However, considering the cost and difficulty to operate, such machines are inadequate for most users. Even though there are very affordable options on the market, these are very limited in usable work volume and cutting capabilities.

The present work focuses on the development and fabrication of a three axes CNC router that shows a good performance/cost relation. The performance can be translated as a combination of a high volume of work with a good cutting precision and accuracy. The cutting precision and accuracy are verified through a set of experiments designed for that purpose.

The results obtained evidence that user with experience in building equipment can, with relative ease, create CNC routers as the one developed in this work.

Additionally, a fourth axis was also considered for a future iteration of the machine.

Keywords: Computer Numerical Control; Three Axes CNC Router; Low-Cost; Cutting Precision; Fourth Axis

RESUMO

Atualmente existem máquinas controladas numericamente por computador (CNC) com até nove eixos, as quais permitem fabricar peças com elevada complexidade com uma única operação de fixação. No entanto, dado o custo e a dificuldade de operação destas máquinas para muitos utilizadores estes equipamentos são desadequados. Por outro lado, existem no mercado máquinas ferramentas a custos acessíveis, mas que tendem a ser muito limitadas quanto ao volume de trabalho e à capacidade de corte.

O trabalho desenvolvido centra-se no desenvolvimento e na fabricação de uma fresadora CNC de três eixos que apresente uma boa relação desempenho custo. O desempenho traduz-se na conjugação de um grande volume de trabalho com uma boa exatidão de corte. A exatidão do corte verifica-se através de um conjunto de ensaios elaborados com esse propósito.

Os resultados obtidos evidenciam que os utilizadores com boa experiência na construção de equipamentos podem, com relativa facilidade, implementar fresadoras como a desenvolvida neste trabalho.

Foi também considerada a implementação de um quarto eixo numa próxima versão da fresadora.

Palavas chave: Controlo Numérico por Computador; Fresadora CNC de três eixos; Baixo custo; Exatidão de corte; Quarto eixo.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

NC	Numerically Controlled
CNC	Computerized Numerical Control
3D	Three-Dimensional
2D	Two-Dimensional
DoF	Degrees of Freedom
PNP	Pick and Place
PLA	Polylactic Acid
CAX	Computer Aided Systems
CA	Computer Aided
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
PD	Product Development
PDP	Product Development Process
PP	Post Processing
AM	Additive Manufacturing
SM	Subtractive Manufacturing
NNS	Near Net Shape
RP	Rapid Prototyping

3DP	Three-Dimensional Printing
SLA	Stereolithography
SLS	Selective Laser Sintering
SLM	Selective Laser Melting
DLP	Digital Light Processing
FDM	Fused Deposition Modeling
CN	Customer Needs
LN	Latent Needs
PS	Product Specifications
DFX	Design for X
DFM	Design for Manufacturing
CPU	Central Processing Unit
OS	Operating System
BOM	Bill of Materials
VFD	Variable Frequency Drive
AC	Alternating Current
DC	Direct Current
PSU	Power Supply
EPB	Emergency Push Button
NoC	Normally Closed
SSC	Spindle Speed Controller
RPM	Rotations per Minute
LS	Limit Switch
EA	Engagement Angle
NS	Nominal Size
TOL	Fundamental Tolerance

BP	Bad Part
GP	Good Part
PP	Post Processor
UGS	Universal Gcode Sender
CAE	Computer Aided Engineering
FEA	Finite Element Analysis
DoE	Design of Experiments

NOMENCLATURE

δ_{max}	Maximum deflection	[mm]
P	Load	[N]
E	Elasticity Modulus	[N/m^2]
I	Moment of Inertia	[mm^4]
g	Gravitational Acceleration	[m/s^2]
a_P	Depth of Cut	[mm]
V_f	Feed Rate	[mm/min]
V_S	Spindle Speed	[rpm]
Ø	Diameter	[mm]
a	Angle of Engagement	[º]
Z	Number of Flutes	
F_t	Cutting Force	[N]
σ	Tensile Strength	[N/m^2]
A_C	Chip Cross Section Area	[mm^2]
Z_C	Number of flutes engaged	
E_f	Engagement Factor	
T_f	Tool Wear Factor	
f_Z	Feed per Tooth	[mm]
H_{BP}	Timing Belt/Pulley system Hysteresis	[mm]
D	Deviation	[mm]

$\boldsymbol{ED}$	Experimental Dimensions	[mm]

1

INTRODUCTION

The first industrial revolution, largely confined to Britain, dates back to the 18th century when, fueled by the infamous invention of the steam engine [1], various different kinds of machinery and manufacturing techniques were created, such as the first turning machines, offering increased precision and replacing handcrafted techniques [2]. During this period, society took a huge leap in terms of technology, production rate and quality, which led to the rise of standards of what was considered an acceptable commercialized product. Naturally, evolution sparks evolution, so, to obtain a higher level of detail and quality, the human factor had to be removed from the equation. It wasn't until the second industrial revolution, during the 19th and early 20th century, that the first numerically controlled (NC) machines emerged, a way of automating machine tools that are operated by abstractly programmed commands on a storage unit. These mechanisms were comprised of tools modified with motors that were controlled by points fed into the system on a punched plastic tape [3]. Soon after, these were upgraded with the addition of analog and digital computers creating the nowadays known as computerized numerical control (CNC) machine tools that are indispensable to the design and manufacturing industry [4].

1.1 Scope and Motivation

Due to its complexity, this technology has always carried a big price tag which prevented the average consumer to own it, however, during the last decade, this aspect has been rapidly changing and today, thanks to the ease of access to electronic components and software, the average consumer can easily buy and use a 2 or 3 axis CNC machine under 400 €, commonly known as a desktop CNC machine. Nonetheless, these machines, being more affordable, tend to fall short in terms of available working area, so, to challenge this premise and anyone who is passionate about these technologies and above all, prototyping, this work aims to be the guide to the creation of an affordable three axis CNC Router machine with variable working area and the concept of a modular fourth axis.

1.2 Objectives

As stated in 1.1, every day users are very restricted on what CNC machine they can buy because being affordable means having a very small working area and simple hobbyists don't think it's worth to spend more than 1000€ on a machine. Instead, their only option would be to recur to machining shops, which is a big hassle and not always available. On that note, this thesis focal point is to develop and produce a low-risk, high-reward product that revolves around already established and tested components that allow for a reliable, low-cost machine while granting a work area as big as the user deems necessary. Furthermore, the speed with which technology is developing and the ever-growing amount of information available online, work as a warranty for the ease of use of this machine. Additionally, this work seeks to take a small leap forward by introducing a concept for a modular fourth axis.

The most demanding and essential task of this project is the calculation of the structure deformation and cutting limitations, because even though this CNC machine is affordable, it must be able to cut wood, acrylic and aluminum without failure.

To achieve this goal, the main tasks to fulfill are the following:

- Research the CNC machine market;
- Study the working principle of CNC machines;
- Determine the essential components of a CNC machine;
- Study and research each component and their compatibility;
- Determine main dimensions of the machine;
- Plan for design (provisional part placement, rough sketch);
- Design all electrical components, structural parts and hardware;
- Create an assembly;
- Fabricate the necessary parts through additive manufacturing;
- Prepare all electrical components, structural parts and hardware;
- Build and test the prototype;
- Determine performance limitations;

1.3 Dissertation structure

The thesis is structured in 8 chapters:

- Chapter 2 and 3 exhibit a theoretical and historical background on CNC Machines and the process of product development process.
- Chapter 4 presents the state of the art of the CNC Machines.
- Chapter 5 displays the design and development of the prototype.
- Chapter 6 shows an analysis, discussion, and future improvements for the current prototype.
- Chapter 7 discloses the proof of concept of a fourth axis rotational motion.
- Chapter 8, the last one, highlights the conclusions and potential future work.

2

CNC Machines

The technique used in CNC machining was firstly developed in the 18th century as mentioned in chapter 1, with the first turning machine, marking the beginning of industrialization.

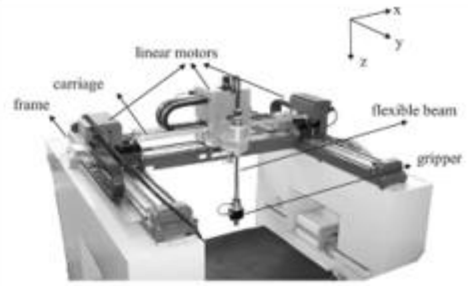
However, it was only during the 20th century that the development of automation was truly addressed. Pressured by the Cold War, John T. Parsons, motorized the axes of the production line machines and studied the possibilities of controlling them by computer, to increase productivity. About a decade later, Richard Kegg filed a patent for a "Motor Controlled Apparatus for Positioning Machine Tool", which was the commercial birth of the CNC technology [5].

As the years went by, these machines evolved exponentially and continue to evolve to this day where it's possible to complete and fully finish an entire product in a single operation [6]. Naturally, the higher end machines are in the ranges of the hundreds of thousands of euros (€), deeming highly unlikely for an average individual to own one.

The most common and affordable CNC machines have either 2 or 3 axes and as the name implies, they are numerically controlled by a computer to manipulate a wide array of tools.

It is a common misconception that a CNC machine is always correlated to subtractive manufacturing, when, in reality, it can have multiple other functionalities such as pick and place, laser engraving/cutting and even three-dimensional (3D) printing [7], which is an additive manufacturing technology. An example of these three variations of the CNC technology can be seen in Table 2.1.

Table 2.1 - Few variations of the CNC technology [8], [9], [10] and [11].

CNC Machine	Product	Main Function
Pick and Place		A pick and place (PNP) machine uses vacuum or a gripper to lift a component off of a surface, rotate it to the right orientation, then place it on a different surface.
Laser Cutter/Engraver		A CNC laser cutter/engraver uses a focused, high-powered laser beam to cut, or engrave a material to create custom shapes.
3D Printer		3D printers are used to fabricate objects from previously modeled designs by extruding a certain material, most commonly, polylactic acid (PLA) and stack it layer upon layer.

2.1 Working Principle

After briefly analyzing the Table 1, it's clear that despite having a completely different function, all three machines look mechanically similar. That's due to their working principle being the same, in other words, they work through a system of coordinates and use motors together with an arrangement of pulleys/timing belt or a leadscrew to transform the rotational movement to linear movement, which will then be transferred to a gantry that will consequently move in a given axis.

The most important part of each one of the three machines is the one that tells them apart, the tool, which is explained in section 2.4. So, it's safe to say that the working principle is to precisely move the tool in a two-dimensional (2D) plane or a 3D space.

2.1.1 Degrees of Freedom

Degree of freedom (DoF) is a concept most used in statistics and physics. It defines the limits of a system, position, or size of what is being analyzed i.e., it is the number of directions in which a particle or body can move freely, in other words, the total number of coordinates required to describe completely the position and configuration of the system. In this case, the mechanism is analyzed through the tool point of view [12].

To achieve the intricate and high-quality results that CNC machines are known for, they must be able to move the tool in multiple directions, which is only possible if they have more than one DoF. The number of DoF of these instruments usually equals to the number of axes, hence why the laser cutter/engraver in Table 2.1 is called a 2 axes CNC machine (2 DoF), while the PNP is a 3 axes CNC machine (3 DF).

Whenever a machine has one of the three axes fixed, for example, the Z, it means that this equipment is limited to two dimensional operations, as seen in Figure 2.1, having both the X and Y axis working at the same time, while the tool remains at the same height.

Figure 2.1 - Two axes CNC writing machine [13].

On the other hand, if the part to be machined is a 3D object, it's imperative to add another DoF, i.e., a new axis. Once the tool, which previously was restricted to the same plane, XY, is able to move up and down on Z, the CNC machine has three translational axes, enabling three dimensional operations such as carving, sculpting etc. As explained in section 2.1, examining the Figure 2.2, it's possible to conclude that the movement of each axis is achieved by transforming the rotational motion of a stepper motor shaft into linear action, which is usually done using either a leadscrew or a timing belt/pulley system.

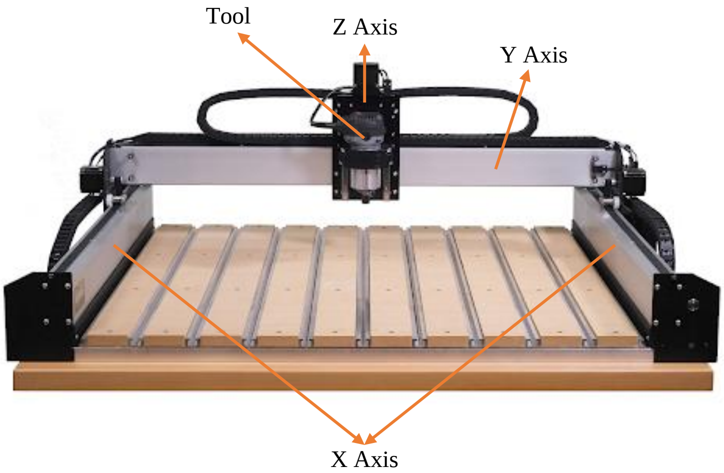


Figure 2.2 - Three axes CNC Router machine [14].

Even though a new axis allows for more detailed and complex machining operations, that addition also carries another layer of complications in fields such as maintenance, software, and setup. However, with that in mind and considering the values listed in Table 2.2, it's clear that an upgrade from a 2-axes to a 3-axes CNC machine is a worthwhile investment since the 3-axes option can do everything the other can and more.

Table 2.2 - Cost of randomly selected desktop CNC Machines.

	Machine	Price (€)	Average Price (€)
2-Axes	1	180	255
	2	500	
	3	234	
	4	105	
3-Axes	1	540	313
	2	325	
	3	161	
	4	226	

2.1.2 Computer Aided Systems

Computer Aided Systems (CAX) are a resource that grant us the capability of analyzing, modifying, and optimizing multiple stages of the Product Development Process (PDP). The acronym CAX can be divided in two parts. While CA stands for Computer Aided, the X is variable, depending on the Product Development (PD) phase, illustrated in Figure 2.3.

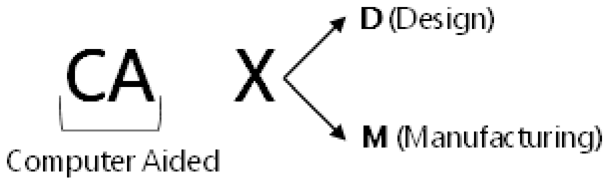


Figure 2.3 - Visual representation of the meaning of the acronym CAX.

2.1.2.1 Computer Aided Design

Taking a few steps back, there are a couple of fundamental stages during the preparation for a machining job. The first one is the computer aided design (CAD) stage.

Since the first CAD tool was invented (in the 60's) [15], it has undoubtedly become one of the fundamental steps in every engineering process. It enables the creation of 2D drawings and 3D models of real-world products and more importantly, it allows you to share, review, simulate, and modify designs easily, optimizing and streamlining the designer's workflow [16]. Despite giving engineers a lot of freedom to create new things, the aim is always to prepare the model of the product for manufacturing, and for that, there are two core phases, highlighted in the Table 2.3.

Table 2.3 - CAD process stages, adapted from [17].

Phase	Objectives
Conceptual and structural design	Where the designer transforms a complex idea of a product into a three-dimensional solid model while following its mechanical and functional requirements.
Construction design	Where the designer as to take into consideration the construction stage of the project, i.e., what is the assembly order, what tools to use and above all, making sure that those tools fit in all those tight spaces.

CAD is often used in tandem with digital manufacturing processes, such as Computer Aided Manufacturing (CAM), which is crucial for the working principle of a CNC machine.

2.1.2.2 Computer Aided Manufacturing

CAM is crucial in PD, and it focuses on the use of software and computer-controlled equipment to automate the manufacturing process.

Think of CAD as a car without wheels, all components work perfectly fine, but, if it can't actually drive forwards, backwards or turn, it isn't worth much. That's why the CAM stage (wheels) is fundamental, i.e., if a product can't go past the design process, it would only be a waste of time and money.

As stated in section 2.1.2.1, during the PDP, engineers create 3D designs/models, which integrate a set of physical properties that are later reproduced by a CAM system to create a real object. Initially, this works by transferring the part file from the CAD to the CAM software, then, the user defines what tools to use in each machining operation and the right parameters, such as, feed rate, depth of cut, etc. These configurations depend on the geometry of the part as well as the material and tooling available [18]. Finally, a toolpath is generated, and the user can preview the machining job, which is where he or she must look for potential safety hazards, like collisions.

Once the toolpath is created and carefully checked, it is then processed into a list of instructions represented as a geometric code [19], which is then read and translated by a microcontroller into different types of commands, such as the spindle speed, feed rate, depth of cut, cutting direction and many others [20].

If one of these steps isn't carried out perfectly, even with a perfectly designed product and a brand-new CNC machine, that job is most likely going to fail.

Based on this, a CAM system needs three components to function [21]:

- Software capable of analyzing the model and generate toolpaths accordingly.
- Post Processing (PP), where the toolpaths are transformed into a language that machines can understand.
- Machines that can turn raw material into a finished product.

2.1.2.3 G-Code and M-Code

As previously said, the post-processor has the important task of transforming the movements predetermined in the toolpath into a code file. Firstly, there is the geometric code, known as, G-Code, which job is to tell the machine where it is and how to move from point A to point B and at what speed it travels [22]. Then, in the same file, there is another type of code, the M-Code, which role is to provide all the information that the G-Code overlooks, such as the use of coolant, tool changes, limit switches, spindle ON/OFF, among others, i.e., directing non-cutting operations [23], as exemplified in Figure 2.4.

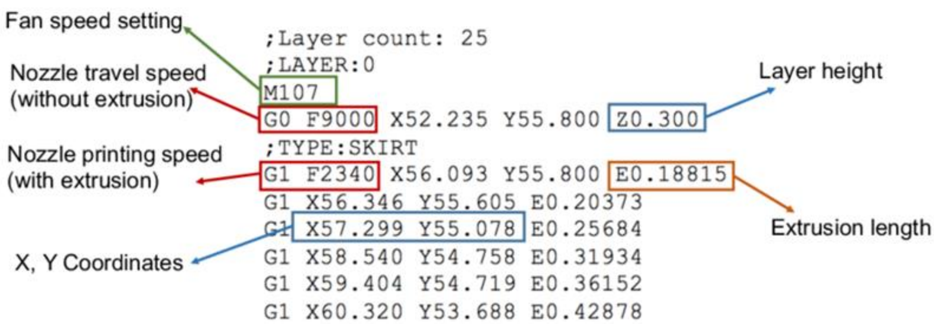


Figure 2.4 - Example of G- and M-Code for a 3D printer [22].

2.2 Additive Manufacturing

In the ISO/ASTM 52900 standard, Additive Manufacturing (AM) is defined as “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies”, in other words, it is a technology that enables the production of complex geometries and Near Net Shape (NNS) components using a wide array of materials [24].

About 30 years after the birth of the first CAD tool, that the first AM technology, named stereolithography (SLA), started being commercialized (late 1980s), which was used as a technique for rapid prototyping (RP).

Unlike Subtractive Manufacturing (SM), AM is a non-traditional manufacturing process and since its creation, it has become the go-to tool when it comes to RP, which is the creation of real-life models in the least possible time, using CAD data, i.e., it serves as an indispensable tool for shortening product design and development time cycles [25].

Today, this technology has a wide field of use, from large-scale manufacturing to engineering of highly complex parts, personal use or even in healthcare, in particular, 3D printing, enables more patient-specific interventions, including surgical planning and implant design [26], thus, this method has greatly impacted the industrial and commercial world. It's even possible to gauge the perceived value of this technology over the course of its maturity life cycle in a Gartner Hype Cycle graph [27], as presented in Figure 2.5.

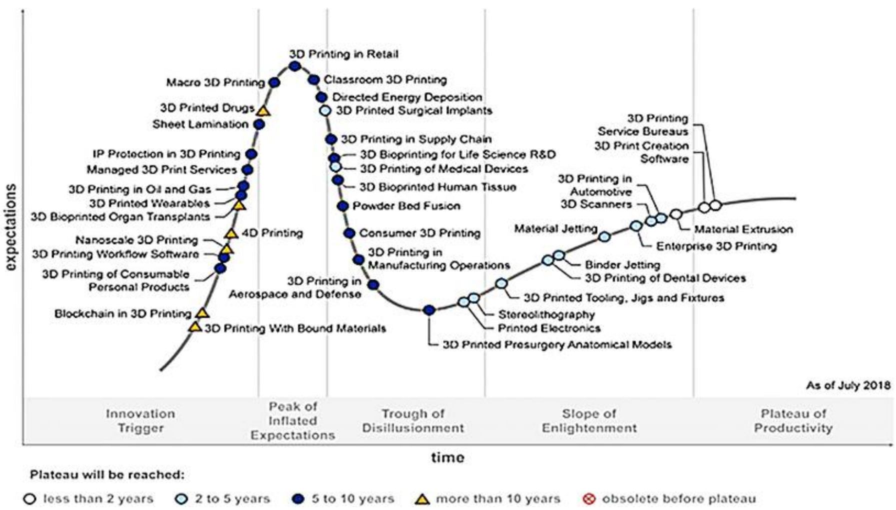


Figure 2.5 - Additive manufacturing Gartner Hype Cycle until 2018 [28].

2.2.1 3D Printing Technologies

AM, widely accepted as 3D printing (3DP), enables the fabrication of various kinds of models and prototypes, which are used for visual inspection, concept evaluation and functional testing in various stages of the PDP, and for this, there are different 3DP methods available, such as Selective Laser Sintering (SLS), Digital Light Processing (DLP) and Fused Deposition Modeling (FDM), however, this work will only go in-depth on FDM, nonetheless, it suffices to say that they differ widely in the amount and type of materials used, in speed, accuracy, and in their domains of application [29].

Just like SLA, fused deposition modeling (FDM) was among the first successful 3DP methods, initially used for industrial prototyping. Despite the multitude of 3D technologies available today, some are highlighted in Figure 2.6, FDM remains the most affordable and widely used, moreover, even though there are methods capable of creating amazingly detailed products, with an excellent surface finish, FDM 3DP isn't far behind, being able to produce models otherwise impossible to, even with the most complex of SM machines [30].

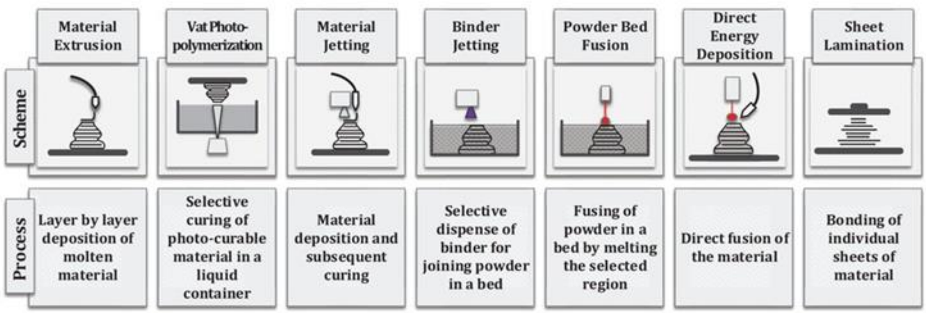


Figure 2.6 - Existing 3DP methods and their working principle [30].

Widely accepted as the simplest way of 3DP, FDM is a method of AM where, usually, a polymer, is stacked layer upon layer in a pattern which will eventually form the finished part. The material is usually melted, and then extruded through a nozzle, illustrated in Figure 2.7, that is moving according to a G-Code file sent to the controller [31].

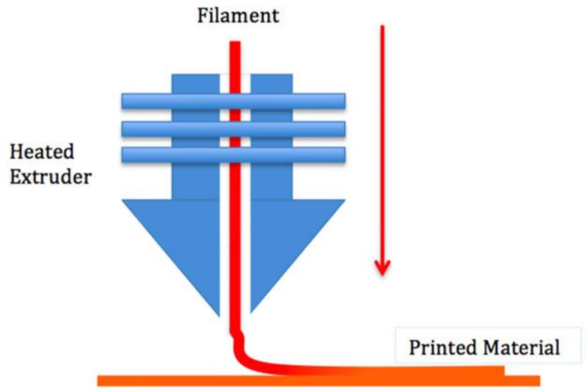


Figure 2.7 - 3DP extrusion working principle [31].

2.3 Subtractive Manufacturing

Even though these approaches are fundamentally different, SM and AM processes are often used side by side due to their overlapping range of applications, nonetheless, the process used to manufacture a prototype or part is dependent on other factors such as production volume and the stage of PD [32].

Unlike 3DP, this manufacturing process leans on removing material from raw stock like solid blocks, bars, rods of plastic, metal, or other materials, using operations such as cutting milling, lathing, drilling, among others… These conventional machining methods can be performed manually, however it is much more common to have a CNC system controlling them.

As stated previously, CAD and CAM software enable a simulation that combined with the user input, can generate toolpaths that guide the cutting tool through the raw stock to create the part geometry. These cuts are achieved by chip cutting, i.e., chip by chip, material is removed from the raw stock until the part is formed and these chips are many times the indicator for a properly set up machine [33]. Figure 2.8 illustrates the interaction between the tool and the material.

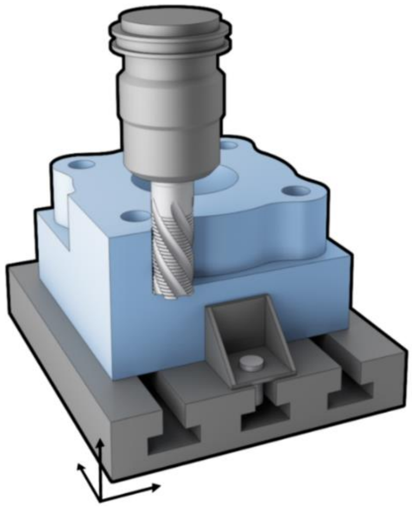


Figure 2.8 - Illustration of the interaction between the endmill and the material [34].

SM processes offer a variety of material and processing methods, and they are ideal for applications that demand tight tolerances and geometries that are difficult to mold, cast, or produce with other traditional manufacturing methods.

2.4 AM/SM - Pros & Cons

AM has certainly proven its value as a manufacturing technology, having in many cases, advantages over the traditional processes. It can easily create complex structures without needing post-processing stages while also allowing for user specific customizations with almost no set up time added. Furthermore, it functions with materials that are unusable in the traditional processes which implies the creation of products with new properties, and thus, fueling further innovation. Another great aspect of 3DP, is the surprisingly low amount of wasted material during production, contrasting with its counterpart, the SM technologies. Figure 2.9 demonstrates this difference.

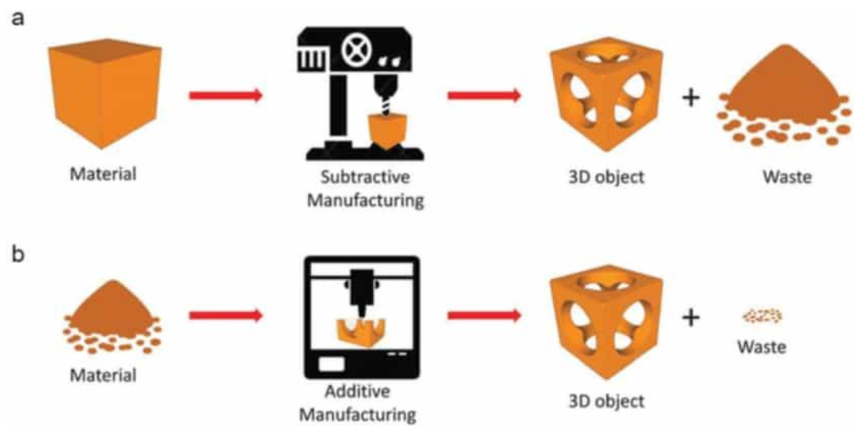


Figure 2.9 - Waste material comparison between AM and SM processes [32].

If the G-code of a certain model is fed into a SM machine, its job is to remove all the excess material in the form of shaves/chips, until that model is carved out of the raw stock, on the other hand, a 3D printer uses only the minimum indispensable amount of material to build the part [25]. It's safe to assume that from a machining job, about 30 to 60 % of the raw stock is wasted material while in a 3D print, only 5 to 15 % is lost in the form of support material, as shown in Figure 2.10 a) and b).

Figure 2.10 - Wasted material a)- 3D printed support; b)- Metal Shavings [35], [36].

Despite the high amount of waste, SM technologies have the edge in terms of accuracy, in other words, they can work with much tighter tolerances, some in the range of ±0.025mm [37], while the most precise 3D printers can only go as small as ±0.1mm. Naturally, tighter tolerances demand higher machine costs, so, this is another field where AM stands out, however, lately, SM technologies are becoming much more affordable with the introduction of desktop CNC Routers.

All in all, although AM is an excellent alternative for low-volume, high-value items, it still can't surpass the surface finish, building quality and overall structural integrity of the traditional manufacturing methods, hence why most industries still prefer these. Table 2.4 exhibits a summarized view on the comparison between both technologies.

Table 2.4 - Side by side comparison of AM and SM, adapted from [32], [38] and [39].

Feature	Additive Manufacturing	Subtractive Manufacturing
Material Options	Mostly polymers, polymer derivatives, biochemical, resin, and some metals.	Wood metals, plastics, foam, stone, and glass.
Attainable Complexity	Surpasses 5 axis CNC machining in the development of complex and intricate designs.	Ideally used for designs with simple geometry.
Working Accuracy	Less accurate than the traditional process. The most accurate AM process has a tolerance level of 0.100 mm.	It achieves tolerance levels as tight as 0.025 mm.
Properties of Finished Parts	Since production occurs through layering, this compromises some properties and thus, it has a weaker structural integrity.	The parts produced have excellent heat resistance and are structurally sound.
Surface Finish	Depends on the 3DP method. The best is achieved with SLA, which has an average roughness of 2.40 μm Ra.	Depends on the method. The lowest roughness achievable is 0.4 μm Ra.
Speed	Faster and less costly when the prototype and the production batch is small.	Faster and less costly when the prototype has large parts or production batches.

3

PRODUCT DEVELOPMENT

A product is something tangible or not that is sold by an entity to its customers and usually, unlike many people may think, the creation of a product isn't the most challenging task, it is however, the development of something that appeals to the highest number of consumers, in other words, transforming market opportunity, technological innovation and customer needs into successful products. Having a well-defined PDP, greatly improves the process by ensuring higher product quality, better team coordination and overall better project planning, hence why it has such an important role in a company success rate.

The successful products are most of the time characterized as such when they can be produced and sold profitably. This is measured according to five specific parameters [40]:

- **Product Quality** - Reflected in the price that consumers are willing to pay.
- **Product Cost** - Reflected in the manufacturing cost (equipment, tooling and building the product).
- **Development Time** - Reflected on how quickly the company receives economic returns.
- **Development Cost** - Reflected on how much was spent to develop the product.
- **Development Capability** - A company with more experience means a more efficient and economic PDP.

The average time needed to properly develop a product is between 3 and 5 years and some can take up to 10 years, however, rarely, there are products that only take 1 year to develop. Naturally, during this period, the enterprises face many challenges such as **trade-offs** where companies must abdicate of something to reduce cost or development time, **details** like deciding between screws or snap-fits, which could have an economic impact of millions of euros, **time pressure** due to the deadlines imposed and **economics** because developing, producing and marketing a new product is very costly [40]. On the other hand, many people consider product developing very interesting precisely due to all the challenges, since it allows them to be creative, feel satisfied in achieving societal and individual needs and work in a multidisciplinary team environment.

3.1 Product Planning

With the company's goals, strengths and constraints in mind, this phase is usually addressed before a PD project is approved and its aim is to maximize the effectiveness of the PDP by answering questions such as:

- " What new technologies (if any) should be incorporated into the new product?
- What are the manufacturing and service goals and constraints?
- What are the financial targets for the project?
- What are the budget and time frame for the project?" [40]

Before these questions are answered, the team starts by identifying product opportunities, prioritizing projects and only then, during the project planning, will those be answered. It's fundamental to understand that these questions are related to each other, for example, are the company's manufacturing technologies capable of producing the new technologies? If not, how much will the budget change to accommodate such innovation? And how will the financial targets be affected by this? Enterprises can then use this stage to remedy or even prevent known or potential flaws that otherwise could grow to much more severe and expensive situations.

3.1.1 Customer Needs

Zairi stated "Customers are the purpose of what we do and rather than them depending on us, we very much depend on them. The customer is not the source of a problem, we shouldn’t perhaps make a wish that customers ‘should go away’ because our future and our security will be put in jeopardy" [41]. This is directly linked to customer satisfaction and loyalty which, consequently, are connected to the method of identifying customer needs (CN), and the importance of fulfilling them.

CN are characteristics of products or services that instigate the customer to make a purchase. Identifying the **known** CN is a critical job and should be done by those who directly manage the details of the product, such as engineers and designers. Most of the time they try to experience the environment of use of the product to have a better understanding of where to correctly make potential technical trade-offs, how to bring innovative solutions to fulfill the needs and above all, to develop a commitment to meet those. On the other hand, there are **unknown** needs, also named latent needs (LN) [42], which are not yet recognized by customers as such, since they haven't been fulfilled by any other existing products. For example, in a not-so-distant past, there was a period where mobile phones didn't have a built-in camera, and until the first phone with a camera was invented, people didn't know they needed that feature. This means that the needs exist, they are just yet to be seen as such. Finding these LN is, therefore, crucial for firms to create products that carry a surprise and beneficial factor to their consumers.

All in all, the key objectives of this method are:

- "Ensure that the product is focused on customer needs.
- Identify latent needs as well as explicit needs.
- Provide a fact base for justifying the product specifications.
- Create an archival record of the needs activity of the development process.
- Ensure that no critical customer need is missed or forgotten.
- Develop a common understanding of customer needs among members of the development team." [40]

3.1.2 Product Specifications

There is a very important distinction between CN and product specifications (PS). In any point in time, even when there's no certainty as to what concept will be chosen, a team should be able to identify CN, deeming the needs highly independent from the product being developed. On the contrary, PS are dependent of the chosen concept, i.e., they will be affected not only by CN, but also by what is technically and economically possible.

PS are usually seen as a precise description of what the product has do to. For example:

- The product can be assembled in under 60s.
- The product weights between 10Kg to 15kg.
- The product as only one motor.
- The product is made of aluminum.

Ideally, PS should be established once and early in the PDP, however, this becomes exponentially harder the more complex the project is, so, in these cases, PS are revisited more than once.

Final specifications are defined once the technological constraints and expected costs are assessed. Still, during this refinement, the team often comes across difficult choices due to unmatching trade-offs like the reduction of weight which can influence the cost and sometimes, the stability.

3.2 Design for Manufacturing

Even though firms commonly practice design for X (DFX), where the "X" stands for different attributes or quality criteria, this work will focus solely on DFM (design for manufacturing) due to its universal importance. The focal point of this stage is to achieve an economical successful design, which means, lowering manufacturing costs while improving or, at least, maintaining, product quality, development time, and development cost. However, it can be very hard to find a balance since the team may have to make trade-offs between multiple desired performance characteristics.

To reach the best outcome, DFM is forced to integrate information from multiple sources, such as, sketches, drawings, PS, production, and assembly processes, estimates of manufacturing costs and producing volume. Naturally, to be trustworthy information, it has to come from an expert in the area, for instance, someone has to decide whether manufacturing a certain part is feasible, and if not, whether it has to be sub-divided into smaller pieces or, on the other hand, it can be solved through component integration, which would reduce the number of components and possibly, the cost.

The team must always consider the constrains that the product architecture brings to the manufacturing process and design the components accordingly. Solutions may include new component design concepts or incremental improvement of existing designs through simplification and standardization.

John R. Page states "Design is an iterative process. The necessary number of iterations is one more than the number you currently have done. This is true at any point in time." [43]. This means that assuming N to be the number of design iterations, a team would need N+1 iterations to achieve the perfect design. Figure 3.1 presents an abridged overview of the entire DFM process.

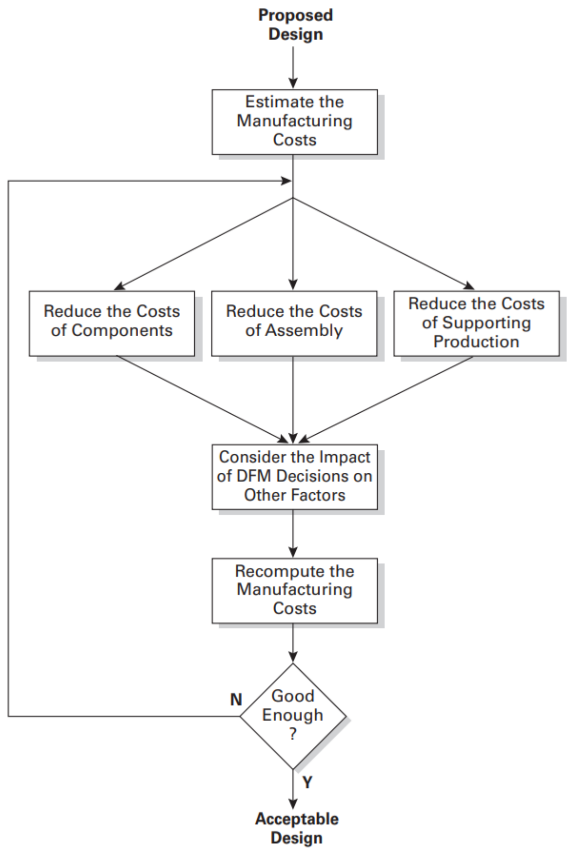


Figure 3.1 - DFM process overview [40].

3.3 Prototyping

"Will it work?", "How well does it meet CN?". These questions can only be answered by testing and experimenting which could be very costly if the team used and tested a product with all its final attributes. In this case, usually, companies use the art of prototyping to develop an approximation of the final product by transforming the 3D geometry from CAD, into tangible models, while keeping costs as low as possible.

There are different kinds of prototypes which can be divided into two groups, as briefly presented in Table 3.1.

Table 3.1 - Types of prototypes, adapted from [40].

Group	Type of Prototype	Definition	Example
1	Physical	Tangible artifacts that have characteristics of interest to the development team, which are used to test and experiment.	Models that look/feel like the product; experimental hardware to validate the functionality.
	Analytical	Aspects of the product are analysed mathematically, which means, it's a nontangible thing.	Computer simulations; computer models of the geometry.
2	Comprehensive	Has most, if not all, of the attributes of the product. Full scale, and fully operational.	Version alpha or beta of a product, used for customers to identify remaining flaws.
	Focused	Has only one or a few of the product's characteristics.	Foam models; hand-built circuit boards. Easily answers questions about performance.

The prototyping process begins by **identifying the purpose of the prototype** which is chosen by evaluating the learning needs of the team. Then the team must **establish the level of approximation** to the final product by choosing one of the prototypes listed in the Table 3.1. Usually, the best one is the simplest that will also fulfil the desired purpose. After this, the team comes up with a good **experimental plan** to bring forth the maximum amount of information. Finally, an assembly and testing **schedule** is created.

It's important to understand that testing assemblies and physical links of all parts, is a huge help in **identifying problems** and consequently, **reducing** the possibility of future **risks** that would result in loss of money and time. Prototypes are also key elements in the PDP, because they **enrichen the communication** with partners, team members, costumers, and investors. Having a visual, three-dimensional representation of a product is much easier to understand than a verbal description or a sketch.

Therefore, firms recognize the importance of the prototyping role as an indispensable tool to support the creation of new products.

3.3.1 Prototyping Technologies

Prototypes can be developed using a wide variety of materials, methods, and technologies. These technologies may be manual modelling, mockup, carpentry, conventional machining, CNC machining and two particularly important and recent technologies, 3D computer modeling and AM which is a free-form fabrication method and is further explained in section 2.2. This stage of the PDP benefits immensely from these last two technologies as they opened the doors for a new kind of prototyping, already mentioned in this document as RP. RP on PDP is reported to reduce new product costs by up to 70% and the introduction time to market by 90% [29].

Figure 3.2 illustrates an abridged overview of the framework between the design and prototyping process.

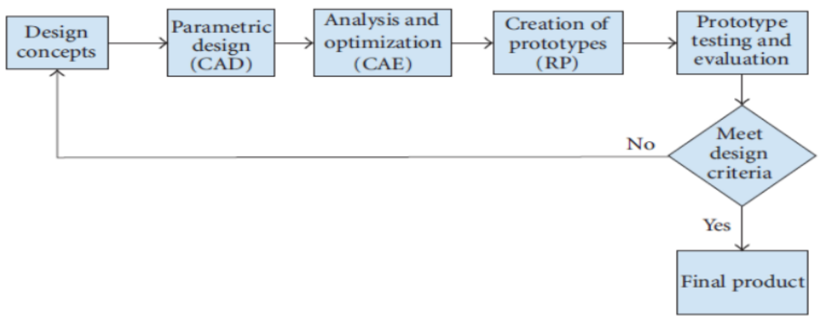


Figure 3.2 - Design and prototyping framework [44].

3.4 Key Factors When Choosing a Manufacturing Method

When fabricating a prototype or even the final product, the team must choose the manufacturing method wisely, since doing the opposite could be as detrimental to the project as not being able to fabricate anything. For this, they must evaluate the pros and cons of AM and SM technologies (section 2.4).

Because of its additive working principle, **AM** is several steps ahead in terms of achievable product **complexity**, which adds up to its **customizability** and **flexibility** attributes. It can not only produce unique products, but it can also easily switch between different parts, in case there's a small batch being created. On the other hand, **SM** has perks such as being much faster in larger scale production, i.e., it has a shorter **turnaround time** and bigger **production volume**, being able to produce hundreds of parts in the time it takes AM to make one. SM is also superior when accuracy is on the line.

Nevertheless, there are areas which will depend on the team needs. If they need a large number of items, SM is the best choice in terms of **production cost** because cost per unit decreases with volume, however, in AM it always stays the same, deeming this option more economical for small quantities. The last key factor to be taken into consideration is the **material of the component**, which will mainly depend on what the team wants to develop. The material choice will most of the times, dictate which technology must be used.

All in all, section 3, puts forward a clear perception that the PDP not only gives birth to a product, but it also has a critical role in defining its life and death, as Figure 3.3 perfectly illustrates.

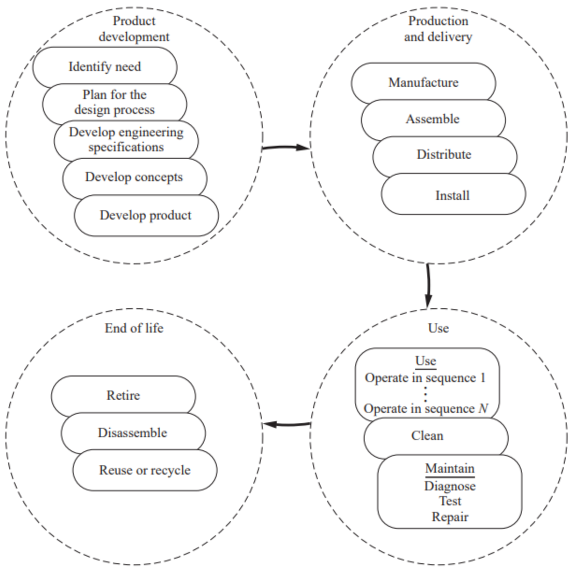


Figure 3.3 - Life-cycle of a product [43].

4

State of The Art - CNC Machines

As mentioned in section 2, there are several types of CNC machines, and depending on the product's dimensions and geometric patterns, there'll be a type that best suits those needs, i.e., each one has its own purpose in the manufacturing process. The most common machines in the industry can be classified as 2, 2.5, 3, 4 or 5-Axes CNC machine [45]. Some examples of machines used today are:

- **CNC Milling Machines**- These machines make use of a variety of rotary cutting tools to remove material from a workpiece through mechanical means. Ideal for making notches, grooves, shapes, and pockets. Available primarily as 3-axes machines, but they can go up to 6-axes [46]. Figure 4.1 presents one of these instruments.

Figure 4.1 - Industrial Milling Machine [47].

- **CNC Plasma-Cutting Machine**- This machinery utilizes electrically conductive gas to transfer energy from an electrical power source through a plasma cutting torch to the material being cut. This way, it can cut metal sheets or wood [48]. Figure 4.2 shows this machine.

Figure 4.2 - Industrial Plasma-Cutter [49].

- **CNC Laser-Cutting Machine**- Laser Cutting is the process of using a Laser beam to vaporize, melt, or otherwise gradually remove material. It has high accuracy, and it can cut custom designs and shapes into the raw material. Unlike plasma-cutting, it can precisely cut a wide variety of materials [50]. This equipment can be seen in Figure 4.3.

Figure 4.3 - Industrial CNC Laser-Cutter [51].

Apart from these three examples, there are others such as CNC Lathes, CNC Grinders, among others. This is, however, industrial level machinery, which means that it's not in the same market as the product being developed in this work.

For the general public, having access to machinery of such dimensions is highly unlikely, and even if it was possible, it wouldn't be practical. This issue was solved with the creation and development of desktop CNC machines, which are nowadays widely available in the market.

Currently, the most sought out, and perhaps, the most evolved desktop CNC machines, are 3D printers, Laser-Cutters/Engravers, and CNC Routers. Table 4.1 gives an abridged overview of the available options found today, in the market.

Table 4.1 - Specification range of Desktop CNC machines.

Machine	Working Area (mm^2)	Price Range (€)
3D Printer	100x60 to 600x600	90 to 7000
Laser-Cutter/Engraver	100x100 to 600x500	150 to 8000
CNC Router	180x120 to 800x850	200 to 6500

It's important to recognize that the values listed in Table 4.1 are only considering machines that can be categorized as desktop CNC machines, in other words, there is larger scale and more expensive equipment that isn't industrial grade, nor it is a desktop machine.

4.1 Key Components

Being industrial or desktop grade machines doesn't affect its main objective which is to precisely control a tool with a given input [52]. For this goal to be conquered, there's a set of indispensable components that must be present in the machine architecture. Notice that there are very few parts in a CNC machine that are truly dispensable, however, apart from those being listed in this section, other components are mostly structural, and don't have any control over the movement of the machine.

To assist the understanding of information, it possible to use an analogy stating that a CNC machine is like the human body, i.e., it needs certain elements to properly follow commands as intended. For instance, the structural parts of the machine can be considered the skeleton.

4.1.1 Central Processing

Also known as CPU, the central processing unit, can be considered the brain of CNC machines, as it stores data inputted by the operator and converts it into electronic signals that control other components of the machine [53]. Since this work is tailored around desktop CNC machines, there won't be any further information about industrial grade CPU's. Instead, it focuses on more affordable and widely available microprocessors such as the Arduino Uno and Raspberry Pi.

The Arduino is an open-source product which was developed by Banzi et al. ("Arduino Uno Hardware") at the Ivrea Interaction Design Institute as an easy tool for RP, built for students with no knowledge in electronics and programming [20].

It reads electronic signals and creates outputs, such as signals to turn on a motor or a light diode. Its core has a chip that is easily programmable to perform various operations [19]. It's user friendly in terms of programming and it is cross-platform, which means, it runs on multiple operating systems (OS), contrary other microcontrollers. Finally, it is also inexpensive making the Arduino Uno, seen in the Figure 4.4, ideal for projects on tight budgets.

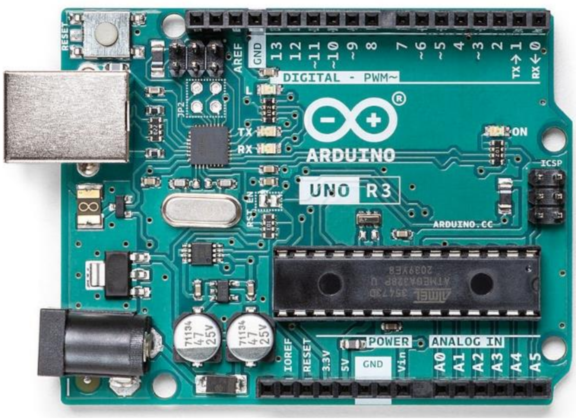


Figure 4.4 - Arduino Uno unit.

Another option available is the Raspberry Pi, which in general, is a much more capable instrument. It is a single-board computer [54] that people use worldwide to learn programming skills, build hardware projects, do home automation and even in the industrial environment. However, unlike the Arduino, this equipment can only be used in Windows or Linux OSs [55], and since it has a wider array of functionalities, it also carries a bigger acquisition cost. Figure 4.5 displays this unit.

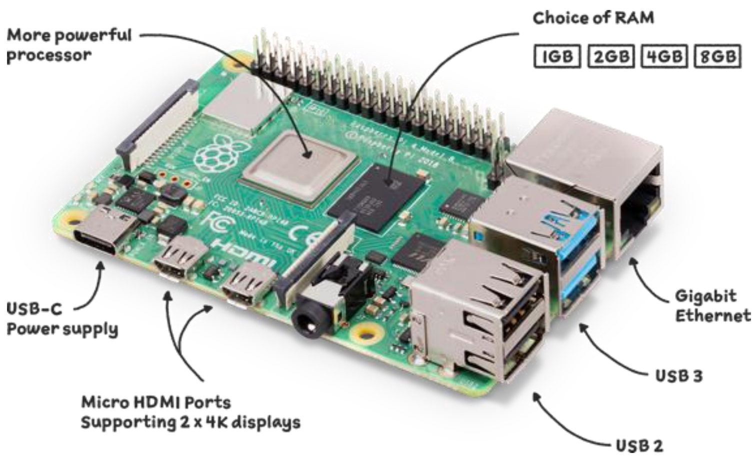


Figure 4.5 - Raspberry Pi 4 unit [56].

4.1.2 Motors

Also considered the muscles of the machine, the motors are responsible for transforming electrical current to mechanical movement.

Usually, in automation and robotics projects, there are four types of motors which contribute for a wide range of applications [57], servo motors, linear motors, spindle motors and stepper motors, however, this work will only talk about three of those.

Firstly, even though most people don't notice, **servo motors** are used in multiple different situations in their everyday life. Despite its usual small dimensions, these motors have high torque values while also retaining good level of precision and in addition, they can actuate through rotary or linear movement. On the other hand, these items tend to be costly, they can lack reliability on environments with vibrations [58], and they are more often used in industrial machines instead of hobby level machines [59]. Figure 4.6 shows an example of this device.

Figure 4.6 - Servo Motor [60].

Spindle motors are becoming the core of modern production systems due to their small size, high precision, and reliability. They have a flexible and durable structure, which is ideal for working under big loads and most of the time, they are used as the tool for machining jobs, hence why they have the capability to perform drilling/hole-making, milling, routing, and engraving operations. Figure 4.7 shows an example of this component.

Figure 4.7 - Spindle Motor [61].

Despite having many options, selecting the proper kind of motor for a specific application depends on design criteria such as positional accuracy, cost, availability of drive power, torque, and acceleration requirements [62].

For instance, the **stepper motor** is the only plausible choice for the ongoing study due to its optimal performance in applications that require accurate positioning and repeatability with a fast response in starting, stopping, reversing, speed control, high holding torque, and lower acceleration. As its name implies, the stepper motor does not rotate in a continuous fashion, instead, it moves in discrete steps or increments. Another key feature of the stepper motor is its ability to lock the shaft and hold the load steady once the required position is achieved.

Among these motors there are some variations, which differ mainly in size and torque. For example, a Nema 17, seen in the Figure 4.8, is a smaller stepper motor with a torque of about 3,2 Kg/cm [63], while a bigger and much more expensive Nema 34 has a torque about ten times higher (42 Kg/cm) [64].

Figure 4.8 - Nema 17 stepper motor [62].

4.1.3 Timing belt/Leadscrew

Being considered the tendons of CNC machines, timing belts are usually working in tandem with a set of pulleys, which transfer the motor shaft rotary movement into the CNC machine's gantries in the form of linear motion, which will consequently allow the movement of the machine tool.

Another drive system is the leadscrew, which utilizes a threaded rod combined with a special nut, to translate its rotational motion into linear movement. Table 4.2 lists a few pros and cons of both systems.

Table 4.2 - Timing belts VS Leadscrews, adapted from [65].

	PROS	CONS
Timing Belt	Longer strokes; Higher linear speed; Higher efficiency; Lower input rpm; Higher duty cycles.	Higher cost; Lower accuracy and repeatability; Velocity ripple (cogging effect); More input torque required; Periodic belt tensioning.
Leadscrew	Lower cost; Higher accuracy and positional repeatability; Large range of diameters; Quicker response; Smoother and quieter; Non corrosive; Ideal for short strokes.	Limited load capabilities; limited speed (rpm).

4.1.4 Tool

Finally, the feature which defines the purpose of a CNC machine is always the tool it commands. It can be seen as the hands of the machine, as it interacts with the raw material in a way that will change its shape or place.

The technical designation of the machine is always closely related to the tool it carries, for instance, the CNC Plasma cutter referenced in section 4 has a plasma torch as its tool, the Laser cutter/engraver has a laser module, a CNC Water jet cutter has a water jet, and so on (observe Figure 4.9 a), b) and c) to see an example of these three tools). In spite of that, this work focuses only on tools such as spindle motors and trim routers that are commonly used by hobbyist and shop owners for desktop CNC Router machines, however their performance tends to differ (section 5.5.1 has a more in-depth explanation of this matter).

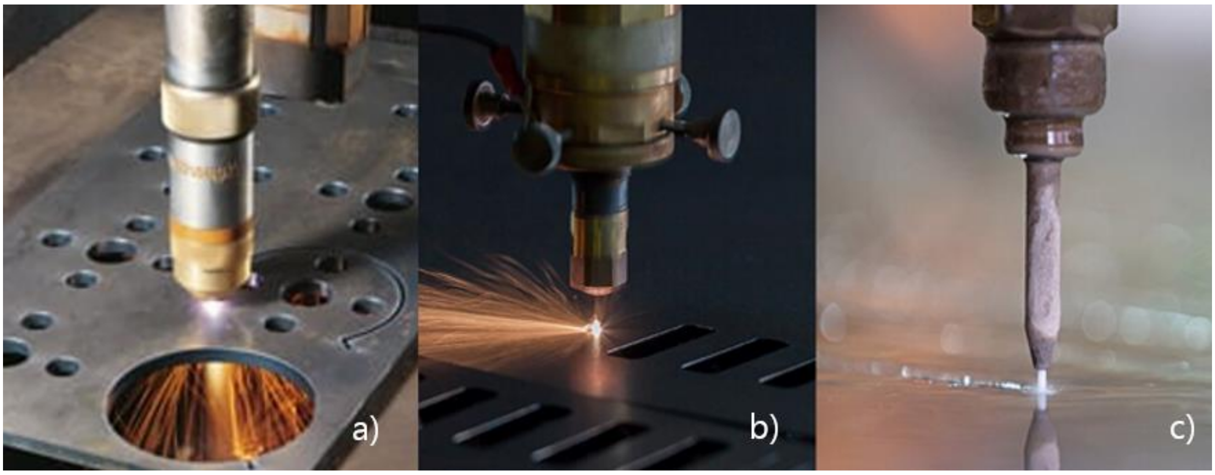


Figure 4.9 - a) Water Jet; b) Laser Cutter; c) Plasma Cutter [66], [67].

4.2 CNC Router

As stated in section 1.2, " this work aims to be the guide to the creation of an affordable three axis CNC Router machine with variable working area and the concept of a modular fourth axis." To achieve this goal, it's critical to do in-depth research on what is already socially accepted as a good product and then, try to adapt the gathered information into fulfilling the project objectives. These machines are of relatively small size and low weight, they are usually used in small woodworking or manufacturing shops and having proven their worth, the demand increased, which lead to the prices going down [68]. This ultimately allows hobbyist to widen their tool arsenal by acquiring this equipment and use all its assets to prototype and potentially develop their own commercially successful products. Depending on the machine specifications, it can perform operations such as engraving, routing, and carving in various materials.

Considering the high amount of offer in the market, Table 4.3 shows a brief comparison between the four most successful commercially available desktop CNC Router machines.

Table 4.3 - Commercially available machines, adapted from [69], [70], [71] and [72].

	X- Carve	Shapeoko 4	Onefinity X-50	Genmitsu 3020
Price ($)	2600	2500	2700	550
Assembly Time (h)	16	3	1	0.5
Cutting Capability	Woods, plastics, aluminum and brass	Woods, plastics, aluminum and brass	Woods, plastics, aluminum and brass	Woods and Plastics
XY Drive	9mm Belts	15mm Belts	Leadscrew	Leadscew
Stepper Motors	Nema 23	Nema 23	Nema 23	Nema 17
Working Area (cm^2)	75x75	83x83	81x81	30x20
Size Options	1	3	2	1
Weight (Kg)	46	75	53	11

Analyzing the information listed in Table 4.3, it's possible to conclude that there are three premium products that offer added perks that the more affordable machine lacks, however, apart from the working area, those differences are not that drastic. Still, there's a considerable price gap between them, which is commonly the main reason to opt for the cheaper product.

What should be changed to reduce the price of the first three products? The answer is "nothing". Instead, this work aims to answer another question: Having cheaper machines as a base, what can be changed to improve their attributes, while maintaining a low cost?

5

Design And Development of The Prototype

5.1 Prototype Requirements

What should the machine do? How does it answer those "what's"? These are the key themes being discussed in this section. This project was born through the necessity and will to develop a product that is good for RP and capable of working with metals, such as aluminum or brass. Even though it is for personal use, to maximize the project chances of success, there are many procedures mentioned in section 3 that were followed attentively.

5.1.1 Customer Needs

In this case, instead of going through the usual interviews and knowledge assessment stage, the CN taken into consideration were only from the developer's point of view, nonetheless, considering the results shown later in the document, this product could potentially be sold successfully as a kit to other consumers. Table 5.1 lists multiple features the developer deemed fundamental for a reliable and high-quality product, according to different categories.

Table 5.1 - Customer requirements for the product.

Category	Requirements
Objective Clarification	-The machine moves in X, Y and Z. -The machine can cut aluminum. -The machine costs under 1500€.
Structure	-The machine fits on a 1500x950x500mm space. -The machine is rigid enough to be picked up. -The machine can be disassembled. -The machine is very stable. -The machine withstands the hardships of time. -The machine bed is leveled.
Maintenance	-The machine is easy to maintain. -It's fast to change the waste board.
Functionality	-A machining operation is easy to set up. -The machine can be manually controlled. -The machine tool has variable rotation speed.
Safety	-The machine can be shut off at any moment. -The machine doesn't catch fire. -The machine can't go off limits. -The machine can't have loose cables.
Work Environment	-The machine can be in a closed environment. -The machine is not to laud. -The machine as little vibration. -All collets and bits are stored on the machine.

At the time that this document is being written, there are no LN identified.

5.1.2 Product Specifications

Having established the CN, the immediate product specifications are defined and can be seen listed below.

Objective Clarification:

- The **three-dimensional movement** achieved by the machine is possible through the use of <u>stepper motors combined with CNC software</u>.

- **Cutting aluminum** is possible by using powerful stepper motors (Nema 23), spindle motor and having a rigid structure.
- The total **cost** is about 700€.

Structure:

- The main **dimensions** of the machine are 954x897x466mm.
- The **rigidity** of the machine structure is ensured by using steel and aluminum parts.
- **Disassembling** the machine is possible because all the parts are tied together using bolted connections.
- Having an overall weight of 50kg gives the machine very good **stability**.
- **Durability** is increased by painting the steel parts, avoiding rust and having easy to replace parts that are more prone to wear.
- To make sure the machine **bed is leveled**, it is faced after its installation.

Maintenance:

- Every 200 hours of use, the **maintenance** consists of checking the belts tension and lubing the leadscrews and linear guide rails.
- **Changing the waste board** takes 1min.

Functionality:

- It takes 5min to **set up** a machining operation.
- The user can **manually jog** the axes through computer inputs.
- The user can easily **change the spindle speed** by rotating the potentiometer on the control box.

Safety:

- To instantly **shut off** the machine, the user can press the emergency button (EM).
- To **avoid overheating**, most of the electronic components have heatsinks and there are two cooling fans, one for the electronics box and the other for the spindle motor.
- During an operation, the machine stays inside the **limits** established by the limit switches.
- To **avoid loose cables**, these are routed through cable tracks.

Work Environment:

- The machine can be installed in a **closed environment** because it has a dust collection system.
- The machine does not surpass 100dB.

- **Vibrations** are reduced by using rubber shims and feet.
- The **tools are organized** by being stored in a specific compartment.

Although most of these specifications are already applied the current prototype, some will only be present in the finished product, which means, they will be part of future improvements mentioned in section 6.3.

5.2 Methodology

To successfully build a completely functional and operational prototype for this work, there were multiple techniques, technologies and methods used, of which, CAD, CAM, 3DP and laser cutting are highlighted, however, before that, the developer started by **planning** things such as budget, materials, production methods and estimated production time.

After gathering this information, the **design stage** started, more specifically, DFM. Leaning over the facts given in section 3.2, this stage is critical for the whole process, since it combines data provided from multiple different sources.

Firstly a few 2D hand drawn sketches were created, as shown in Figure 5.1. During this step, the developer considered basic dimensions, production methods, feasibility, and potential cost.

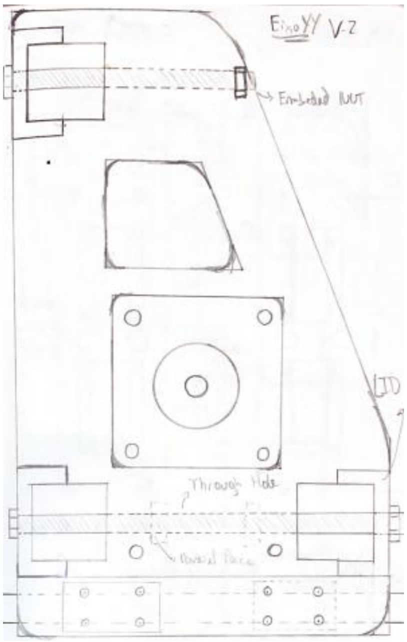


Figure 5.1 - 2D sketch of the right-side X axis gantry.

Once the initial sketches were completed, the **3D modelling** phase began. Using the 3D modelling software *SolidWorks 2020,* all the parts were carefully modeled in a way that would allow their production, for instance, a part that is designed to be 3D printed, can be much more complex than those designed to be produced by SM technologies or even by manual techniques. Moreover, it is fundamental to create a 3D CAD assembly exactly like the desired real-life prototype, which is when it's possible to find and solve potential assembly process conundrums, like overlaps or even lack of space, i.e., while assembling components, there must always be space for tools to tighten bolts, for hands to grab something, among others. In this stage, designing a single hole out of place or having the wrong dimensions, could prove to be a very expensive and time-consuming mistake, because the completed CAD assembly acts as a roadmap for the production and assembly stages. To avoid this, the developer had to use well thought tolerances, presented in section 5.7.

Having deemed the design phase concluded, the developer proceeded to the **production** stage, where all the structural components were created by 3DP, laser-cutting and manual metal work. Supported by the technical drawings presented in Appendix D, the developer had to perfectly replicate the modeled parts, since that would most likely guarantee a successful assembly process.

Finally, upon confirming the correct geometry of all the required parts, the developer moved forward to the **assembly** of the prototype. At this point, the developer’s task was to link all the individual components, following a specific predetermined order, until the prototype was built. Although this process was being planned from the beginning of the project and even with the visual confirmation from the 3D CAD assembly, there were still a few setbacks that made the developer rethink and redesign a few parts, quickly taking care of the issues.

None of these stages is ever really concluded until the final product is built, because until then, there are many unpredictable obstacles that need upgraded or even completely new parts to be overcame.

5.3 Materials Choice

During the planning stage, the developer concluded that there were two key sets of parts for which, the choice of materials would be very important. The first group covers all the structural parts that make the **main frame**, i.e., structural square tubing. Having to support the weight and loads generated by the other components, the developer had two viable options for these parts, aluminum, or steel. Although both options would work, there were four basic parameters to consider in order to make a decision. On the one hand, **strength** wise, steel is the obvious choice considering it is a very tough and resilient material, contrary to aluminum that can be shaped and be worked with in ways that are impossible with steel, thanks to its great **elasticity/malleability** [73]. On the other hand, in terms of **weight**, steel is about three times heavier than aluminum [74], which can hinder the machine's portability. Finally, regarding the **price**, aluminum can be 30% more expensive than steel [75].

Usually, when the requirements for a final product are to be light weight, have excellent resistance to corrosion and to be easily machinable/deformable, aluminum is an obvious choice [76], however, being easily deformable proves that it is a soft metal, which explains its high levels of elasticity [77], illustrated in the Figure 5.2.

Since the CNC router developed for this work aims towards extremely precise operations while being low cost, balancing the limitations and advantages from the information listed above, the developer choose steel as the main frame material. However, he acknowledged that the ideal combination of material properties wouldn't be possible, which meant, a few trade-offs had to be made. Choosing steel over aluminum, greatly reduces the chances of the structure to warp, deform underweight, force or heat. This, combined with the fact that steel is generally cheaper (per kilogram) than aluminum [76], is enough to ignore the higher weight.

A desktop CNC machine is usually linked to a certain level of portability, nonetheless, the developer concluded that even though this feature would be reduced, the added weight would bring increased structure stability and cohesion, which is beneficial to the quality of any machining operations.

Figure 5.2 - Illustrative example of aluminum's deformability [78].

Once this group of parts had its material chosen, the developer moved on to the connecting parts, which have the job to link all the main frame components. For the final product, these parts are intended to be made of machined aluminum, however, for the current prototype, they were designed to be 3D printed using the FDM method. Many types of materials can be used with FDM techniques, including the most common thermoplastics, chocolate, pastes, and even exotic materials like metal/wood-infused thermoplastics, yet, for the presented work, the focal point will be the thermoplastics.

Having narrowed down the material options, there were still a considerable number of possibilities, however, the developer further narrowed the options to the most common and widely available, PLA, ABS and PETG [79].

Upon analyzing the data gathered in the Table 5.2 and weighting the polymer limitations according to the working requirements of the developed CNC router, both PLA and PETG would be a good choice. Despite ABS having a very good heat resistance, it was quickly ruled out due to its high printing difficulty and the toxic fumes it generates during the extrusion process.

Table 5.2 - Important properties of 3D printing materials, adapted from [80], [81].

	PLA	PETG	ABS
Tensile Strength (ZZ) [MPa]	37	30	27
Density [g / cm3]	1.3	1.3	1.0
Heat Resistance	Bad	Good	Very Good
Printing Difficulty	Very Easy	Moderate	Hard
Cost [€ / Kg]	22	25	22

Knowing that the printed components structural integrity could be customized in the 3D printing slicer software, the main concern was the eventual heat buildup from the motors, but after testing them under load, the developer learnt that they would only heat up to be warm to the touch, which wouldn't have any effect in PLA or PETG. Nevertheless, to have a bigger safety margin, the developer decided to choose a variation of PLA, named **PLA+**, which with the help of a few additives, maintains the properties of normal PLA, except for its heat resistance, which is increased. Figure 5.3 shows the white colored PLA+ filament spool.

Figure 5.3 - 1 Kg filament spool of white PLA+.

5.4 Prototype Architecture

This sub-section has its sights on the deconstruction of the current prototype, seen in Figure 5.4, into its main subassemblies. However, taking into consideration the overwhelming number of small steps needed to assemble each subassembly, to reduce the information input and to facilitate the understanding of each subassembly, the detailed technical drawings for the subassemblies, individual parts and even the bill of materials (BOM), can be found in the Appendix D section. On this note, this sub-section leans towards a more illustrative and abridged approach on the subassembly's composition, rather than an extensively explicative method.

Nevertheless, the complexity of this project demands the clarification of a few details, such as the analysis of the main dimensional and geometrical tolerances, which is shown in section 5.7.

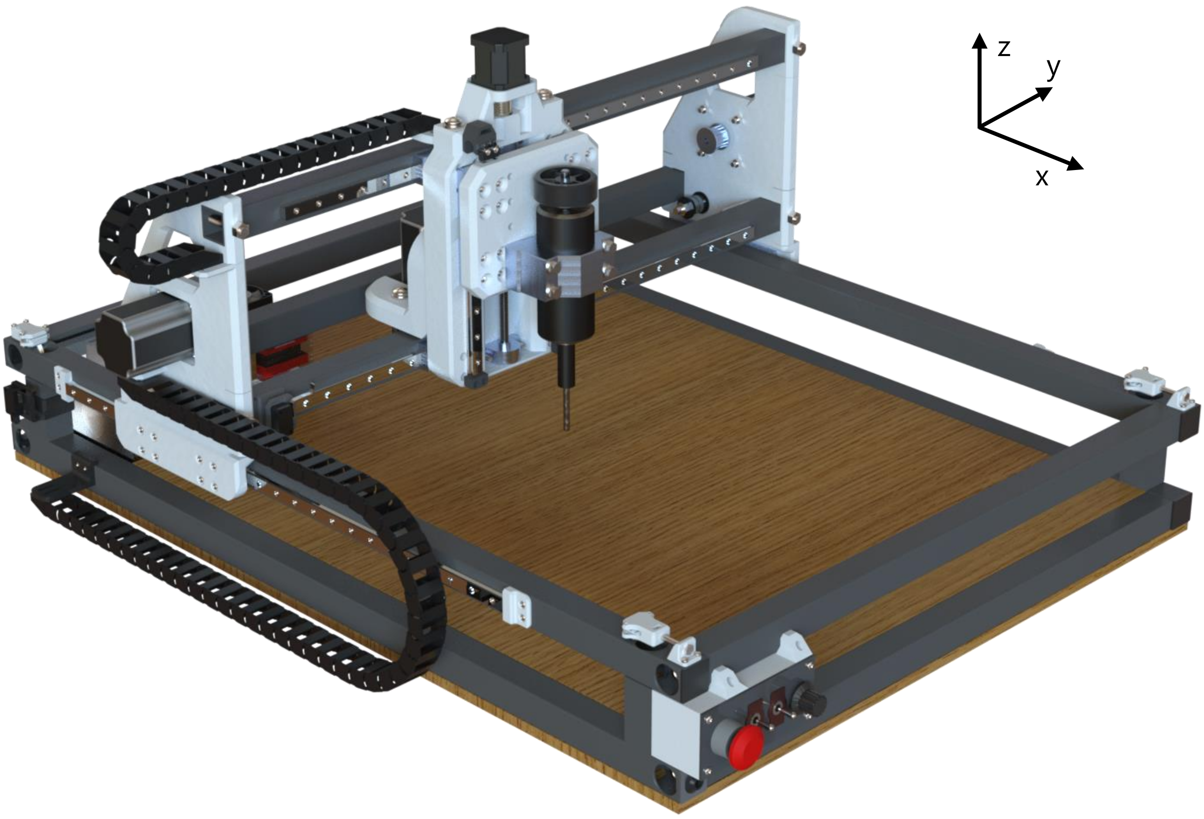


Figure 5.4 - 3D render of the current prototype and working coordinate system.

5.4.1 Main Frame

Even before starting the development of the CAD file and having already chosen the material for the square tubing of the main frame, it's essential to do market research to define which of the available sizes is the adequate for the purpose at hand. The catalog shown in the Figure 5.5 a), shows the dimensions of the profile used, among all the others available.

Tubos de Aço Quadrados

PESO EM QUILOGRAMAS POR METRO

(mm)	ESPESSURA DA PAREDE	
	1,5	2
10	0,45	
12	0,57	0,69
16	0,74	0,97
20	0,92	1,23
25	1,16	1,54
30	1,41	1,85
35	1,65	2,17

(mm)	ESPESSURA DA PAREDE		
	1,5	2	3
40	1,88	2,48	3,63
45	2,12	2,80	
50	2,33	3,09	4,57
60	2,80	3,72	5,52
70		4,35	6,26
80	2,50	4,98	7,39
90			8,01
100		6,23	9,67
120			10,80

Figure 5.5 - a) Profiles sizes and weight; b) Chosen dimensions in millimeters [82].

As previously stated, the main frame is composed of steel square tubing which was bought in lengths of six meters by the developer on a supplier that specializes on the trade of steel and construction materials [83].

A dimensionally correct 3D model is crucial to avoid any problems during the assembly of the prototype, so, even the steel tubing must be modeled to perfection. Figure 5.6 presents the CAD 3D model of the assembled main frame and in Table 5.3 are listed all the utilized components.

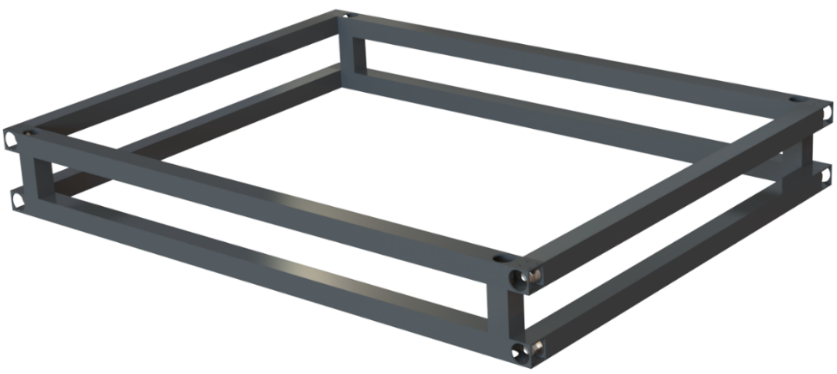


Figure 5.6 - 3D render of the main frame subassembly.

The frame is the combination of 30x30 millimeter structural square steel tubing cut to specific lengths, linked by bolted connections, through threaded rods, nuts, and spring washers, as illustrated in Figure 5.7.

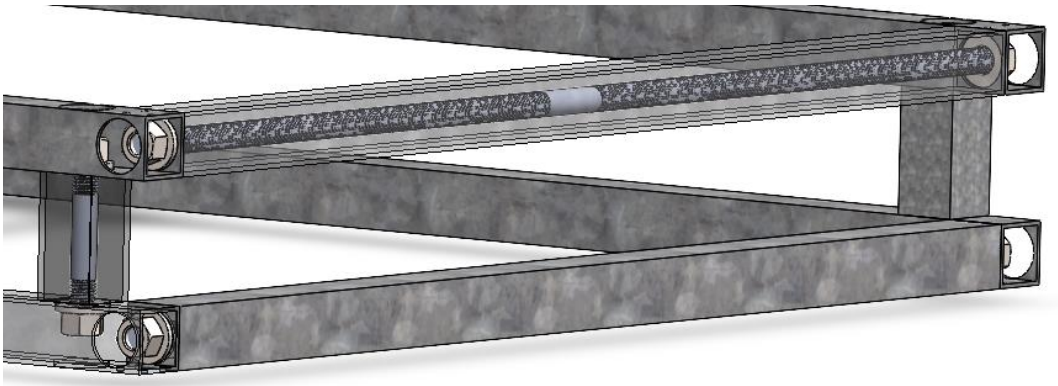


Figure 5.7 - SolidWorks 3D model, main frame bolted connections.

The hardware used for the entire prototype, is presented in Appendix A, thus, Table 5.3 lists only the main components needed for this subassembly. Additionally, Appendix C displays the technical drawing of this subassembly.

Table 5.3 - Main components used in the main frame subassembly.

Component	Quantity
30x30x900 square steel tubing	4
30x30x630 square steel tubing	4
30x30x60 square steel tubing	4

5.4.2 X Axis

The function of the subassembly seen in Figure 5.8, is to carry the Y and Z gantries along the X axis. It is mainly composed by two 3D printed mirrored gantries, which are connected via three square steel tubing profiles, which serve not only as stabilizers but also as mounting surfaces for the other gantries.

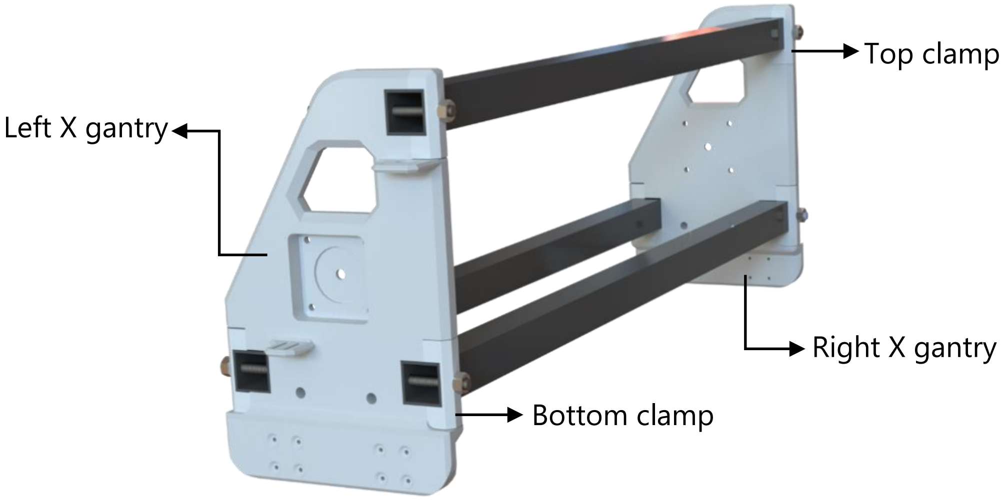


Figure 5.8 - 3D render of the basic components of X axis sub-assembly.

As Figure 5.9 a) and b) suggest, the steel profiles are fitted in purposely designed tight slots, by lightly hammering them in and are then secured with 3D printed clamps. This is all held in place using threaded rods, hex nuts, and spring washers.

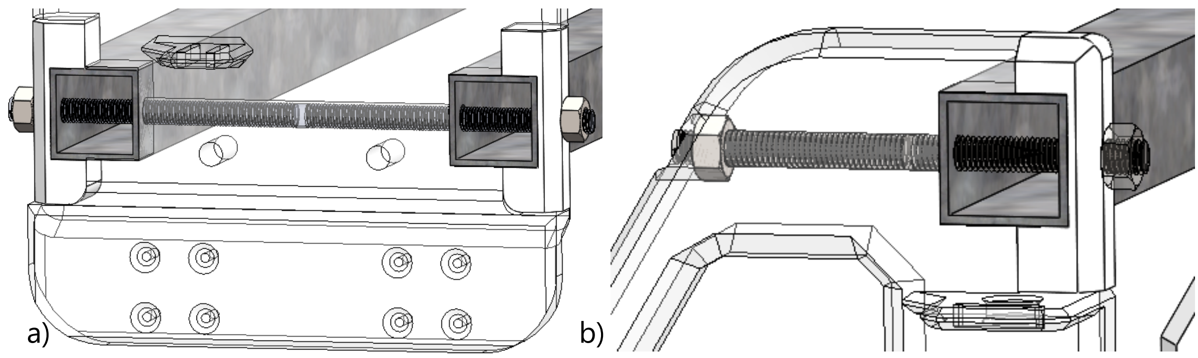


Figure 5.9 - Bolted connections a) Bottom X left gantry; b) Top X left gantry.

Apart from hardware, this subassembly incorporates the parts listed in Table 5.4. The technical drawings for the non-standardized components of the sub-assembly can be seen in Appendix C.

Table 5.4 - Main components used in X axis subassembly.

Component	Quantity
30x30x728x2t square steel tubing	3
X_Gantry_Right	1
X_Gantry_Left	1
X_Gantry_Clamp_Bot	4
X_Gantry_Clamp_Top	2

5.4.3 Y Axis

Mainly made of PLA+, the focal point of this axis is to transport the Z axis and consequently, the spindle motor, along the width of the machine. Unlike the X axis, this one has only one gantry and it isn't directly connected to the main frame, it is, however, connect to the YZ gantry, which in turn, is connected to the frame by linear rail guide blocks, as illustrated in Figure 5.10 a) and b).

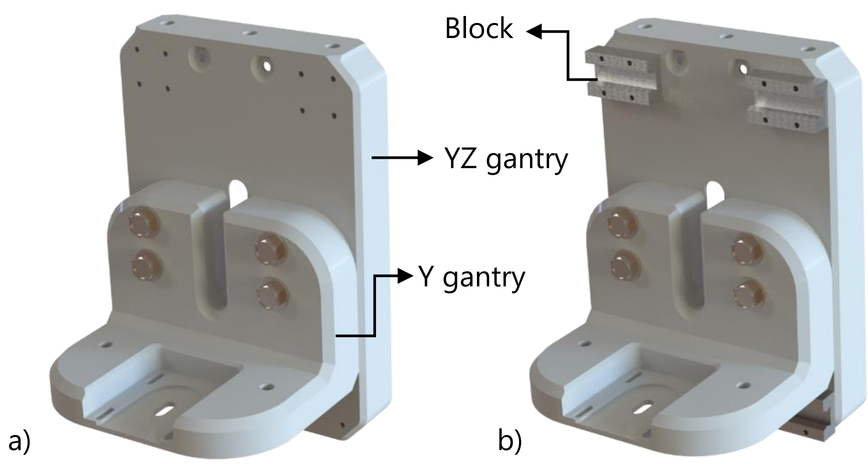


Figure 5.10 - Y axis subassembly a) without mounting points; b) with mounting points.

While Figure 5.11 a) shows that the Y gantry is linked to the YZ gantry through four hex bolts, Figure 5.11 b) clarifies that there are four Hex nuts embedded in the YZ gantry structure, which is where the bolts are fastened.

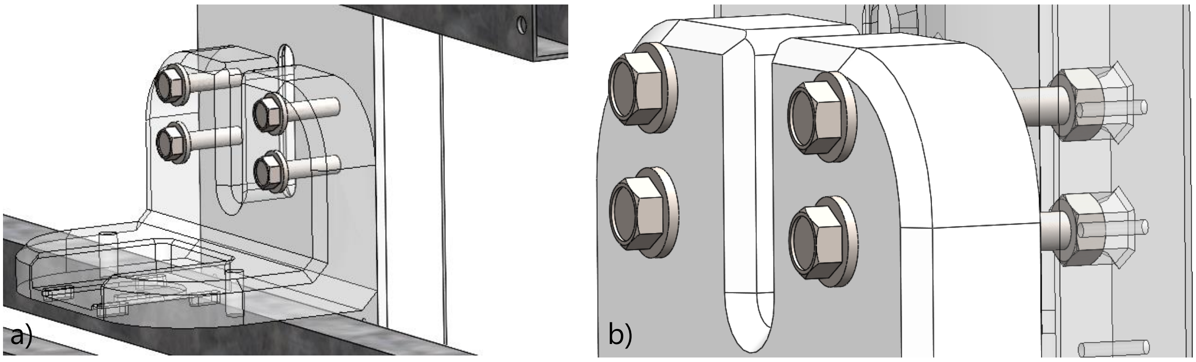


Figure 5.11 - Bolted connections a) Transparent Y gantry; b) Transparent YZ gantry.

Apart from the hardware used, this is the simplest subassembly, as it only integrates two main components, seen in Table 5.5. The technical drawings for the non-standardized components of the subassembly can be seen in Appendix C.

Table 5.5 - Main components used in Y axis subassembly.

Component	Quantity
Y_Gantry	1
YZ_Gantry	1

5.4.4 Z Axis

Responsible for the vertical movement of the tool, the Z axis subassembly shares the YZ gantry, which is proven by the Figure 5.12. Considering that the Z gantry and motor mount rely on the YZ gantry to be linked to the main frame, which means, it is part of both the Y and Z axis subassemblies, resulting in the YZ subassembly, seen in Appendix D.

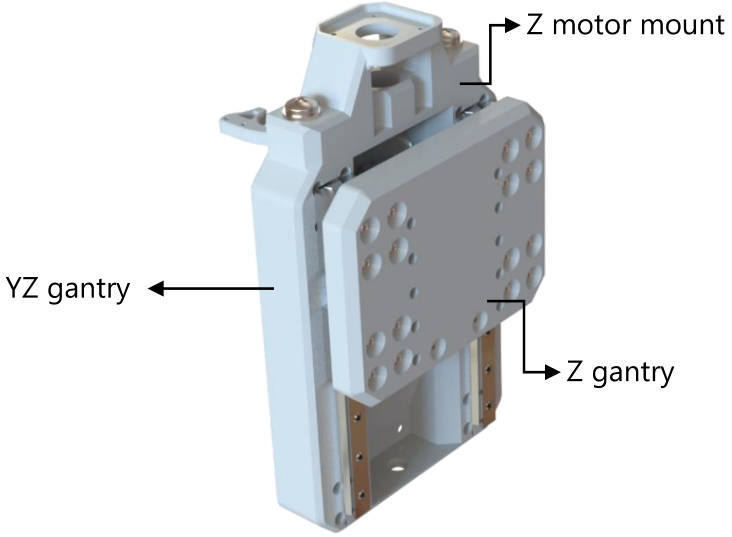


Figure 5.12 - 3D render of the Z axis subassembly.

As Figure 5.13 a) demonstrates, the Z gantry is linked to the YZ gantry through linear rail guides and blocks, which allow the upwards and downwards movement of the spindle. On the other hand, the Z motor mount is assembled with two bolts fastened to two embedded hexagonal nuts, as shown in Figure 5.13 b).

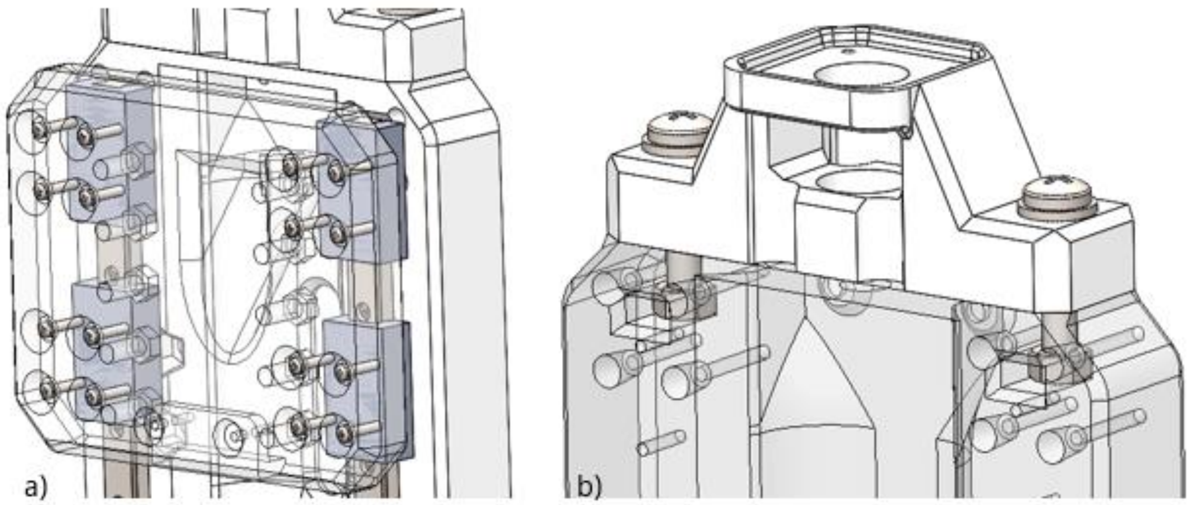


Figure 5.13 - Bolted connections a) Transparent Z gantry; b) Transparent YZ gantry.

Apart from the hardware used, this subassembly is composed by three main components, listed in Table 5.6. The technical drawings for the non-standardized components of the sub-assembly can be seen in Appendix C.

Table 5.6 - Main components used in Z axis subassembly.

Component	Quantity
Z_Gantry	1
Z_Motor_Mount	1
YZ_Gantry	1

5.5 Electronics

Following up with the anatomy analogy used previously in this work, the electronics of a machine are equivalent to the nervous system, which, like Figure 5.14 suggests, may seem very complex and hard to follow. For that reason, analogously to sub-section 5.4, the focal point of this sub-section is to simplify and break down the electronics used into four categories, the **motors**, the **power supplies**, the **control box**, and the **limit switches**.

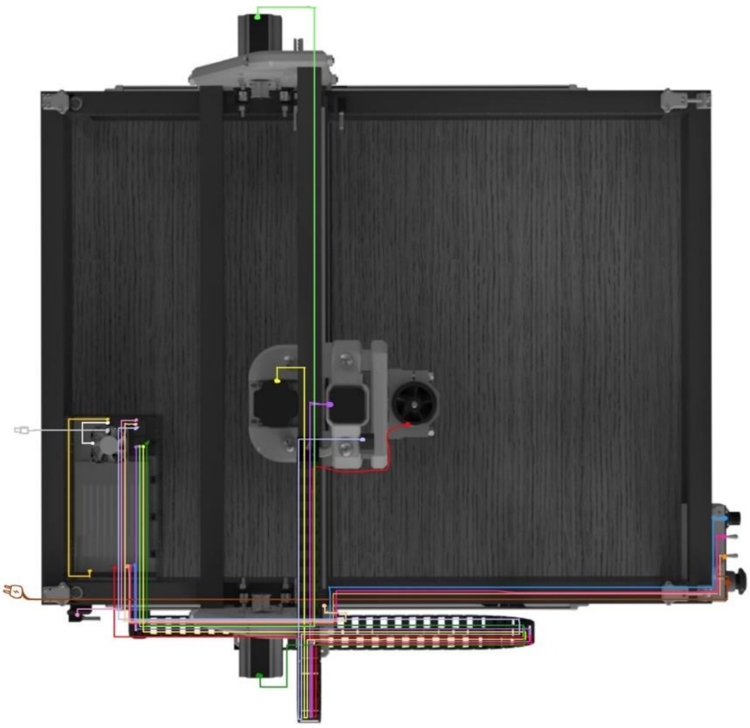


Figure 5.14 - Simplified representation of the cable routing.

5.5.1 Motors

In this prototype, there are two kinds of motors, the **stepper motors,** and the **spindle motor**. As stated in section 4.1.2, there are many variations of stepper motors, as they can vary in size, torque, precision, shaft dimensions, among others.

Nowadays, there are many CNC router machines running only on Nema 17 stepper motors, however, while this project must be as low cost as possible, the difference in price relatively to the more powerful Nema 23's, didn’t justify the possibility of the weaker motors being a probable limiting factor in future machining operations. Taking this into consideration, the Table 5.7 illustrates the motors utilized in the prototype as well as their key function.

Table 5.7 - Stepper motors used in the prototype.

Motor Type	Function
Nema 17	Moving the Z axis
Nema 23	Moving the X axis Moving the cloned X axis Moving the Y axis

The use of a Nema 17 is due to the lack of necessity for a high torque motor in the Z axis. This way, the cost as well as the weight, was reduced.

Initially, during the planning phase, the developer pondered the use of only one stepper motor per axis, since that's what's commonly done in desktop CNC machines, however, considering the distance between the X gantries (730mm), any movement on this axis would generate torque (τ), which would be applied to the motorized gantry, resulting in an offset between the left and right X gantries. On this note, since these must be perfectly aligned horizontally, while moving the exact same distances and directions, the developer decided to use two synchronized motors, avoiding that one of the gantries lags relatively to the other, as exaggeratedly represented in Figure 5.15 a).

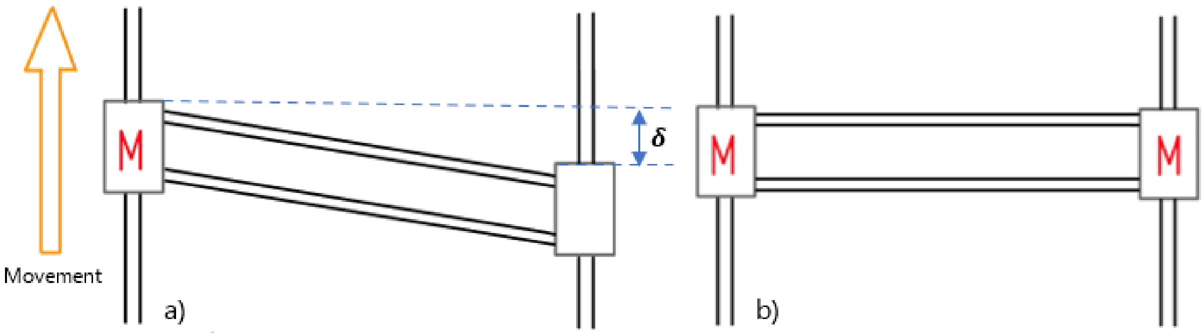


Figure 5.15 - a) Mono-motor X axis with lag (δ); b) Bi-motor X axis with no lag.

As previously stated, CNC machines don't always have to be associated to a subtractive manufacturing technology. Their purpose is, above all, linked to the tool that is being moved through a 2D plane or 3D space.

Even though the current denomination of the machine is "*3 Axes CNC Router*" the cutting tool is not a **trim router**, such as the one in the Figure 5.16, it is instead, a **spindle motor**. These two are commonly seen in homemade CNC machines, yet, their performance tends to differ.

Figure 5.16 - Makita woodworking trim router [84].

One of the reasons that leads hobbyists to choose a woodworking router over the spindle, is the ease of use. While a simple router is a "plug and play" instrument, a spindle, on the other hand, is connected to a variable frequency drive (VFD), which controls the motor speed and torque by varying the input frequency [85]. This difference in setup work is, after all, noticed in other parameters, such as power ratings, where a spindle, contrary to a router, can continuously hold the same power and if needed, it can maintain it for hours upon hours whereas a router will overheat and eventually, break down. Another big distinction is the noise levels each one produces [86]. Whilst a woodworking router is extremely loud (around 95dB) [87], a spindle motor is practically silent (around 70dB) [88], making it much more tolerable to be around when machining. All these perks come with a hefty price tag, which most of the time ends up being the deciding factor.

Nevertheless, continuing with the ideology of a low-cost machine, the choice was a 500W air cooled spindle with a dedicated VFD power supply, presented in the Figure 5.17. Typically, for this use, a spindle will provide more value for money than a router, yet, section 6.2.3 suggests an eventual upgrade for this component.

Figure 5.17 - 500W air cooled spindle motor, mounting bracket and power supply [89].

5.5.2 Power Supplies

This machine is divided into two systems, the **main system,** and the **spindle system**. For these to work as they should, there must be something that transforms the alternating current (AC) coming from the wall outlet, into direct current (DC). This is achieved with a power supply (PSU), which has to be chosen according to the **maximum current load** and **power** needed from the stepper motors. To avoid opting for an improper PSU for the main system, the developer used the information in Table 5.8 to make a few simple calculations.

Table 5.8 - Stepper motors, quantity and rated current, adapted from [90], [91].

Motor Type	Quantity	Rated Current [A]
Nema 17	1	2.0
Nema 23	3	2.8

The first variable to define is the driving voltage (V). Usually, Nema 17 stepper motors are indicated to use PSUs with V between 12 and 24VDC, while Nema 23 stepper motors, can use PSUs with V gaged between 24 and 48VDC [92]. Upon understanding this, the developer decided to choose the common value for both types of motors, a 24VDC PSU. Additionally, "it is always a good rule of thumb to add 20 percent more power and current to your calculations as a safety factor (SF)" [93], yet, considering this is an homemade product, the developer increased the SF to 60%.

- Equation 5.1, defines the PSU power value:

$$P = \left(\sum_{n=1}^{i} (n \times I_n) \right) \times V \times SF = Power \tag{5.1}$$

$$\sum_{n=1}^{i} (n \times I_n) = (3 \times 2.8) + (1 \times 2.0) = 10.4\ [A] = Motor\ Load$$

$$P = 10.4 \times 24 \times 1.6 = 399\ W$$

- Equation 5.2 determines the maximum current load for main system PSU.

$$SF = \frac{Max\ Load}{Motor\ Load} \Leftrightarrow Max\ Load = Motor\ Load \times SF \tag{5.2}$$

$$Max\ Load = 10.4 \times 1.6 = 16.6\ A$$

Considering the values discovered, the developer chose to use a 24VDC, 400W and 16.7A rated PSU, as illustrated in Figure 5.18.

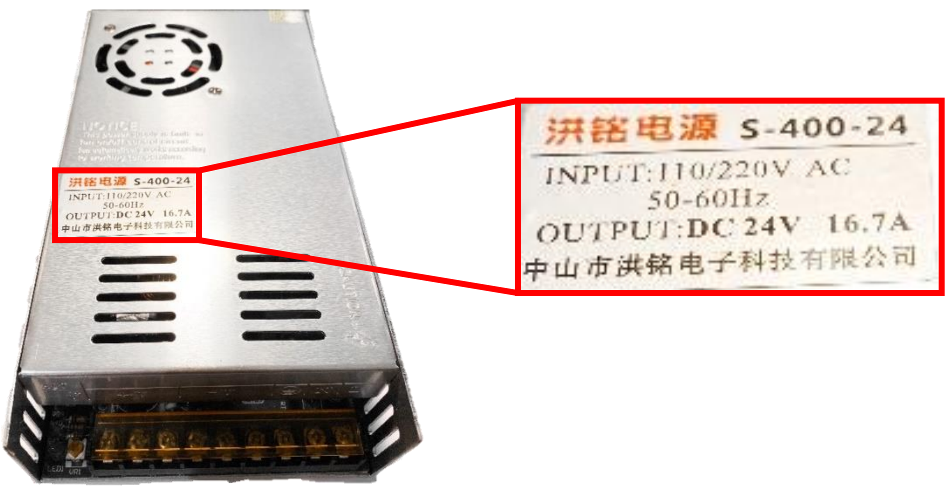


Figure 5.18 - Main system PSU and specifications.

Considering that the spindle came with its own VFD PSU (seen in Figure 5.17), the developer didn't have to choose. Nonetheless, it's important to notice that if precision is key, regardless of the machine, having a spindle motor demands a dedicated PSU. This is true because a spindle motor generates a lot of electrical noise that can easily interfere with the stepper motor drivers, leading these to operate ineffectively. Despite the existing electrical noise, the prototype has the PSUs and microcontroller crammed in an electronics box laser cut from acrylic as seen in Figure 5.19.

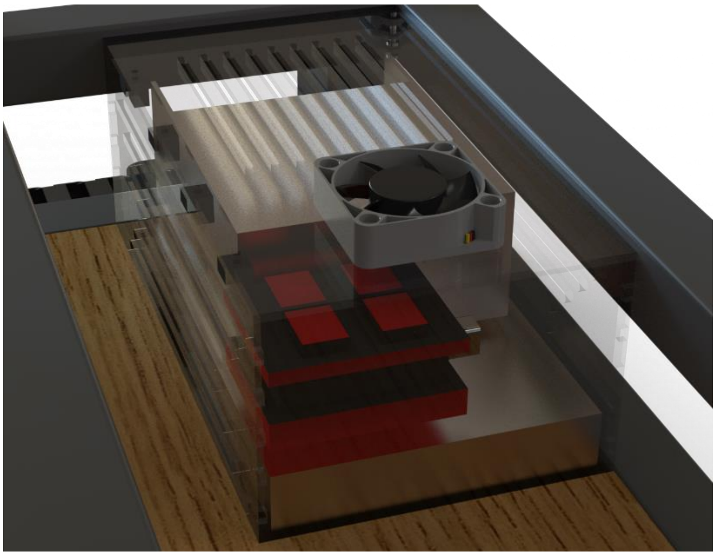


Figure 5.19 - 3D render of the electronics box.

5.5.3 Microcontroller

In view of the microcontrollers mentioned in section 4.1.1, the developer weighted parameters such as, acquisition cost, learning curve, and project integration complexity, which resulted in opting for the Arduino Uno.

Even though controlling motors with an Arduino board is as simple as connecting a few wires, controlling a stepper motor is not that straight forward. For this, it’s essential that each stepper motor has a dedicated driver, shown in Figure 5.20 a) for each stepper motor, which will greatly increase its accuracy, smoothness, and noise reduction during motion. On the one hand the addition of these drivers had great value to any CNC machine, on the other hand they significantly complicate the cable management/tidiness of the electronics section of a machine, which could lead to problems such as faulty connections and bad airflow, resulting in overheating. This conundrum was fixed with the creation of an Arduino expansion, known as a CNC shield, which will greatly reduce the system complexity. This unit plus the stepper drivers are fitted on top of the Uno board, as illustrated in Figure 5.20 b).

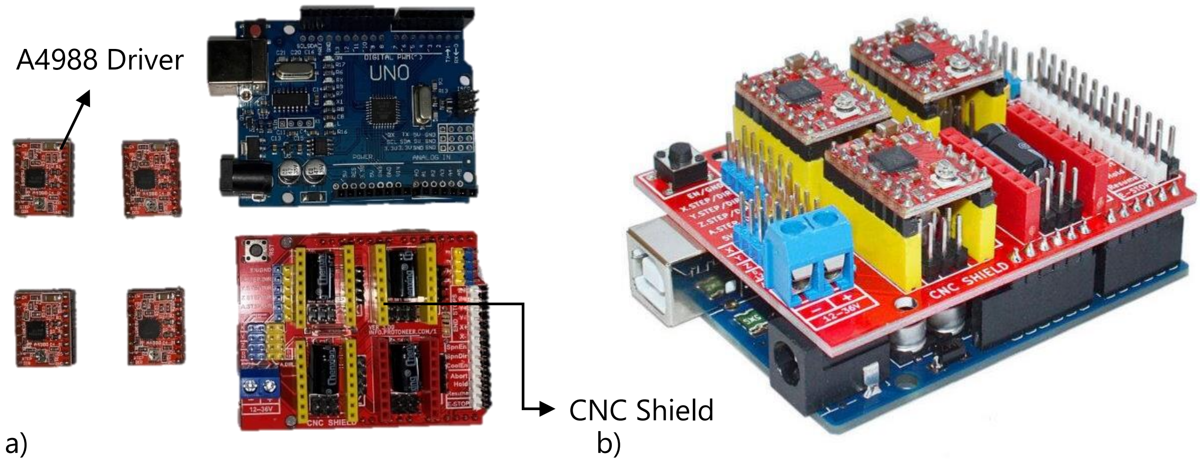


Figure 5.20 - a) Arduino Uno, shield and A4988 drivers; b) Assembled microcontroller [94].

As Figure 5.21 proves, it's important to notice these CNC shields have three slots, one for each stepper motor of each (x, y, z) axis, and a fourth slot (A) to connect a fourth stepper motor, in case one axis needs a cloned motor, which is verified in this work's prototype.

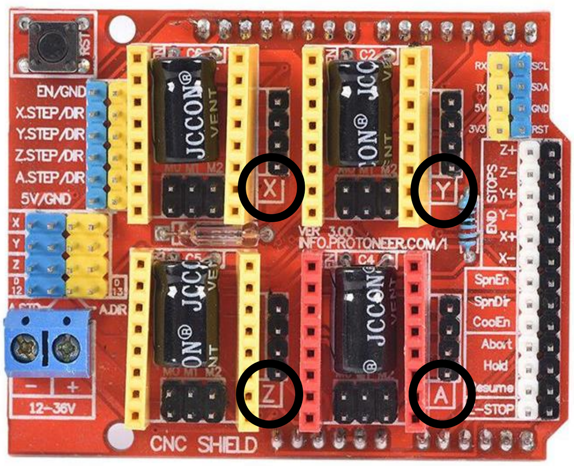


Figure 5.21 - CNC shield, stepper motor slots.

5.5.4 Control Box

Main commands such as jogging the axes, starting/stopping a machining operation, homing the machine, among others, are done through instructions given to a computer which is hooked to the microcontroller.

Considering that one of the developer's goals was to build a clutterless machine, the control box was designed to hold only three switches and one potentiometer as Figure 5.22 a) and b) exemplifies.

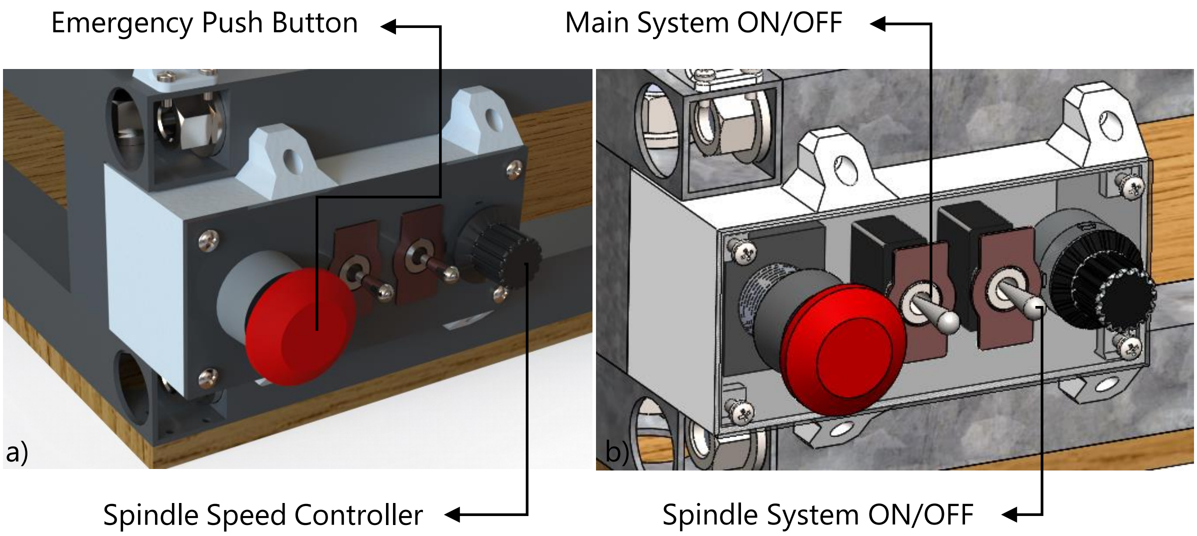


Figure 5.22 - a) 3D render of the control box; b) Inside view of the control box.

Of these, the most important and indispensable for most machines, is the emergency push button (EPB), which is a crucial safety measure and should be pressed in any unpredicted situation. Things like weird noises, wrong endmill, wrong settings, overheating, among others, are reason enough to press the EPB. Considering that the developer wired this EPB in the normally closed (NoC) position, the pressing of this button opens the circuit, resulting in an instant "all systems shut down" that can avoid costly damages to the machine or even, the user. It's also important to understand that once the EPB is pressed, all the other switches become invalidated. Next to the EPB is the main system ON/OFF lever switch, which as its name implies, turns ON the main system's PSU, activating the stepper motors, or OFF, shutting down all movement in the axes. Right besides this, there is another ON/OFF lever switch, however, this one affects the spindle VFD PSU. Finally, the potentiometer on the right, acts as the spindle speed controller (SSC). The SSC plays an important role in a successful machining job because every material, bit and combination of settings needs the spindle to rotate at a specific number of rotations per minute (RPM).

After the wiring seen in Figure 5.23 a), the developer faced the challenge of neatly routing the cables to the inside of the structure, which was achieved as Figure 5.23 b) demonstrates.

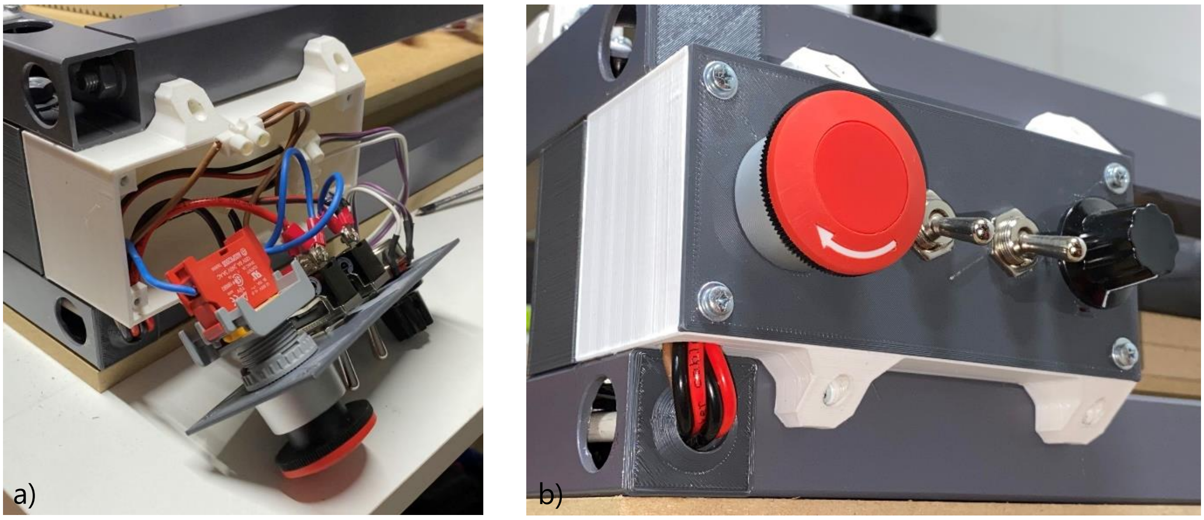


Figure 5.23 - Prototype, a) control box wiring; b) control box cable routing.

5.5.5 Limit switches

Perhaps the most challenging component to integrate reliably, the limit switches (LS) allow the machine to be spatially aware of the tool's position. The developer considered this to be a great asset because it enables the machine to possess coordinates of origin, i.e., where the coordinates are $(x,\ y,\ z) = (0, 0, 0)$. Consequently, this gives the machine the ability to avoid going off limits and possibly wreck itself. Furthermore, this feature immensely facilitates the CAM stage of a machining process, considering that it is possible to standardize the position of the stock in a certain $(x,\ y,\ z)$ set of coordinates relatively to the origin, which saves time during the set-up phase. Figure 5.24 a), b) and c) shows the 3D render of the LS used in each axis.

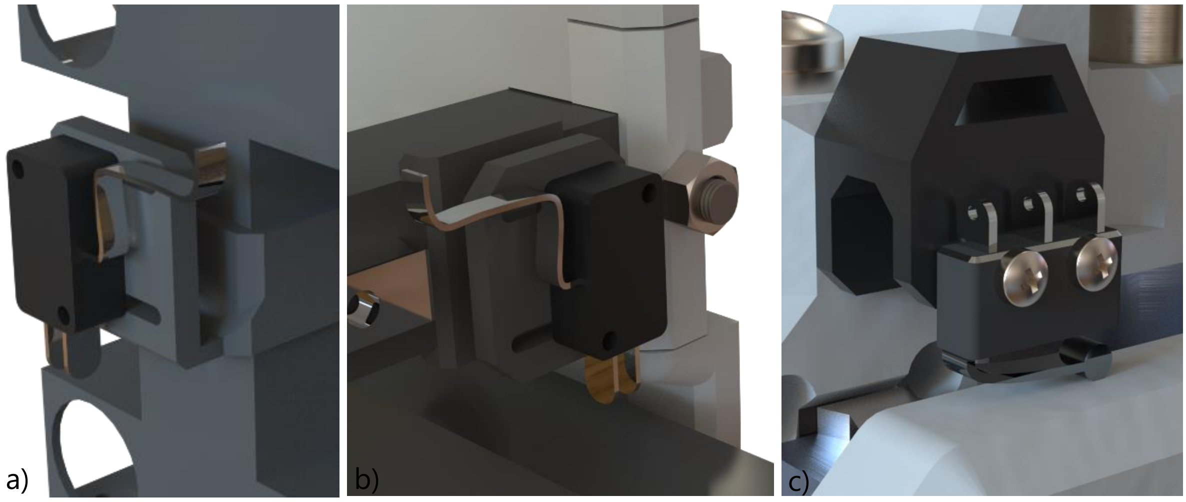


Figure 5.24 - 3D render of a) X axis LS; b) Y axis LS; c) Z axis LS.

Although it seems like an easy component to install and set-up, it took the developer an entire month of troubleshooting and problem solving to figure out that the key issue was electrical noise. Nonetheless, before arriving to that conclusion, the developer tried a wide array of things such as different LS, tampering with the *config.h* file, different positioning, thicker cables, among others. However, after researching through many forums and videos, the developer understood that these switches have also the designation of "sensor" which usually is connotated with hypersensitive equipment, that can be triggered with the smallest disturbance. Taking that into consideration and supposing that there could be high amounts of electrical noise in the electronics box, the developer tried scattering the PSUs and micro-controller, instead of having them crammed inside the box, which isn't ideal for electrical noise reduction. Once this test was deemed successful, the developer changed the LS cabling to shielded cables, which "reduce volume and intensity of all kinds of electrical noise" [95], finally solving the problem. Figure 5.25 shows the shielded cables used in the prototype.

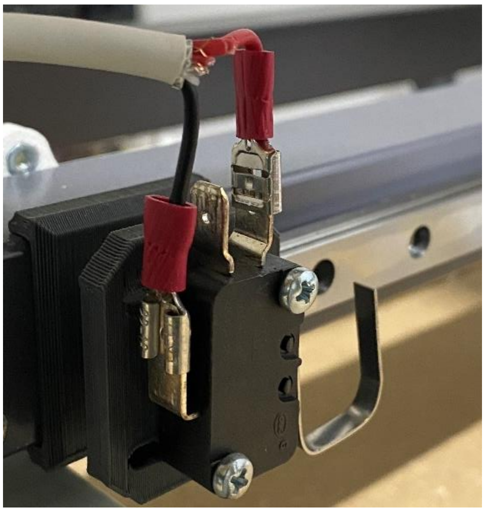


Figure 5.25 - Y axis LS with shielded cable.

5.5.6 Electronics Schematics

Although Figure 5.14 suggests that the electronics of the machine are difficult to follow, these are quite easy to understand. Nevertheless, this sub-section doesn't go into too much detail on all the connections, instead, it explains the simplified electronics schematic presented in Figure 5.26.

To better understand the schematic, Appendix A shows a table where all the electronic symbols and designations are listed.

- Power coming from the wall outlet (AC) goes through the EPB and is then sent to both PSUs.
- The spindle system VDF PSU powers the spindle and it has a potentiometer connected to control the rotational speed of the spindle.
- The main system PSU powers the Arduino Uno board that is connected to the CNC shield + drivers.
- Connected directly to the Arduino board is a cooling fan, to keep the temperature in the electronics box as low as possible.
- Each stepper motor is connected to a certain stepper driver on the CNC shield.
- Each LS is connected to a certain axis's limit sensor pins.

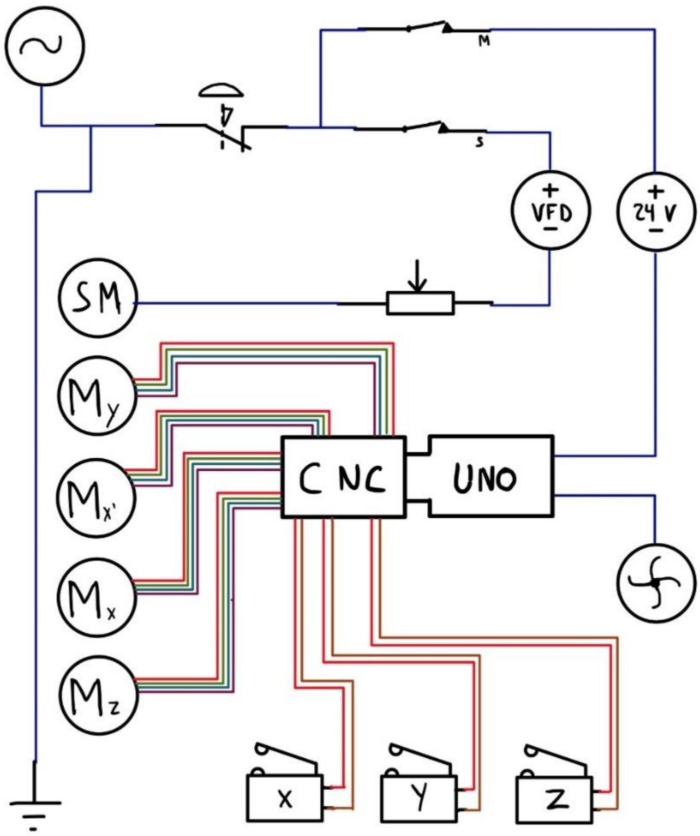


Figure 5.26 - Simplified electronics schematic for the prototype.

5.6 Complete Assembly

This stage's success is almost completely dependent on a good planning phase. If the assembly's chronological order of a single bolt is off, it can turn into a costly mistake. For instance, despite having invested a lot of time carefully planning the process, during the assembly of the prototype, the developer noticed that some parts couldn't be assembled as planned, which ended up costing a few days in manual labor, and more 3D printing resources. Regardless, this sub-section doesn't dive into the detailed order of assembly, on the other hand, it simply demonstrates the way that each axis accommodates its hardware and, consequently, how all three axes link with each other and the main frame.

Figure 5.8 illustrates the general architecture of the X axis, however, to be able to do its job and work in tandem with the other axes, it's fundamental to add the hardware. Firstly, on Figure 27 a), it's possible to observe one Nema 23 stepper motor sunken into the gantry and secured with four bolts and nuts. Next to it, there's the X axis LS, which is screwed on a 3D printed part that snap-fits on the steel profile, as seen in Figure 5.25. Figure 5.27 b) presents the inside of the gantry which integrates the timing belt pulley, a timing belt engagement angle system made of 3D printed spacers and rigid ball bearings held in place by hexagonal nuts and bolts and two linear rail guide blocks secured with 8 bolts. It's important to keep in mind that in the X axis, every piece of hardware needed is duplicated because there are two gantries.

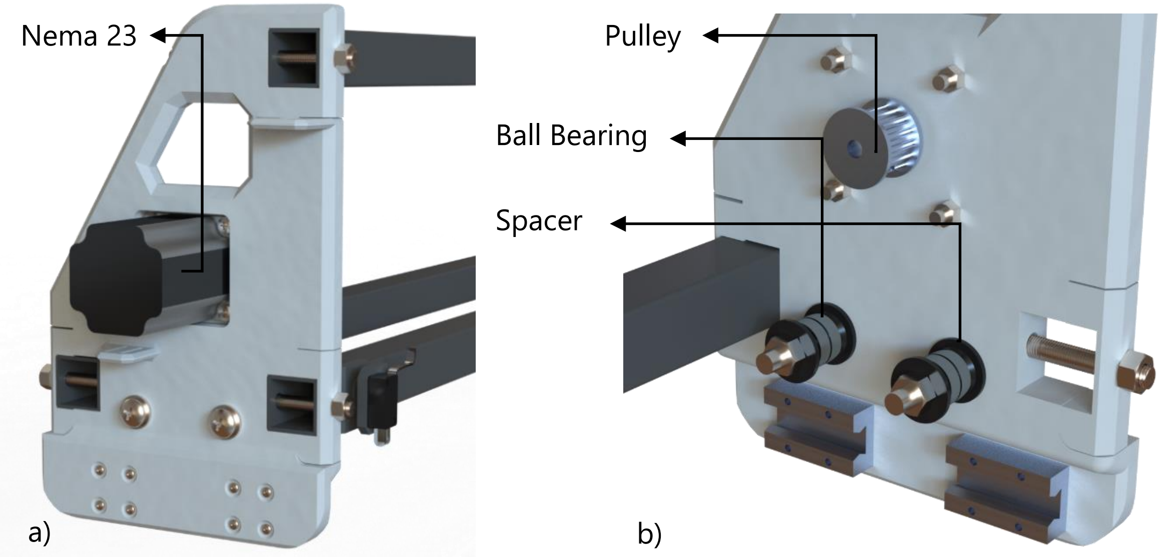


Figure 5.27 - 3D render a) Left X gantry with hardware; b) Right X gantry with hardware.

Following up with the simplest axis, apart from the components shared in section 5.4.3, the Y axis only has one Nema 23 stepper motor and a contact angle system similar to the previous one, as displayed in Figure 5.28. Furthermore, as previously mentioned, the YZ gantry is also part of the Y axis, however, considering that the Z gantry has more dependency with it than the Y, the YZ gantry's hardware is only displayed in the Z axis subassembly portion of this section.

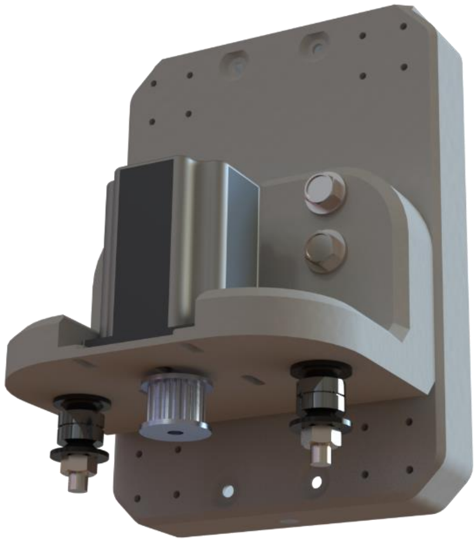


Figure 5.28 - 3D render, Y gantry with hardware.

To facilitate the understanding of the Z axis subassembly, it is divided into two parts. Firstly, the sub-subassembly shown in Figure 5.29 a) integrates the Z axis LS, which is mounted on a bracket that is glued to the motor mount. This mount also holds a Nema 17 stepper motor that has its shaft attached to a coupling, seen in Figure 5.29 b), which is also connected to the leadscrew. To make sure that the leadscrew is constantly perfectly perpendicular to the work area surface, it is guided through two bearings that are fixed on the YZ gantry.

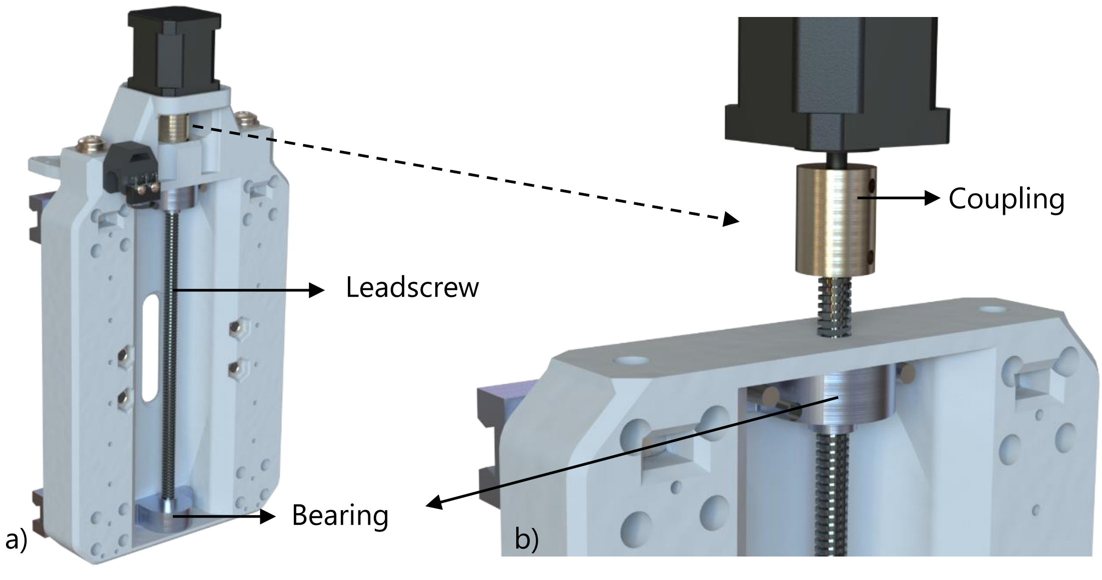


Figure 5.29 - Hardware, a) Z motor mount and YZ gantry; b) Z driving system close-up.

The sub-subassembly in Figure 5.30 a) is composed by the 500W spindle motor that is held by an aluminum bracket that is tightly bolted to the Z gantry. On the back side of the gantry, there are multiple embedded hexagonal nuts that give more flexibility to the mounting point height of the spindle bracket. Furthermore, the developer installed a special nut, designed to have almost no friction, which is where the leadscrew screws into, as shown in Figure 5.30 b).

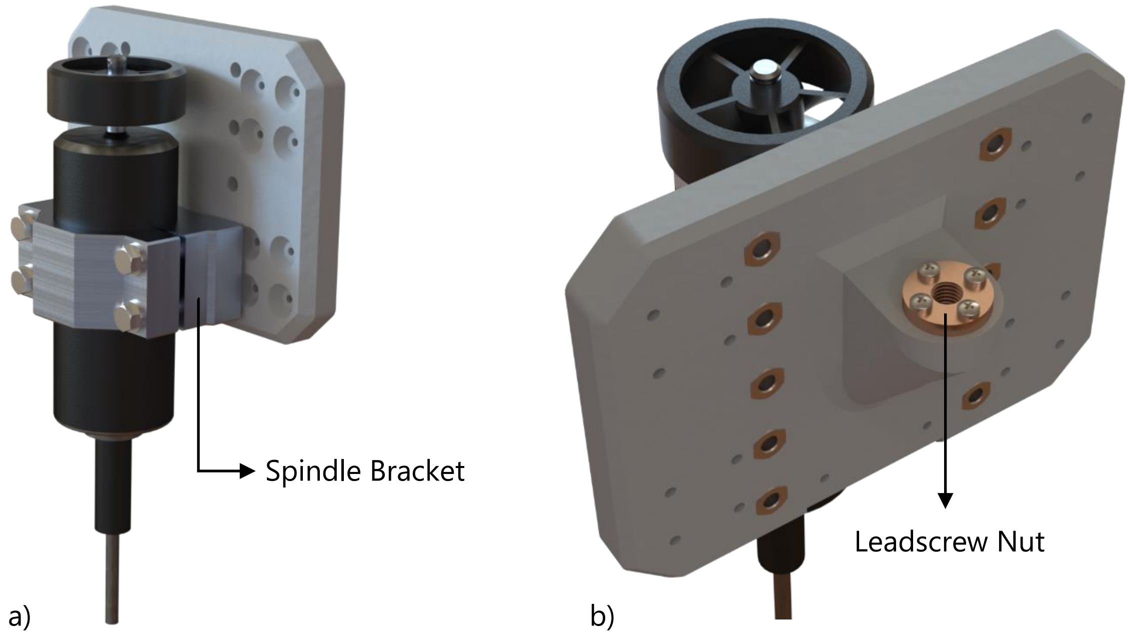


Figure 5.30 - a) Front of Z gantry with hardware; b) Back of Z gantry with hardware.

To link both sub-subassemblies, the developer made use of two linear rail guides, screwed on the YZ gantry, and four rail blocks, secured to the Z gantry. As illustrated in Figure 5.31, considering that the leadscrew nut is fixed to the Z gantry, the rotation of the leadscrew, generated by the stepper motor is then transformed to the linear movement of the Z gantry and, consequently, the spindle. This, combined with the action of the linear guide rails and blocks, enables a predictable and smooth vertical motion.

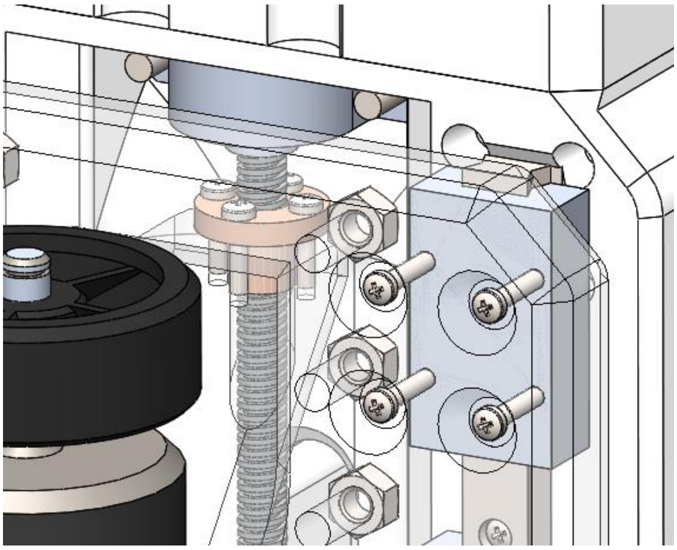


Figure 5.31 - SolidWorks 3D model, Z gantry vertical motion system.

Finally, Figure 5.32 a) and b) shows that all subassemblies are attached to the main frame using linear rails.

Combining the electronics with all the components assembled in a specific way, translates into a properly working prototype with all the subassemblies functioning in perfect harmony.

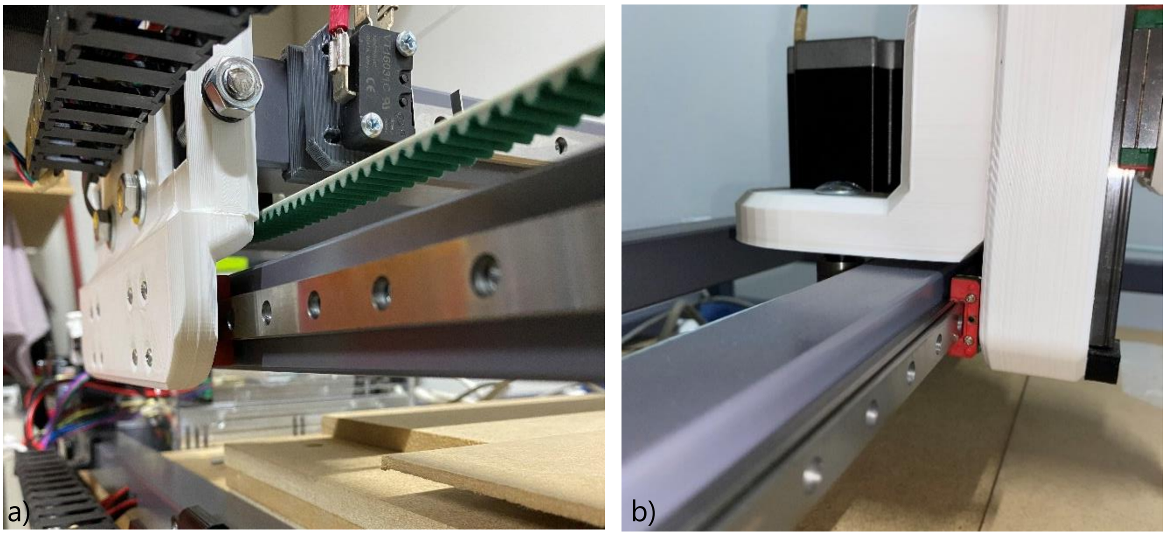


Figure 5.32 - Prototype, a) Left X gantry; b) YZ gantry.

5.6.1 Timing Belt Drive

As previously mentioned, this prototype has two types of driving methods, i.e., two timing belt driven axes and one leadscrew driven axis. At this point, the Z axis vertical movement has already been clarified, yet it's also important to understand the **movement of the X and Y axis**

The key factors of this driving method are simple:

- **Engagement angle (EA)**- Angle of contact between the belt and the pulley, the maximum value being $CA = 180°$.
- **Tension-** How much tension is the timing belt under? It can't be so low that the pulley can't grip the belt's teeth, and not so high that it overloads the stepper motors. It must be somewhere in between.

Although the working principle is the same in both axes, these key factors differ slightly. Comparing Figure 5.33 a) and b), it's clear that the X driving system has a more accentuated EA.

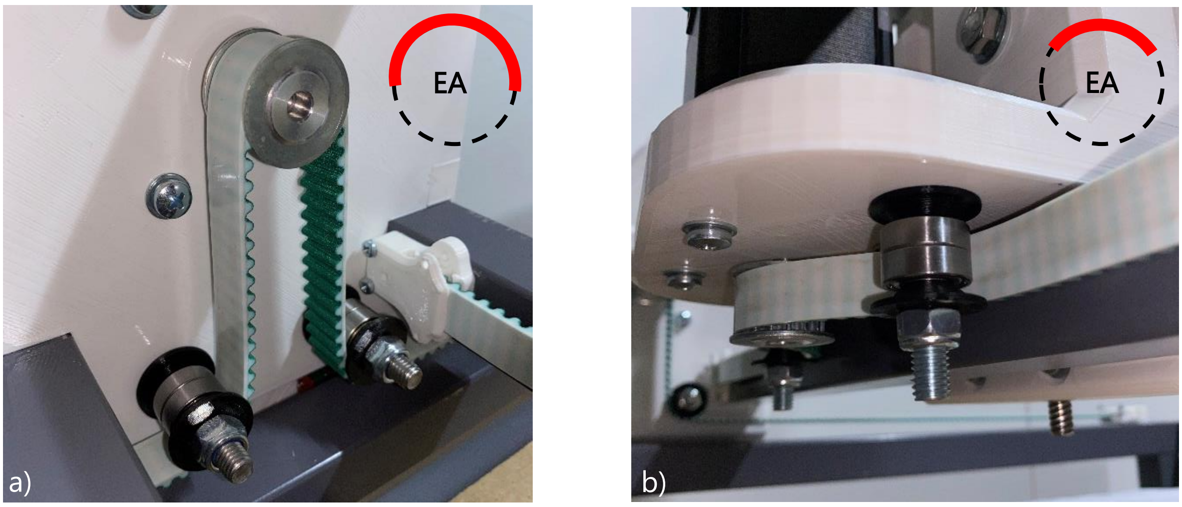


Figure 5.33 - Prototype, EA representations of a) X axis; b) Y axis.

Analyzing Figure 5.34 a), it's clear that the action of turning the bolt clockwise, tightens the belt while Figure 5.34 b) shows a tensioning method that relies on the variable stepper motor placement, i.e., the more it is pulled back, the more tension the belt is under. Considering the different tensioning methods used and the lack of measuring tools, the tension of each axis's belt may vary, which is not ideal, however, after a few stress tests, there was no belt slippage in either system.

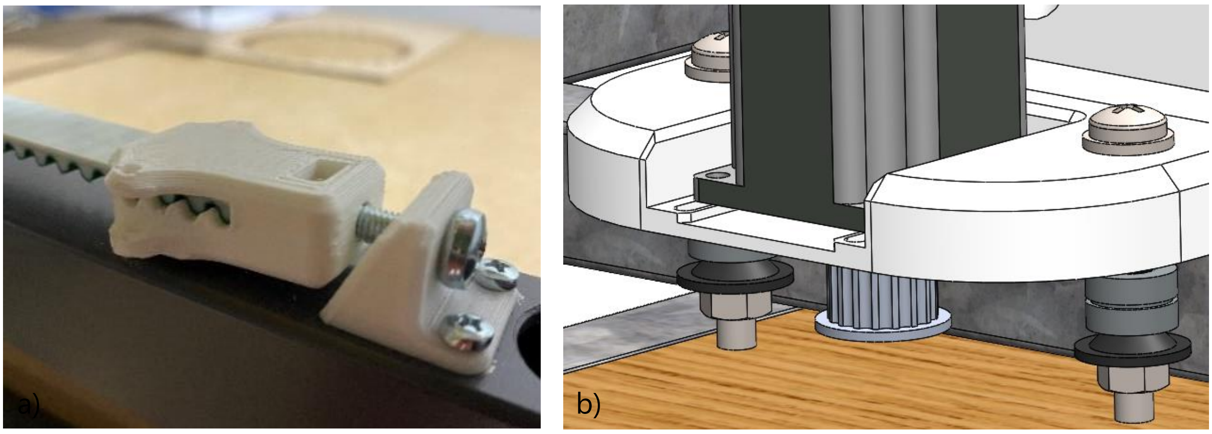


Figure 5.34 - Tensioning system, a) X axis; b) Y axis.

5.7 Tolerance Analysis

Since the functions of this prototype rely heavily on high precision operations, there are some tolerances that must be carefully defined.

The developer started by studying the **dimensional** tolerances by following these steps:

- Determine the nominal size (NS) of the bore/shaft.
- Define the type of adjustment according to the table in Attachment I.
- According to the adjustment and NS, determine the quality (IT) and fundamental tolerance (TOL) from Attachment I.
- Depending on the component being dimensioned, analyze the bore or shaft tables seen in Attachment I to define the superior deviation (DS for bores and ds for shafts).
- Using Equation 5.3, calculate the inferior deviation (DI for bores and di for shafts)

$$TOL = (DS, ds) - (DI, di) \Leftrightarrow (DI, di) = (DS, ds) - TOL \qquad (5.3)$$

Considering that all the bearings, pulleys and couplings are standardized components, there was no need to dimension those as that had already been done by the manufacturers. In this case, the developer only deemed necessary to analyze the tolerances of two fittings, the spindle motor/holder and steel tube/fixture, seen in Figure 5.30 a) and 5.9 b) respectively. Table

5.9 lists the results of this analysis which can be seen applied in the technical drawings in Appendix D.

Table 5.9 - Dimensional tolerances analysis results.

	Spindle Motor	Spindle Holder	Square Tubing	Tubing Fixture
NS & Adjustment (mm)	52h6	52K7	30h6	30N7
Quality	IT6	IT7	IT6	IT7
TOL (mm)	0.019	0.030	0.013	0.021
DS (mm)	0	0.009	0	-0.007
DI (mm)	-0.019	-0.021	-0.013	-0.028
Dimension (mm)	$\mathbf{52^{0}_{-0.019}}$	$\mathbf{52^{0.009}_{-0.021}}$	$\mathbf{52^{0}_{-0.013}}$	$\mathbf{52^{-0.007}_{-0.028}}$

Apart from the dimensional tolerances, there are also **geometrical** tolerances, which are crucial to better understand certain features and relations between components that greatly affect the performance of the machine. Some of these features are perpendicularity, axis alignment, concentricity, parallelism, etc. However, although there are geometrical tolerances in the technical drawings shown in Appendix D, this work doesn't go into detail on how the developer achieved those values.

5.8 Wasted Material & Cost

Unlike the steel tubing preparation and assembly that was conducted exactly as planned, the 3D printed parts created a few challenges. Despite all the preparation, calculations, and tolerance analysis there is always a need to design and print test parts which in the end don't have any use for the prototype, turning them into wasted material. Additionally, there were also a few unexpected situations which led the developer to redesign and reprint some parts. For a project of this magnitude, all these conundrums add up, resulting in an amount of **wasted 3D printing material of about 1227 g**. This value was determined by the developer by weighing the bad parts (BP), adding that to 5% (support material) of the total weight of good parts installed (GP) in the prototype, which was calculated by the adding of the weight values shown in Appendix A, and finally, adding that value to 5% of the BP. Equation 5.4 illustrates this calculation.

$$Wasted\ Material = 0.05BP + (BP + 0.05GP) \tag{5.4}$$

$$Wasted\ Material = 0.05 \times 1050 + \big(1050 + (0.05 \times 2486)\big) = 1227\ g$$

According to section 5.3, translating this value to cost, it would be around 27€, however, this is only relative to the material used i.e., to have a more realistic number, the energy spent, and machine wear would have to be taken into consideration.

Apart from this, the total cost of the prototype is estimated to be around 460€, according to Table A2 and A3 on Appendix A, which means that the wasted material is worth about 6% of the total value.

6

ANALYSIS AND DISCUSSION OF THE CURRENT PROTOTYPE

Regarding all the information presented in section 5, and taking into consideration the knowledge listed in Table 3.1, the prototype can be classified as a "Beta prototype for field testing", as illustrated in Figure 6.1. Recognizing the proximity to the final product, the developer deemed fundamental to conduct an analysis on a few features of the prototype to better understand its limitations, which is the focal point of this section.

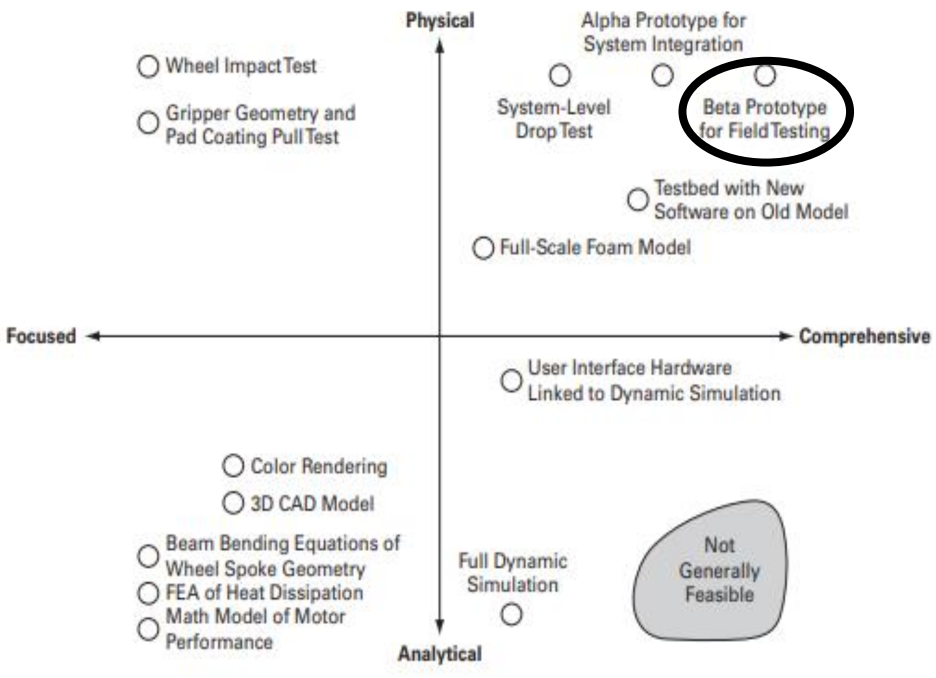


Figure 6.1 - Types of prototypes [40].

6.1 How to Machine a Part

Before starting the testing stage, it is important to fully understand all the machining process steps:

- **2D sketch/ planning**
- **3D Modeling**- Using *SolidWorks 2020* in this case.
- **CAM**- Using *Autodesk Fusion 360* in this case.
- **Post Processing**- Using *Autodesk Fusion 360* in this case.
- **CNC Controller Software**- Using *Universal Gcode Sender* in this case.
- **Machine Set Up**
- **Test Run**
- **Analysis and Fine Tuning**

Even though some of the steps have already been mentioned and clarified in this document, there are a few that still need to be explained.

6.1.1 Post Processor (PP) & CNC Controller

Once the user is satisfied with the toolpaths generated in the CAM stage, it is necessary to translate that information into something that the microcontroller can read, i.e., a G-code file, which is the role of the PP. It's also crucial to use the correct PP since there is a wide array of options for different machines [96]. For this work the developer used the *GRBL* PP option available in *Autodesk Fusion 360* since the library installed in the microcontroller is also the *GRBL* library.

The G-code file is then given as an input to the microcontroller through the Java-based application, *Universal G-code Sender* (UGS) via a serial communication port [97]. Using UGS, the developer can freely jog the machine's axes, adjust speeds, feeds, see the preview of the toolpaths, among others, as represented in the Figure 6.2.

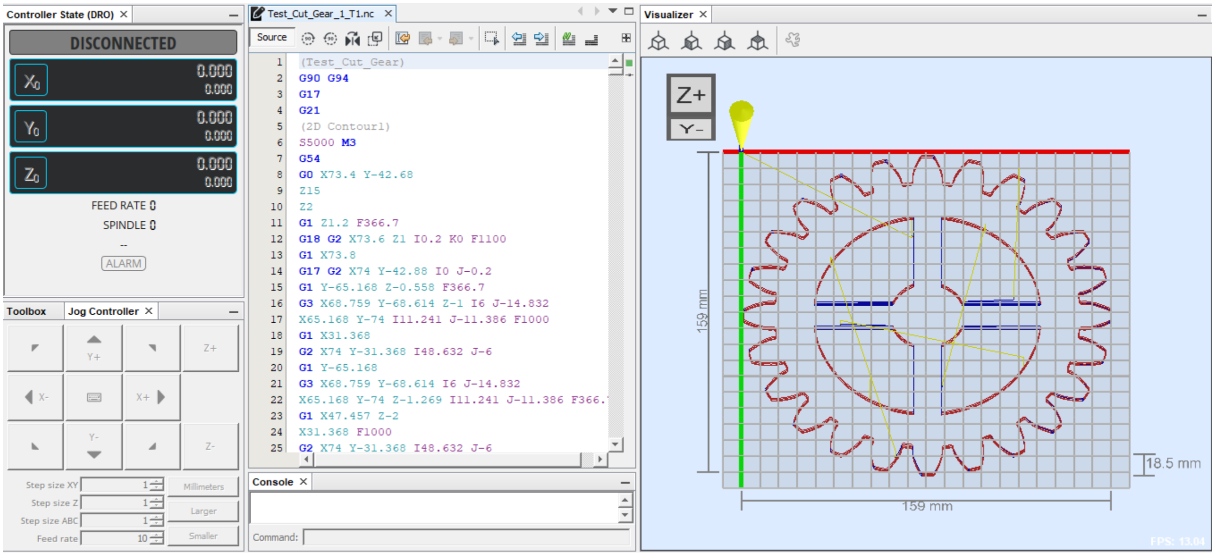


Figure 6.2 - CNC controller software, UGS.

6.1.2 Set Up & Test Run

Before starting the machining operation, the user must set the zeros, i.e., $(x, y, z) = (0,0,0)$, so the machine knows where to cut relatively to those coordinates, it's also crucial to install the correct cutting tool for the operation and then, as safety measure, the user can start the machining job with a Z offset. This technique enables the machine to execute the toolpaths without touching the material, which greatly facilitates the visualization of potential errors.

Once the user verifies the safety of the operation, the machining job can be initialized.

6.2 Performance Analysis

A machine can be expensive, cheap, big, or small but perhaps, its most important and differentiating aspect, is the performance achieved. This section highlights some of the tests and simulations performed by the developer to better gauge the performance and limitations of the current prototype.

6.2.1 Microstepping

As stated in section 4.1.2, "the stepper motor does not rotate in a continuous fashion, instead, it moves in discrete steps or increments". Depending on the stepper motor, it needs a certain number of steps to complete a full rotation. Figure 6.3 acts as an example of a motor which has only 4 steps per rotation, which means that the angle between each step is given by:

$$Angle\ per\ step = \frac{Full\ rotation\ angle}{Number\ of\ Steps} \quad (6.1)$$

$$Angle\ per\ step = \frac{360°}{4} = 90°/step$$

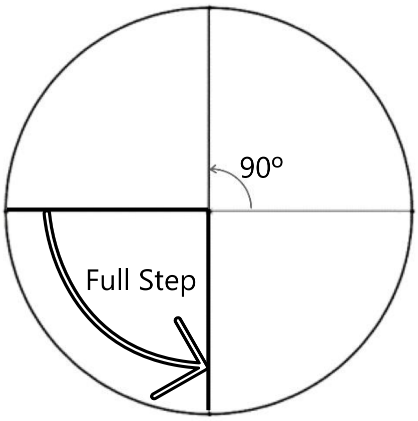


Figure 6.3 - Example of a 90º/step stepper motor.

Out of the box, all four stepper motors used in the prototype have a 1,8º angle separating each step, which according to Equation 6.1, proves that a full rotation is only completed after:

$$Number\ of\ steps = \frac{360°}{1.8°} = 200\ [steps/rotation]$$

Although these motors can already rotate by very small increments at a time, as Figure 6.4 suggests, they still aren't precise enough for the pretended goal.

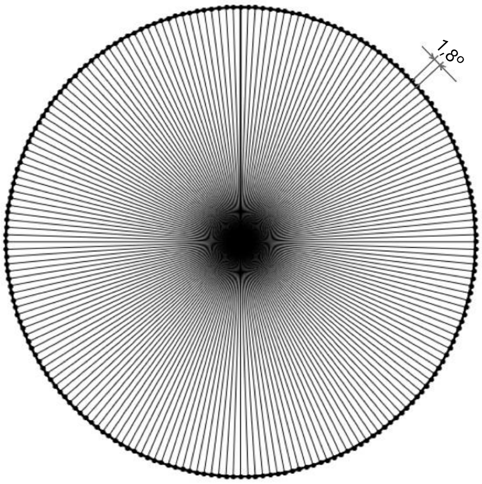


Figure 6.4 - Example of a 1,8°/step stepper motor.

To increase the resolution and precision of the motors, the developer used a feature present in the microcontroller that enables **microstepping**, which in essence, gives the motor the ability to divide steps into smaller steps. For instance, in their original state, stepper motors run on a "Full Step" condition, i.e., $1\ full\ step = 1\ step$, however, the microcontroller seen in Figure 5.20, enables up to a "Sixteenth Step" condition, i.e., $1\ full\ step = 16\ small\ steps$, which transforms the original 200 steps/rotation into:

$$200 \times 16 = 3200\ [steps/rotation]$$

As the microstepping increases, so does the motion smoothness, torque delivery consistency and dimensional accuracy of machined parts. On the other hand, these changes result in less available torque [98]. Knowing this, and considering the options listed in Table 6.1, the developer chose a less extreme microstepping option, the "Eighth Step".

Table 6.1 - Microstepping options and connections for A4988 stepper driver [99].

MS0	MS1	MS2	Microstep Resolution
Low	Low	Low	Full step
High	Low	Low	Half step
Low	High	Low	Quarter step
High	High	Low	Eighth step
High	High	High	Sixteenth step

As the critical issue of microstepping is the loss of torque, the developer decided to calculate the incremental torque produced with each microstep, τ_{INC} (Nm) in Equation 6.2, where τ_{HFS} [Nm] is the motor holding torque, which is a value given in the "Full Step" configuration by the manufacturer, and SDR is the step division ratio, in this case, $SDR = 8$. Taking that into consideration, the "Eighth Step" configuration offers:

$$Number\ of\ steps = 200 \times 8 = 1600\ [steps/rotation]$$

$$\tau_{INC} = \tau_{HFS} \times \sin\left(\frac{90}{SDR}\right) \tag{6.2}$$

For the Nema 17:

$$\tau_{INC} = 0.49 \times \sin\left(\frac{90}{8}\right) = 0.0956\ [Nm]$$

For the Nema 23:

$$\tau_{INC} = 1.9 \times \sin\left(\frac{90}{8}\right) = 0.371\ [Nm]$$

It's important to understand that for the "Full Step" configuration, $\tau_{INC} = \tau_{HFS}$, which means that the incremental torque loss for both types of motor, in percentage is:

$$\tau_{INC}\ Lost = 100 - \left(\frac{0{,}096}{0.49}\right) = 100 - \left(\frac{0{,}37}{1.9}\right) \Rightarrow 100 -\ (0.195 \times 100) = 80.5\ \%$$

After some testing, the developer considered that the elevated precision and overall machining quality of the prototype outweigh this setback.

Analyzing Table 6.1 once more, there is a code which serves as a guide on how to connect the jumper pins to the CNC shield, seen in Figure 6.5, to achieve the desired microstepping configuration.

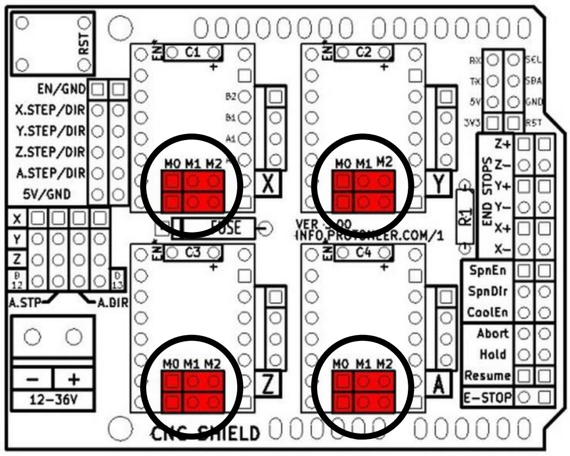


Figure 6.5 - Location of the microstepping pins in the CNC shield [98].

Microstepping is sometimes considered a good alternative to mechanical gearing because it does not introduce backlash into the system or reduce its maximum speed.

6.2.2 Structure Deflection

One of the main reasons for inaccuracies on the machining operations is due to the deflection of the structure itself, which is a consequence of the total weight supported and the cutting force.

Firstly, the developer analyzed the **vertical deflection** of the steel tubing **resulting from the weight supported**. Observing Figure 5.4, it's clear that both the YZ and XYZ subassemblies are always supported by two steel tubes, however, Figure 6.3 a) and b) illustrate a simplification where the developer considered that **only one** steel tube is supporting the load created by the weight. On that note, from this point onward, it's important to know that all the values obtained are approximations due to the impossibility of gauging other important variables.

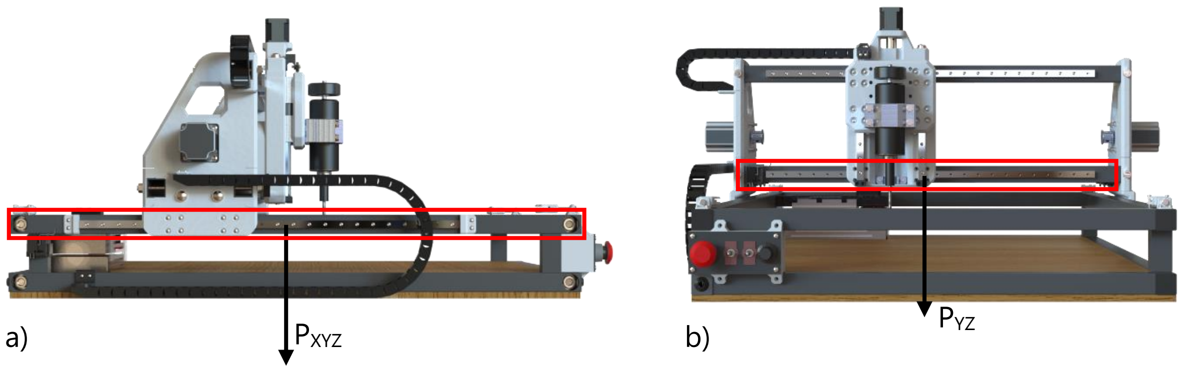


Figure 6.6 - Steel tubes with load applied, a) XYZ load; b) YZ load.

To have a better perception of the prototype limitations, the developer started by stipulating that the maximum displacement admissible (δ_{adm}) is given by the values in 6.2.

(6.2)

- For the **Y axis** steel tubes:

$$\delta_{adm}Y = 1.2\ mm$$

- For the **X axis** steel tubes:

$$\delta_{adm}X = 1.5\ mm$$

The weight of both subassemblies can be determined by adding up all its component's weight which are presented in Appendix A. Knowing those values, it's possible to define the loads applied by simply multiplying those by the gravitational acceleration (g). Once that's complete, it's finally possible to know deflection of both axis's steel tubes.

- For the **Y axis**:

$$Weight_{YZ} = \sum Component_{weight} = 6.3\ Kg$$

$$P = Weight_{YZ} \times g = 6.3 \times 9.81 = 61.8\ N$$

- For the **X axis:**

$$Weight_{XYZ} = \sum Component_{weight} = 11.2\ Kg$$

$$P = Weight_{XYZ} \times g = 11.2 \times 9.81 = 110\ N$$

Using these values, the developer tried a computer aided engineering (CAE) method called finite element analysis (FEA), using *SolidWorks 2020.*

The deflection resultant from load on the Y axis is $\delta_{maxYZ} = 0.02\ mm$, which can be seen in Figure 6.5 (the deformation scale is about 1: 3300).

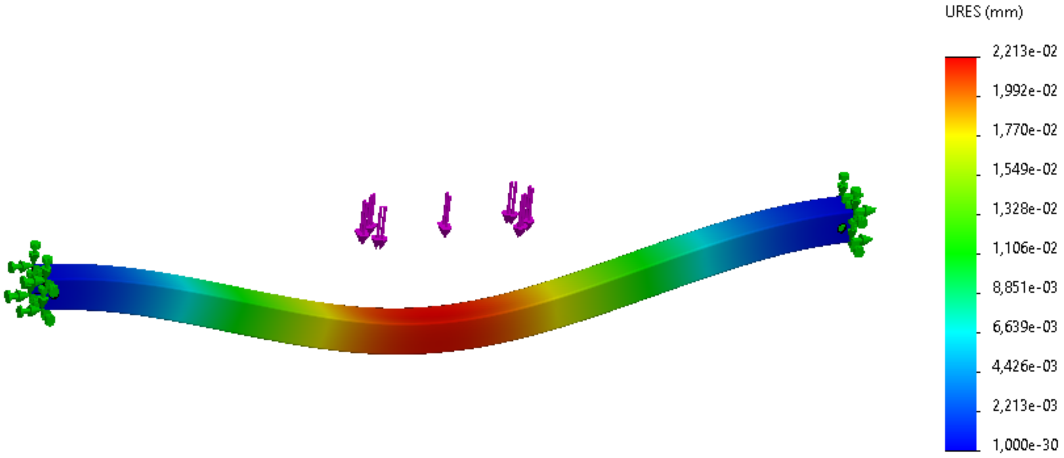


Figure 6.7 - FEA analysis on the Y axis steel tubing vertical deflection.

On the other hand, the deflection resultant from the load on the X axis is $\delta_{maxXYZ} = 0.1\ mm$, as displayed in Figure 6.6 (the deformation scale is about 1: 900).

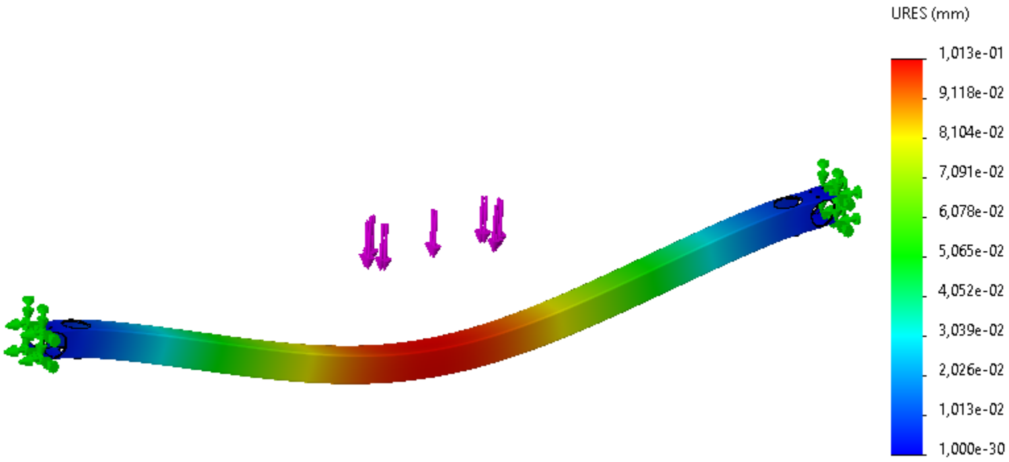


Figure 6.8 - FEA analysis on the X axis steel tubing vertical deflection.

Apart from this, the most noticeable deflections come from the **cutting forces**. These are generated during a machining operation and depend on the depth of cut (a_P), feed rate (V_f), endmill diameter ($\emptyset$), angle of engagement (α), and number of flutes (Z). Figure 6.7 a) illustrates how the cutting forces are applied while cutting along the X axis, while Figure 6.7 b) displays the cutting forces existing during a Y axis oriented cut.

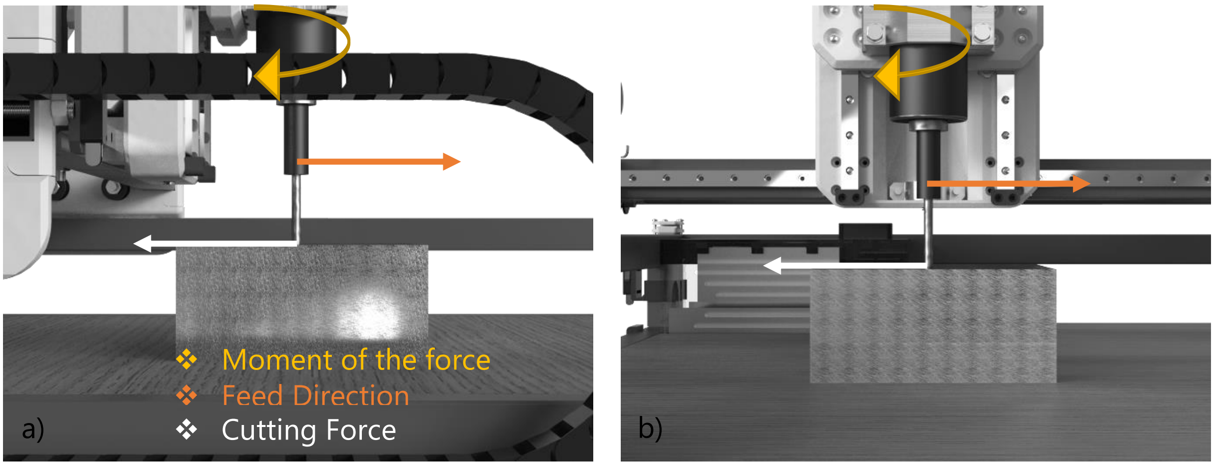


Figure 6.9 - Cutting forces, a) X cut; b) Y cut.

Although Figure 6.7 a) and b) shows a moment of force created by the cutting forces, the developer decided to ignore it by assuming that the spindle mounting points act has a rigid fixture. That way, it's possible to determine an approximation of the deflection occurring on the spindle by using the load case shown in Figure 6.8.

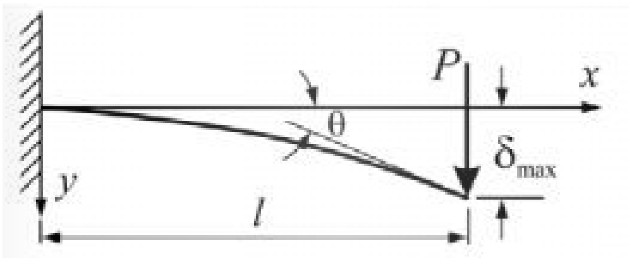


Figure 6.10 - Concentrated load P, at free end [100].

To facilitate the execution of this study, the developer assumed that the deformation of the spindle is similar to a 6061 aluminum alloy $30 \times 30 \times 250\,mm$ tube with a $2\,mm$ wall thickness, as illustrated in Figure 6.9.

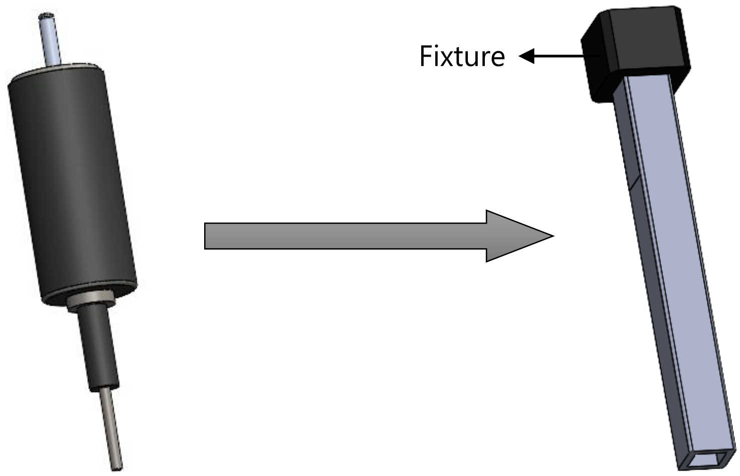


Figure 6.11 - Aluminum square tube equivalent to the spindle.

Through Equation 6.5 it's possible to calculate the cutting forces (F_t). For this the inputs needed are the tensile strength of the material being cut (σ), the chip cross section area (A_C), the number of flutes engaged (Z_C), the engagement factor (E_f), and the tool wear factor (T_f). Equation 6.6 and 6.7 enable the calculation of the Z_C and A_C respectively for which the developer had to define a a_P, Z, α, and calculate the feed per tooth (f_Z), shown in Equation 6.8.

$$F_t = \sigma \times A_C \times Z_C \times E_f \times T_f \tag{6.5}$$

$$Z_C = \frac{Z \times \alpha}{360} \tag{6.6}$$

$$A_C = a_P \times f_Z \tag{6.7}$$

$$f_Z = \frac{V_f}{V_S \times Z} \tag{6.8}$$

The key objective of this study was to fully grasp the capacities of the prototype in terms of depth of cut which meant, using the hardest material it was designed to machine, aluminum ($\sigma_{AL} = 3.1 \times 10^8 \ N/m^2$). To achieve this, the developer established the following experimental plan for a $\emptyset = 6 \ mm, Z = 4$ endmill:

- Set constant values for V_f, V_S *and* α;
- While doubling the a_P, calculate F_t for three iterations;
- Use F_t to determine the deflection on the spindle analytically;
- Compare with control values for the FEA analysis;

Consider the values listed in Table 6.2:

Table 6.2 - Constant values to determine the cutting force.

V_f (mm/min)	1500
V_S (rpm)	4000
α (°)	180
E_f	1
σ_{AL} (N/m^2)	3.1×10^8

When $a_P = 1\ mm$ and $T_f = 1.15$:

$$A_C = 1 \times \frac{1500}{4000 \times 4} = 0.094\ mm^2$$

$$Z_C = \frac{4 \times 180}{360} = 2$$

$$F_t = 3.1 \times 10^8 \times 0.094 \times 10^{-6} \times 2 \times 1 \times 1.15 = 67\ N$$

According to the load case in Figure 6.9, it's possible to analytically determine an approximation of the maximum deflection value using Equation 6.9.

$$\delta_{max} = \frac{PL^3}{3 \times E \times I} \tag{6.9}$$

$$E_{(6061\ AL)} = 6.9 \times 10^{10}\ N/m^2$$

$$\delta_{max} = \frac{67 \times 250^3}{3 \times 6.9 \times 10^4 \times 16278} = 0.31\ mm$$

When $\boldsymbol{a_P = 2\ mm}$ and $\boldsymbol{T_f = 1.45}$:

$$A_C = 2 \times \frac{1500}{4000 \times 4} = 0.188\ mm^2$$

$$F_t = 3.1 \times 10^8 \times 0.188 \times 10^{-6} \times 2 \times 1 \times 1.45 = 169\ N$$

$$\delta_{max} = \frac{169 \times 250^3}{3 \times 6.9 \times 10^4 \times 16278} = 0.78\ mm$$

When $\boldsymbol{a_P = 3\ mm}$ and $\boldsymbol{T_f = 1.45}$:

$$A_C = 3 \times \frac{1500}{4000 \times 4} = 0.375\ mm^2$$

$$F_t = 3.1 \times 10^8 \times 0.375 \times 10^{-6} \times 2 \times 1 \times 1.45 = 337\ N$$

$$\delta_{max} = \frac{337 \times 250^3}{3 \times 6.9 \times 10^4 \times 16278} = 1.56\ mm$$

Once again, looking at Figure 6.13 a), b) and c), it's possible to verify that the analytical values have a slight discrepancy over the FEA values. Nonetheless, it's safe to infer that accounting for the average error of 65% above the control value, the analytical method is a valid way to calculate the deflection since it unintentionally increases the safety factor.

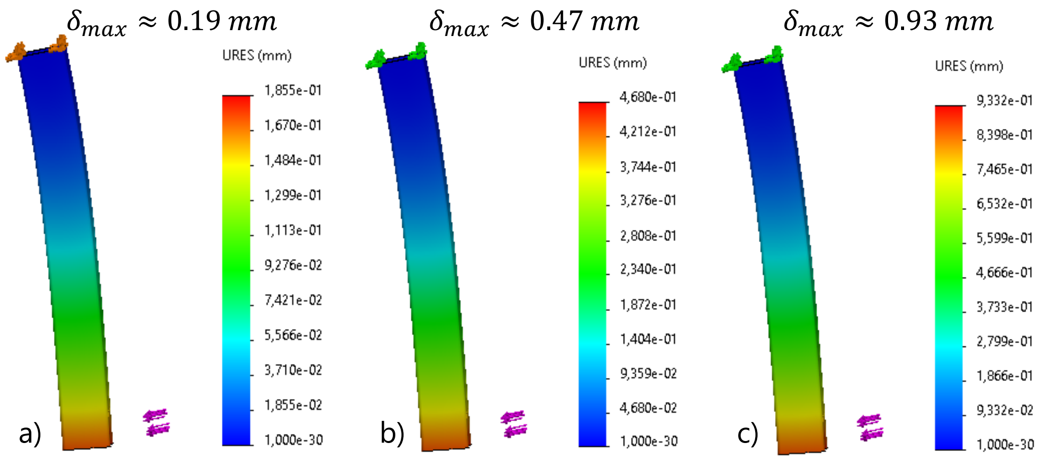


Figure 6.12 - FEA spindle maximum defection, a) $a_P = 1\ mm$; b) $a_P = 2\ mm$, c) $a_P = 3\ mm$.

6.2.3 Design of Experiments (DoE)

Even though theoretically, microstepping greatly enhances precision, it's fundamental to determine the precision of the machine under real working conditions. For this, the developer designed an experimental procedure to understand the level of dimensional accuracy depending on the location of the cut and a_p. Figure 6.14 displays a representation of the 16 cutting locations relative to the working area.

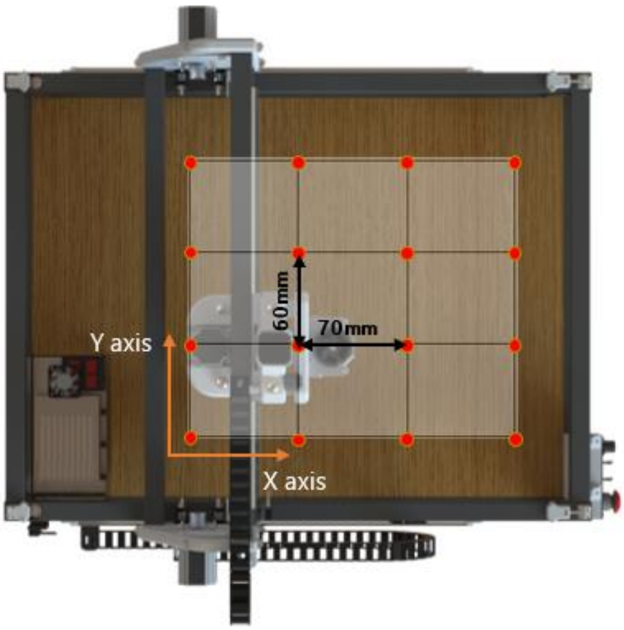


Figure 6.13 - Representation of the cutting locations for the precision test.

The key objective of this analysis was to find out the value of the **hysteresis present in each timing belt/pulley system** (H_{BP}). Considering that the belt-driven axes are the X and Y axis, using *Autodesk Fusion 360,* the developer created a NC program that firstly focuses on Y axis oriented cuts and then, X axis oriented cuts. Figure 6.15 a) and b) show that there is a total of 96 slots, half of them to test the X belt and the other half to test the Y belts.

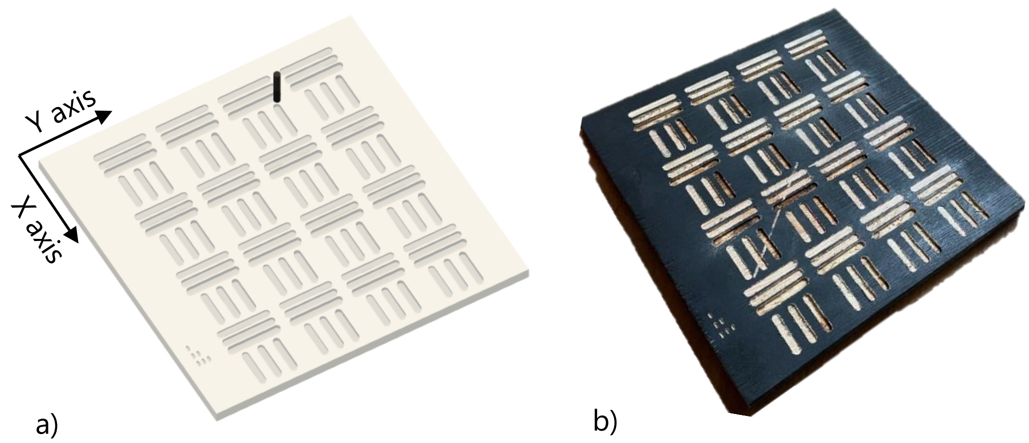


Figure 6.14 - Precision test, a) Fusion 360 CAD file; b) Pine wood test.

As previously mentioned, to further improve the quality of the experiment output, each cutting coordinate has three slots that vary in a_P, as shown in Figure 6.16 a) and b). The procedure was done with a Ø6 mm flat endmill with 4 flutes and V_f and V_S values similar to the ones used in subsection 6.2.2.

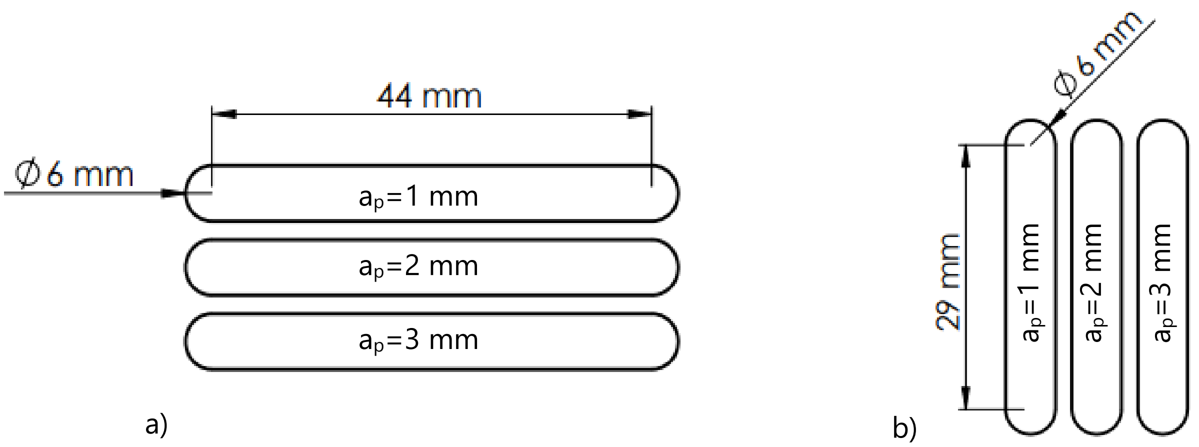


Figure 6.15 - Depth of cut and theoretical cutting length, a) Y slots; b) X slots.

Figure 6.17 clarifies the chosen toolpath for these operations. Firstly, the tool is lowered to the desired a_P at point **A**, then, while maintaining a constant V_f, it travels towards **B**, and upon reaching that point, it instantly inverts the direction of the movement and goes to **C**, which is the exit point. Using this toolpath, the developer planned to maximize the value of H_{BP}.

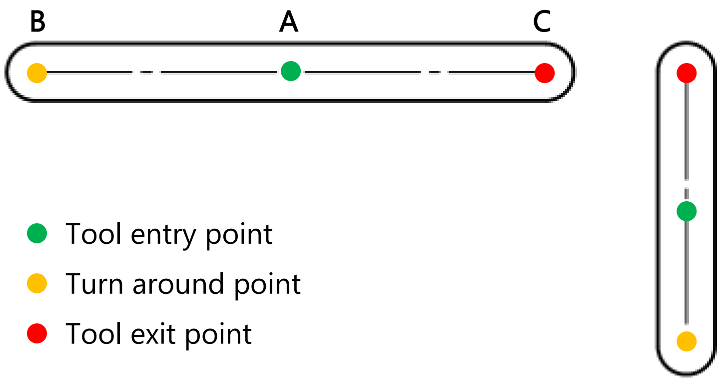


Figure 6.16 - Toolpath used in timing belt/pulley hysteresis test.

6.2.4 Results

After carefully measuring all the slots with a digital caliper, the developer gathered all the experimental dimensions in a *Microsoft Excel* spreadsheet, organized that information by slot orientation and a_P. and divided it into six Tables, seen in Appendix B. Each table generated two charts which were then condensed into a single chart per Table. The left side of the chart (in blue) represents the deviation values (D), while the right side (**in black**) represents the experimental dimensions (ED). The behavior of these two values relatively to each (x, y) coordinate, is the inverse of each other, for instance, for the Y oriented slots with an $a_P = 1\,mm$ on $(x, y) = (0, 60)$, the D *and* ED values are respectively $0.80\,mm$ *and* $49.20\,mm$, which is graphically the opposite, as proven by Figure 6.18.

While ED was obtained through manual measuring, D was determined through Equation 6.10, which was applied to every value of the test.

$$D = Theoretical\ Dimension - ED \tag{6.10}$$

$$D = 50 - 49.20 = 0.80\ mm$$

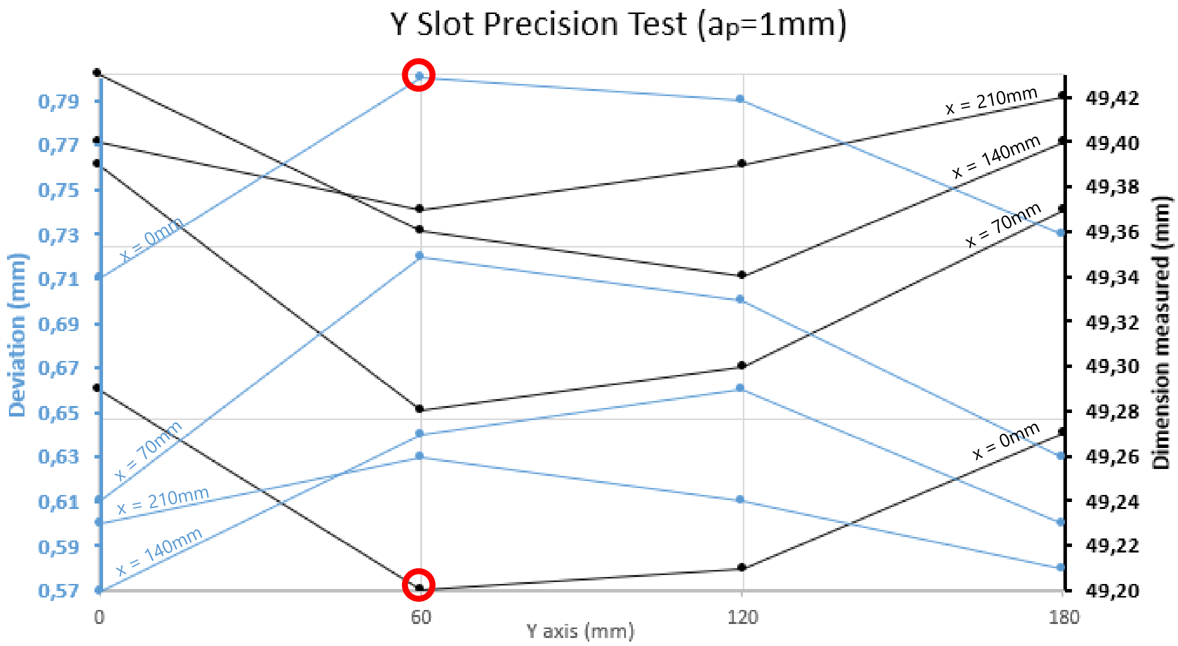


Figure 6.17 - Y slot with $a_P = 1\ mm$.

Analyzing the chart on Figure 6.18, it's possible to conclude that the level of precision drops slightly towards the middle of the machine. For instance, the D values in $y = 60\ mm\ or\ y = 120\ mm$, are almost always higher than when $y = 0\ mm\ or\ y = 180\ mm$, on the other hand, the ED values are lower at the center. This phenomenon can be witnessed in all the charts displayed in Appendix B which was expected by the developer.

There could be a multitude of explanations for this behavior, however, the developer deemed that the most impactful reason is due to $\boldsymbol{H_{BP}}$ being more accentuated at the center of the belt's length, considering that the tension is not constant, i.e., it decreases towards the center and the bigger the length, the more this effect is evidenced. Additionally, the structure deformation can't be rule out, specially, the **spindle deflection**. Considering that this test was done under similar conditions to the ones used for the deflection calculations, it's possible to determine an approximation of H_{BP}, by subtracting δ_{max} to D, as Equation 6.11 suggests

$$H_{BP} = D - \delta_{max} \tag{6.11}$$

Taking into account the 16 values for each a_P, the developer considered the average H_{BP}. Furthermore, it is also assumed that the spindle deflects the same amount in X and Y direction. Knowing this, Equation 6.11 suffer a few changes, resulting in Equation 6.12:

$$H_{BP} = \frac{\sum_{i=1}^{n} D_i}{n} - \delta_{max} \, , n = \{1, 2 \ldots, 15, 16\} \tag{6.12}$$

Considering that the Tables in Appendix B contain all the average deviation values needed, Table 6.3 lists the average H_{BP} values determined using Equation 6.12.

Table 6.3 - Average H_{BP} values for Y and X oriented cuts and variable a_P.

Y Slot	$H_{BP1} = 0.66 - 0.19 = 0.47\, mm$
	$H_{BP2} = 1.01 - 0.47 = 0.54\, mm$
	$H_{BP3} = 1.40 - 0.93 = 0.47\, mm$
X Slot	$H_{BP1} = 0.34 - 0.19 = 0.15\, mm$
	$H_{BP2} = 0.72 - 0.47 = 0.25\, mm$
	$H_{BP3} = 1.17 - 0.93 = 0.24\, mm$

Although the results for Y came out as expected, with an overall average hysteresis value of $\boldsymbol{H_{BPY} = 0.49\, mm}$, the same didn't occur for X, having an overall average hysteresis value of $\boldsymbol{H_{BPX} = 0.21\, mm}$.

The developer expected $\boldsymbol{H_{BPX} \geq H_{BPY}}$ because as previously mentioned, the bigger the length of the belt, the more noticeable the loss of tension at its mid point. On this note, considering that the X belts are about 30% longer than the Y belt, theoretically, regarding this as a linear system, $H_{BPX} = 1.30\, H_{BPY}$. Additionally, it was expected that a system driven by two belts, possibly with different tensions, would have a much bigger imprecision level than a system driven by a single belt.

Nonetheless, an experimental procedure serves exactly to find answers, expected, or not. In this situation, not knowing the real correct answer, the author considered both scenarios.

Assuming that the **results are correct**, the only plausible explanation found for $\boldsymbol{H_{BPX} < H_{BPY}}$ is the **engagement angle**, which is much bigger in the X driving system, according to subsection 5.6.1.

Contrastingly, labeling the **results as incorrect,** the initial justifications proposed by the developer were a possible **poor set up**, an unnoticed **faulty component**, **low quality wood**, among other uncertain theories. However, upon reviewing the experimental procedure, the developer noticed a detail that can greatly affect these values.

As Figure 6.19 clarifies, if V_f is constant, the load and consequently, the deflection, are also constant. Looking back at Figure 6.17, V_f is constant from **A** (entry point) to **C** (exit point) where $V_f = 0\, mm/min$ for about $0{,}5\, seconds$. This fraction of time is enough to allow the tool to straighten while removing some more material, putting into question the results achieved.

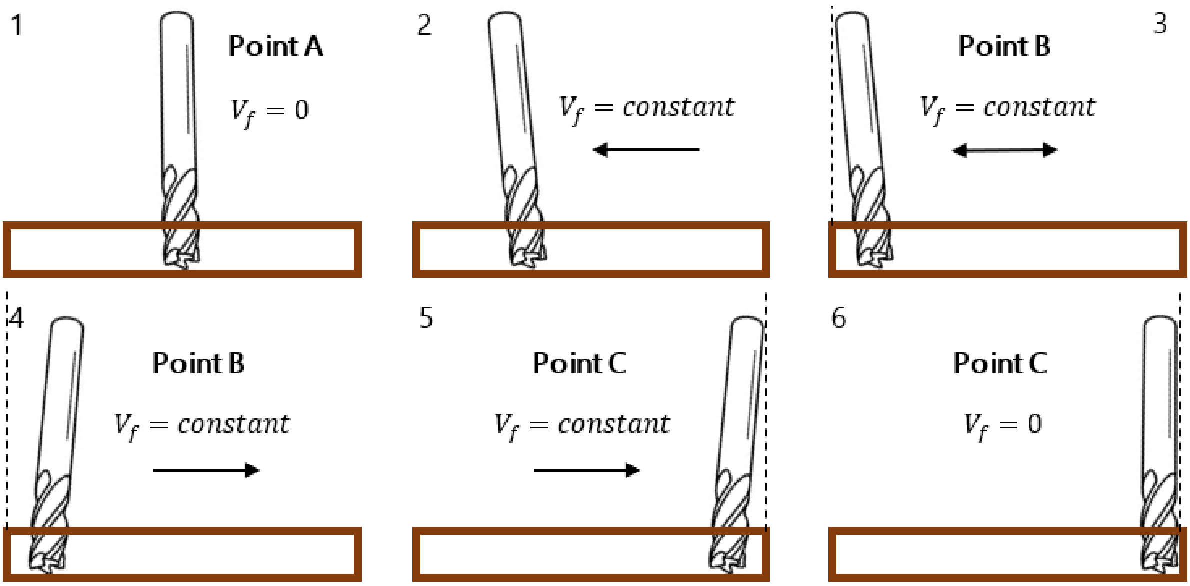


Figure 6.18 - Visual representation of the tool movement and deflection during the test.

Having arrived at this conclusion the developer decided to follow another procedure to retest the H_{BP} values, however, despite this discovery, this time, the test was only executed for the X orientation. This was done because in the previous test, contrary to the X slots, the **Y slots** were machined **against the wood grain**, demanding a much higher load and thus, nullifying the effect considered in Figure 6.19.

The new experimental procedure was designed to ignore the spindle deflection and consider only the H_{BPX}. It consists of:

- Positioning the tool at different coordinates, as demonstrated in Figure 6.20.
- Lower it until $a_P = 2\, mm$.
- Lock the motors (the shaft doesn't rotate).

- Pull directly on the steel structure towards $X(+)$ and then, $X(-)$.

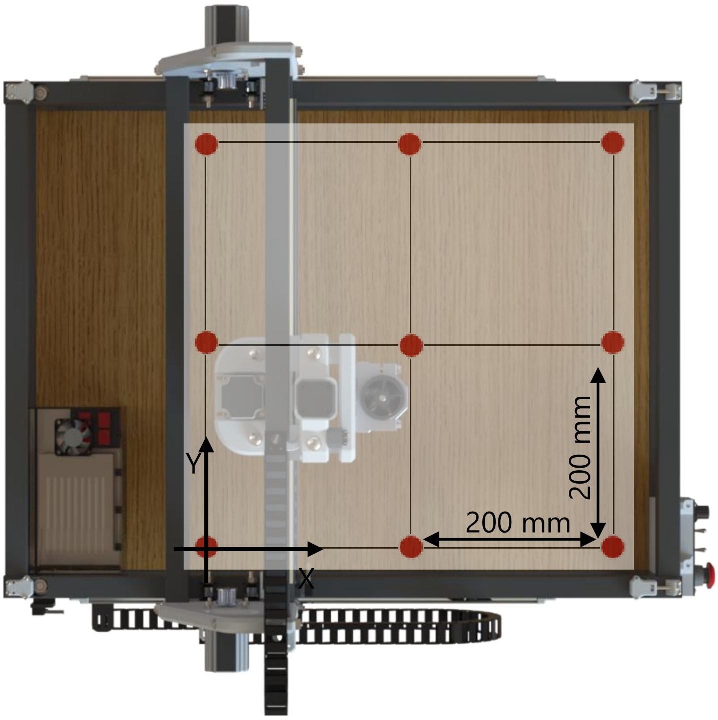


Figure 6.19 - Testing coordinates representation.

Unlike the previous experiment, this was done using a Ø2 mm endmill, which means that initially, once the tool reaches $a_P = 2\,mm$, it should leave a Ø2 mm hole, however, by pulling on the steel structure, if $H_{BPX} \neq 0$, the hole should become a slot. This slot is then measured and H_{BPX} is determined through Equation 6.13.

$$H_{BPX} = ED - Theoretical\ Dimension \tag{6.13}$$

The values were achieved by applying a constant force of 100 N, for 2 seconds. This force was measured with a digital dynamometer, as shown in Figure 6.21.

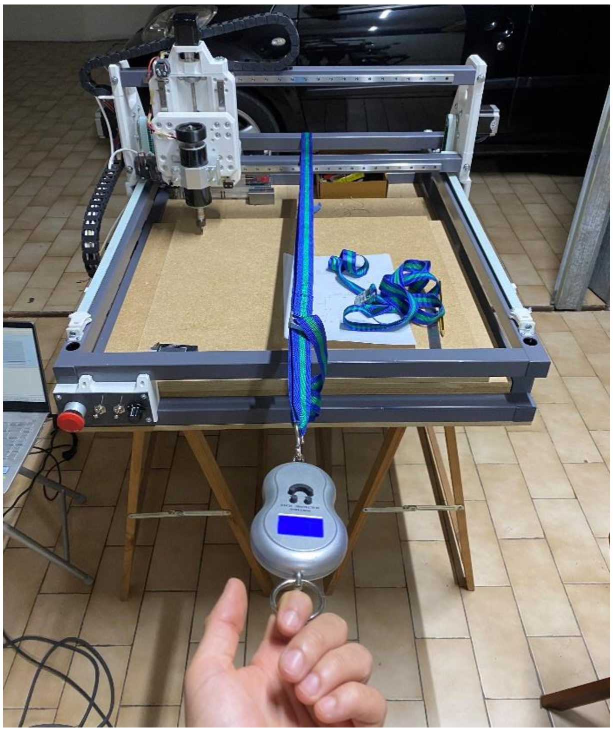


Figure 6.20 - X belt hysteresis experiment assembly.

Once the tests were concluded, the developer gathered the information in Appendix B and posteriorly, created a chart of H_{BPX} relative to the coordinates. This chart can be seen in Figure 6.22.

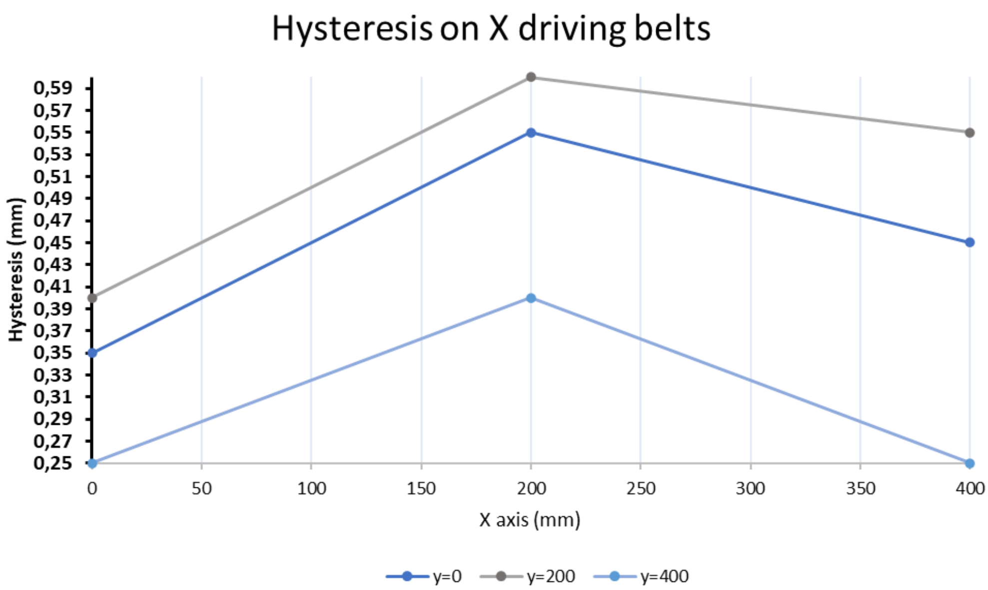


Figure 6.21 - H_{BPX} chart.

Figure 6.22 proves the **success** of this experimental procedure. As the tool travels towards the center of the working area, H_{BPX} increases until $(\boldsymbol{x}, \boldsymbol{y}) = (\mathbf{200}, \mathbf{200})$, where $\boldsymbol{H_{BPX}} = \mathbf{0.60}\ \boldsymbol{mm}$, which was the **maximum** value achieved. Additionally, in theory, the hysteresis values should be the same for $y = 0\ mm$ than $y = 400\ mm$, however, analyzing the chart, the developer noticed that H_{BPX} is slightly higher at $y = 0\ mm$, which led to the conclusion that the **X timing belt on the left** side has a slightly **lower tension** than the one on the right side of the machine. Nonetheless, H_{BPX} was determined by calculating the average of the values presented in Appendix B, resulting in $\boldsymbol{H_{BPX}} = \mathbf{0.42}\ \boldsymbol{mm}$**.**

All in all, the developer regarded the entire experimental stage as a success, having reached H_{BP} values of:

$$\boldsymbol{H_{BPX}} = \mathbf{0.42}\ \boldsymbol{mm}$$

$$\boldsymbol{H_{BPY}} = \mathbf{0.49}\ \boldsymbol{mm}$$

6.3 Future Improvements

As previously mentioned in section 5.8, this prototype is already considered to be in its beta version, which means it is a fully functioning machine designed for "testing in the intended environment to assess reliability and to identify remaining bugs" [40]. On that note, all the testing done until the writing of this document was crucial to identify several improvement opportunities. These improvements are listed in Table 6.4.

Table 6.4 - Current issues and future improvements.

Current Prototype's Issue	**Improvements Suggested**
Having 3D Printed gantries can reduce the structural integrity.	Machined aluminum gantries.
Square steel tubes add too much weight to the prototype making it hard to move.	Since 9 of the 15 tubes aren't under deflection loads, they can be changed for aluminum tubing, reducing the overall weight.
500 W spindle bogs down and overheats if the relation feed rate/depth of cut isn't conservative.	Change for a water cooled 1,5 kW spindle motor. This spindle should be able to keep up with the Nema 23's full potential.
The current electronics box is too small which can result in poor airflow, overheating and electrical noise.	Redesign and build a bigger box to be able to scatter the power supplies and microcontroller.
There is a reoccurring problem with the LS due to electrical noise coming from the cabling.	Upgrade all the machine's cabling to shielded cables to nullify the electrical noise.
For larger machining operations, the dust generated can become a safety hazard.	Design and add an integrated dust collection system.
Setting the zeros is the most time consuming process of the set up.	Install a XYZ probe to automate the zeroing process.

7

CONCLUSION

The focal point of this work was to develop and fabricate a three axis CNC router, by necessity of the developer.

The main goals were achieved, having a working prototype that showcases a good performance without needing to invest large amounts of money. Apart from the hardware, the prototype is composed by eighty individually designed and fabricated components, which can be divided into four subassemblies:

- Main frame, which is the machine's support.
- X axis, which is dependent on the main frame.
- Y axis, which is dependent on the X subassembly.
- Z axis, which is dependent on the Y subassembly.

The developer conducted two experimental procedures that highlighted the timing belts/pulleys system hysteresis values and considering the cost of the prototype, available working volume and ease of use, the results of these tests characterize the CNC router as having a good performance. Nonetheless, an equipment designed to execute precise machining operations must have extensive testing done, to have an exact view of the performance achievable, which starts by reducing the number of approximations done in the calculations of the spindle deflection. This is an excellent topic for a future study, as it would greatly decrease the uncertainty levels, further solidifying posterior performance acquisition test results.

Although it was designed in a small form factor, the developer proved the plausibility of the fourth axis's rotation. This addition can be an asset when dealing with "L" shaped parts, allowing machining operations in two different planes, however, since this concept is in its embryonic stage, it must be further developed in a future study.

Lastly, the work developed is a good contribution for its field, as an inexpensive, fully functional, and reliable three axes CNC router that can be built without any specialized tools and works as a base for an even more capable equipment, following the suggestions in section 6.3.

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52mm-Clamps-and-Power-Supply-Speed-Governor-p-1027937.html?utm_source=googleshopping&utm_medium=cpc_organic&gmcCountry=PT&utm_content=minha&utm_campaign=minha-ptg-pt-pc&currency=EUR&cur_warehouse=CN&createTmp=1&utm_source=googleshopping&utm_medium=cpc_bgcs&utm_content=dcr&utm_campaign=dcr-ssc-ptg-all-0115&ad_id=491732632746&gclid=CjwKCAiA6seQBhAfEiwAvPqu16yldokxthj5Xn9nqFOl_wbUnMDMN5VNOc9wkdATBXMhhoUgpyI13hoC7i0QAvD_BwE. [Accessed: 20-Feb-2022].

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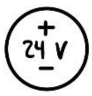
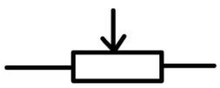
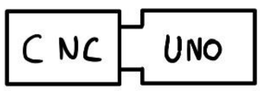
APPENDIX A

Tables:

Table A.1- Nomenclature used in the electronics schematic.

Symbol	Designation
	AC source.
	24 volts DC.
	VFD.
	Potentiometer.
	Arduino Uno coupled with CNC shield.
	EPB
	ON/OFF lever switch for the main system.
	ON/OFF lever switch for the spindle.

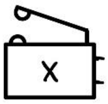
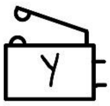
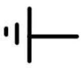
	Spindle motor.
	X axis stepper motor.
	X axis cloned stepper motor.
	Y axis stepper motor.
	Z axis stepper motor.
	X axis LS.
	Y axis limit switch.
	Z axis limit switch.
	Cooling fan.
	Ground.

Table A.2- 3D printed parts printing time, weight and total cost.

Component File Name	Quantity	Printing Time (Hours)	Total Weight (g)	Total Cost
X_Gantry_RIGHT	1	22.5	400	129.30
X_Gantry_LEFT	1	23	410	
YZ_Gantry	1	29.5	490	
Y_MOTOR_Mount	1	18.5	325	
Z_GANTRY	1	14.5	230	
Z_MOTOR_Mount	1	6	100	
Belt_Clamp_X	4	3.5	40	
Belt_Tensioner_X	2	1	15	
Belt_Clamp_Y	2	2	25	
X_Gantry_Clamp_BOT	2	2	25	
X_Gantry_Clamp_TOP	2	2	25	
XY_Block_Stopper	8	2	25	
Z_Block_Stopper	2	0.5	10	
LeadScrew_Stopper	1	0.5	15	
Spacer	12	1.5	15	
CableTrack_holder	1	1.5	20	
Magnet_holder	3	0.15	6	
Rail_Centering_Block	2	2	30	
Square_Tube_Lid	8	2	25	
Control_Box	1	7.5	90	

Control_Box_Lid	1	1.5	20	
Spindle_Fan	1	2	25	
BearingBracket_FourthAxis	1	3.5	50	
ServoPivot_FourthAxis	1	0.5	10	
RouterHolder_FourthAxis	1	4.5	60	

Table A.3- Hardware and electronics quantity and cost.

	Quantity	Cost (€)
M3x16	184	35.50
M3x20	16	
M3x30	20	
M3 Washers	16	
M3 Nuts	4	
M5x20	18	
M5 Washers	12	
M5 Nuts	12	
M6x60	4	
M6 Nuts	10	
M6 Washers	4	
M8x40	2	
M8x60	10	
M8x110 (Threaded Rod)	2	
M8x200 (Threaded Rod)	2	
M8x665 (Threaded Rod)	4	
M8 Nuts	28	
M8 Washers	20	
Nema 23	3	64.50

<table>
<tr><td>Nema 17</td><td>1</td><td>10.00</td></tr>
<tr><td>500W Spindle</td><td>1</td><td>66.00</td></tr>
<tr><td>24V PSU</td><td>1</td><td>20.50</td></tr>
<tr><td>Arduino Uno</td><td>1</td><td rowspan="3">9.50</td></tr>
<tr><td>CNC Shield</td><td>1</td></tr>
<tr><td>A4988 Stepper Driver</td><td>4</td></tr>
<tr><td>Cabling</td><td>-</td><td>18.00</td></tr>
<tr><td>LS</td><td>3</td><td>5.50</td></tr>
<tr><td>Lever Switch</td><td>2</td><td>2,00</td></tr>
<tr><td>Heatsink</td><td>1</td><td>1.00</td></tr>
<tr><td>Steel Tubing (6m)</td><td>2</td><td>34.50</td></tr>
<tr><td>Other materials</td><td>-</td><td>50.00</td></tr>
</table>

Appendix B

Timing Belts/Pulleys Hysteresis:

Table B.1- Y Slots ap=1mm.

Y Slot (ap = 1mm)				
X (mm)	Y (mm)	Dimension (mm)	Deviation (mm)	Hysteresis
0	0	49,29	0,71	0,52
0	60	49,20	0,80	0,61
0	120	49,21	0,79	0,60
0	180	49,27	0,73	0,54
70	0	49,39	0,61	0,42
70	60	49,28	0,72	0,53
70	120	49,30	0,70	0,51
70	180	49,37	0,63	0,44
140	0	49,43	0,57	0,38
140	60	49,36	0,64	0,45
140	120	49,34	0,66	0,47
140	180	49,40	0,60	0,41
210	0	49,40	0,60	0,41
210	60	49,37	0,63	0,44
210	120	49,39	0,61	0,42
210	180	49,42	0,58	0,39
Average		49,34	0,66	**0,47**

Table B.2- Y Slots ap=2mm.

Y Slot (ap = 2mm)				
X (mm)	Y (mm)	Dimension (mm)	Deviation (mm)	Hysteresis
0	0	48,93	1,07	0,60
	60	48,89	1,11	0,64
	120	48,91	1,09	0,62
	180	48,95	1,05	0,58
70	0	48,99	1,01	0,54
	60	48,96	1,04	0,57
	120	48,98	1,02	0,55
	180	49,01	0,99	0,52
140	0	49,01	0,99	0,52
	60	49,00	1,00	0,53
	120	48,98	1,02	0,55
	180	49,02	0,98	0,51
210	0	49,10	0,90	0,43
	60	48,98	1,02	0,55
	120	49,03	0,97	0,50
	180	49,06	0,94	0,47
Average		48,99	1,01	**0,54**

Table B.3- Y Slots ap=3mm.

Y Slot (ap = 3mm)				
X (mm)	Y (mm)	Dimension (mm)	Deviation (mm)	Hysteresis
0	0	48,63	1,37	0,44
	60	48,51	1,49	0,56
	120	48,54	1,46	0,53
	180	48,69	1,31	0,38
70	0	48,61	1,39	0,46
	60	48,52	1,48	0,55
	120	48,56	1,44	0,51
	180	48,63	1,37	0,44
140	0	48,72	1,28	0,35
	60	48,50	1,50	0,57
	120	48,44	1,56	0,63
	180	48,69	1,31	0,38
210	0	48,71	1,29	0,36
	60	48,62	1,38	0,45
	120	48,59	1,41	0,48
	180	48,66	1,34	0,41
Average		48,60	1,40	**0,47**

Table B.4- X Slots ap=1mm.

X Slot (ap = 1mm)				
Y (mm)	X (mm)	Dimension (mm)	Deviation (mm)	Hysteresis
0	0	34,74	0,26	0,07
	70	34,66	0,34	0,15
	140	34,63	0,37	0,18
	210	34,72	0,28	0,09
60	0	34,69	0,31	0,12
	70	34,60	0,40	0,21
	140	34,60	0,40	0,21
	210	34,68	0,32	0,13
120	0	34,70	0,30	0,11
	70	34,60	0,40	0,21
	140	34,61	0,39	0,20
	210	34,68	0,32	0,13
180	0	34,70	0,30	0,11
	70	34,60	0,40	0,21
	140	34,61	0,39	0,20
	210	34,69	0,31	0,12
Average		34,66	0,34	**0,15**

Table B.5- X Slots ap=2mm.

X Slot (ap = 2mm)				
Y (mm)	X (mm)	Dimension (mm	Deviation (mm	Hysteresis
0	0	34,29	0,71	0,24
	70	34,27	0,73	0,26
	140	34,22	0,78	0,31
	210	34,32	0,68	0,21
60	0	34,49	0,51	0,04
	70	34,30	0,70	0,23
	140	34,21	0,79	0,32
	210	34,38	0,62	0,15
120	0	34,20	0,80	0,33
	70	34,18	0,82	0,35
	140	34,09	0,91	0,44
	210	34,21	0,79	0,32
180	0	34,40	0,60	0,13
	70	34,30	0,70	0,23
	140	34,32	0,68	0,21
	210	34,26	0,74	0,27
Average		34,28	0,72	**0,25**

Table B.3- X Slots ap=3mm.

X Slot (ap = 3mm)				
Y (mm)	X (mm)	Dimension (mm	Deviation (mm)	Hysteresis
0	0	33,99	1,01	0,08
	70	33,94	1,06	0,13
	140	33,94	1,06	0,13
	210	34,00	1,00	0,07
60	0	33,79	1,21	0,28
	70	33,70	1,30	0,37
	140	33,74	1,26	0,33
	210	33,84	1,16	0,23
120	0	33,93	1,07	0,14
	70	33,85	1,15	0,22
	140	33,91	1,09	0,16
	210	34,01	0,99	0,06
180	0	34,00	1,00	0,07
	70	33,50	1,50	0,57
	140	33,48	1,52	0,59
	210	33,72	1,28	0,35
Average		33,83	1,17	**0,24**

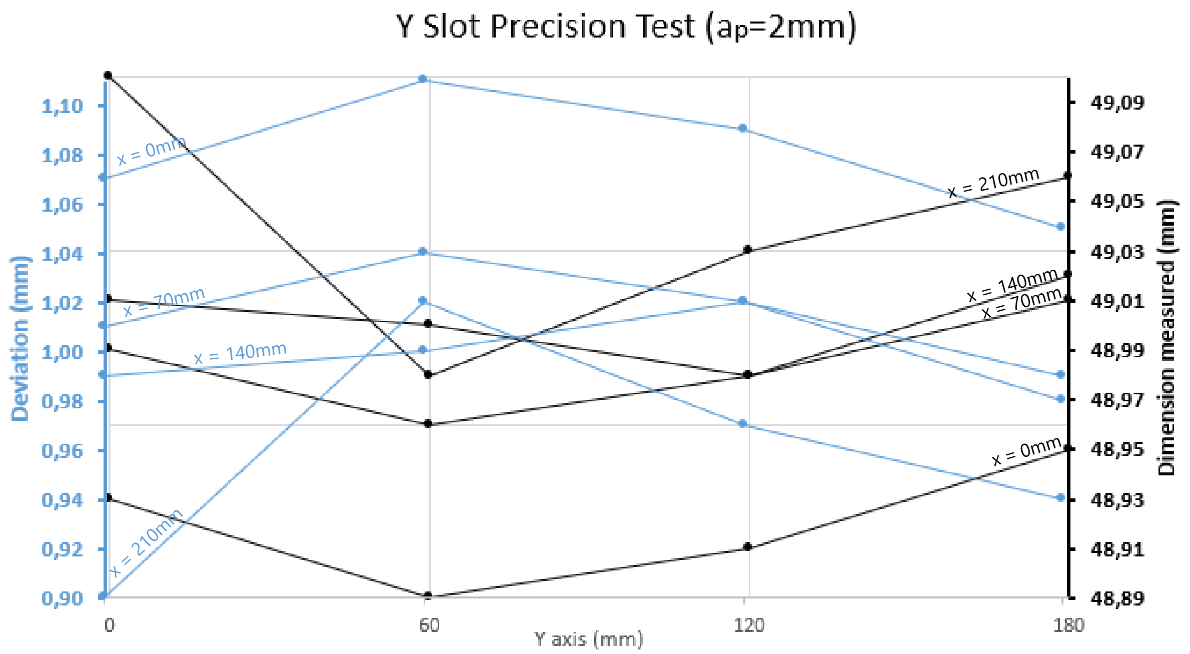


Figure B.1- Y Slots ap=2mm.

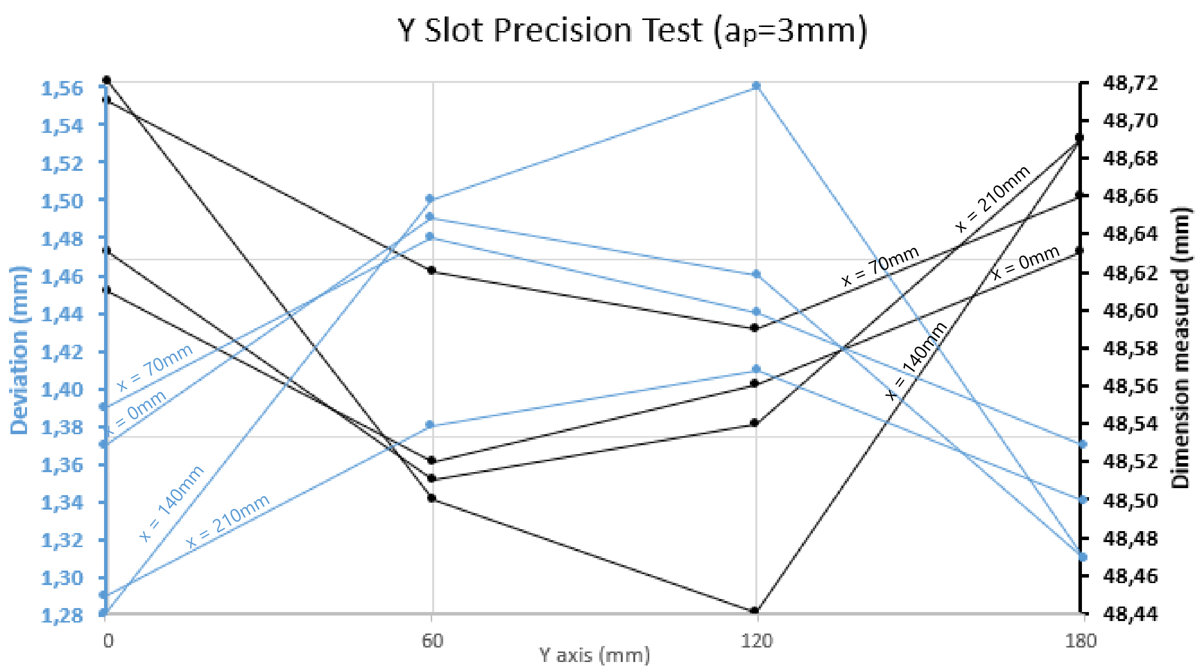


Figure B.2- Y Slots ap=3mm.

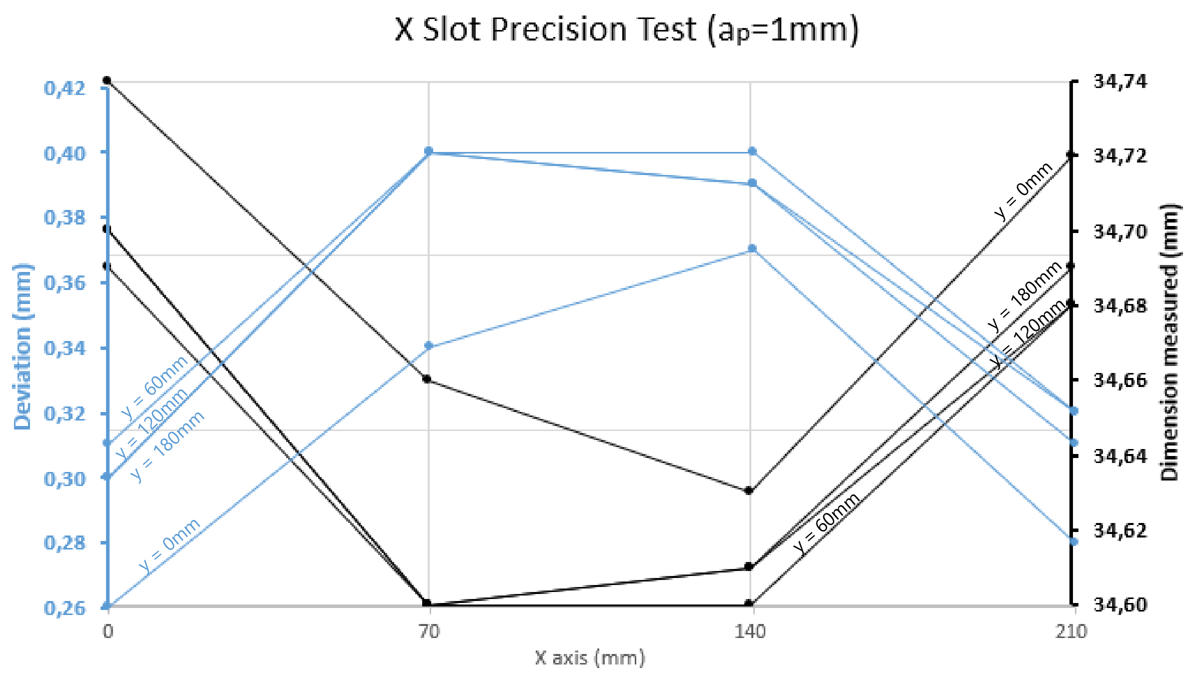


Figure B.3- X Slots ap=1mm.

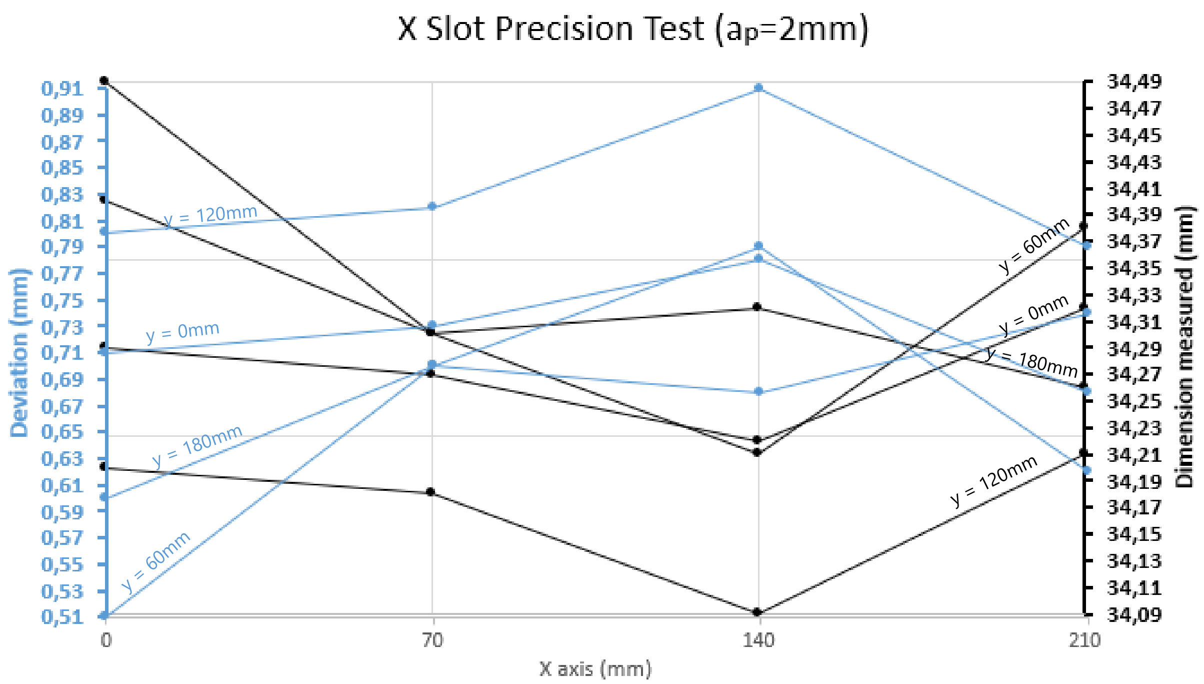


Figure B.4- X Slots ap=2mm.

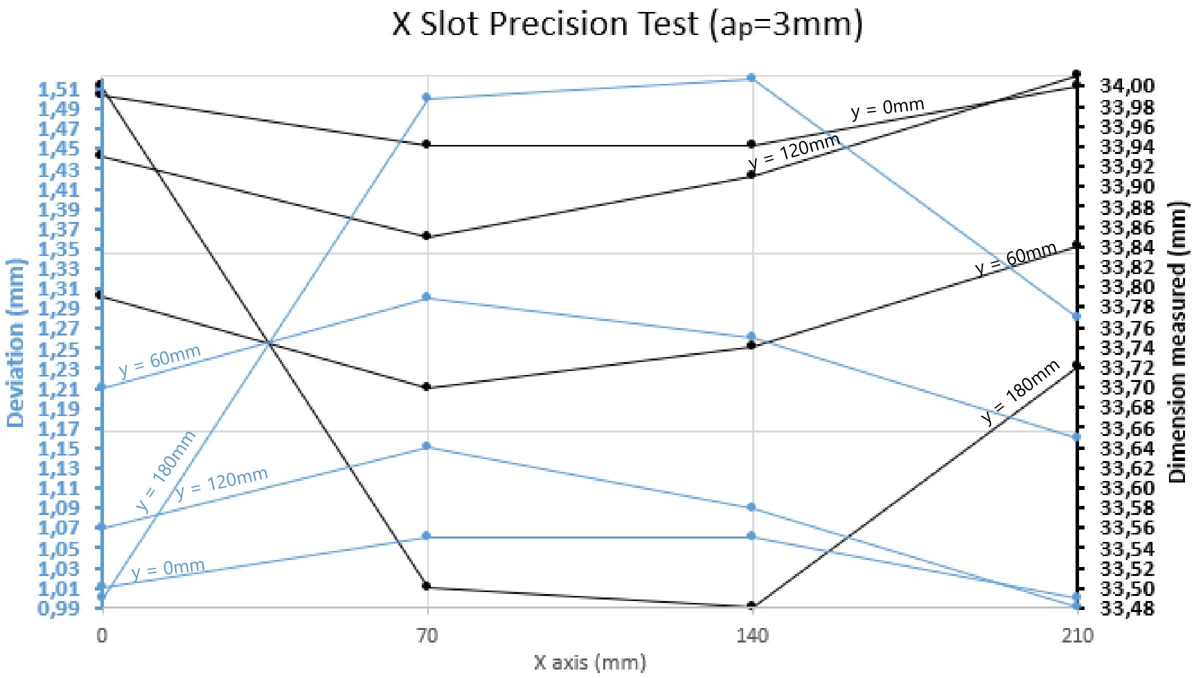
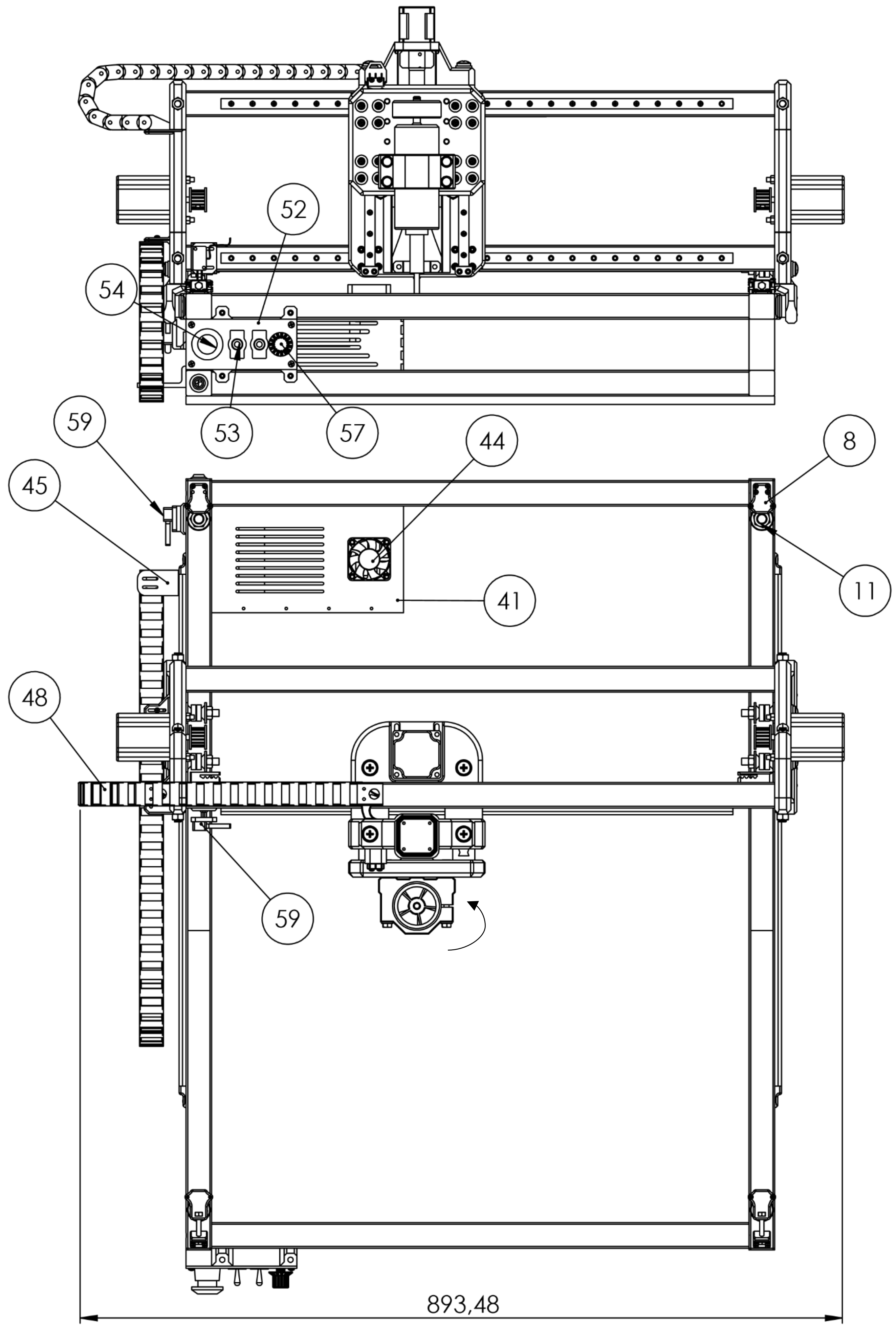
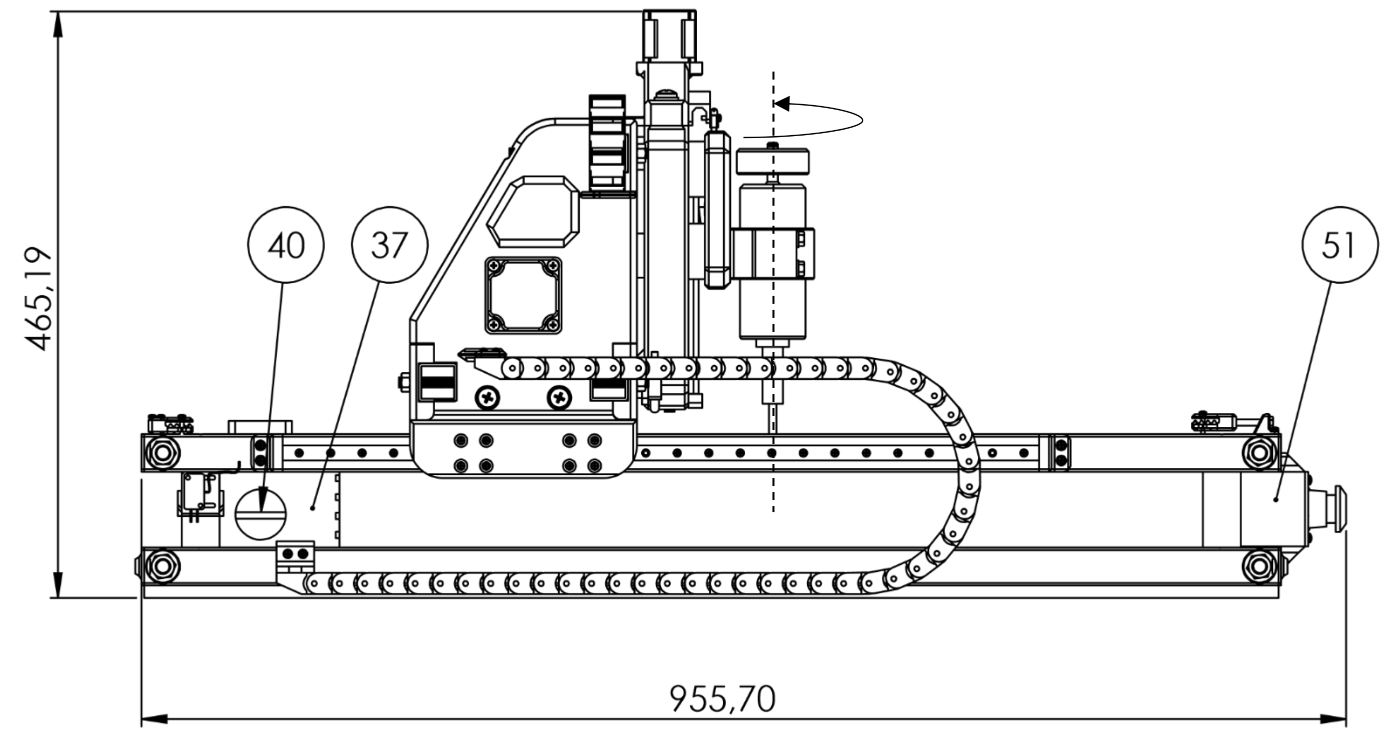


Figure B.5- X Slots ap=3mm.

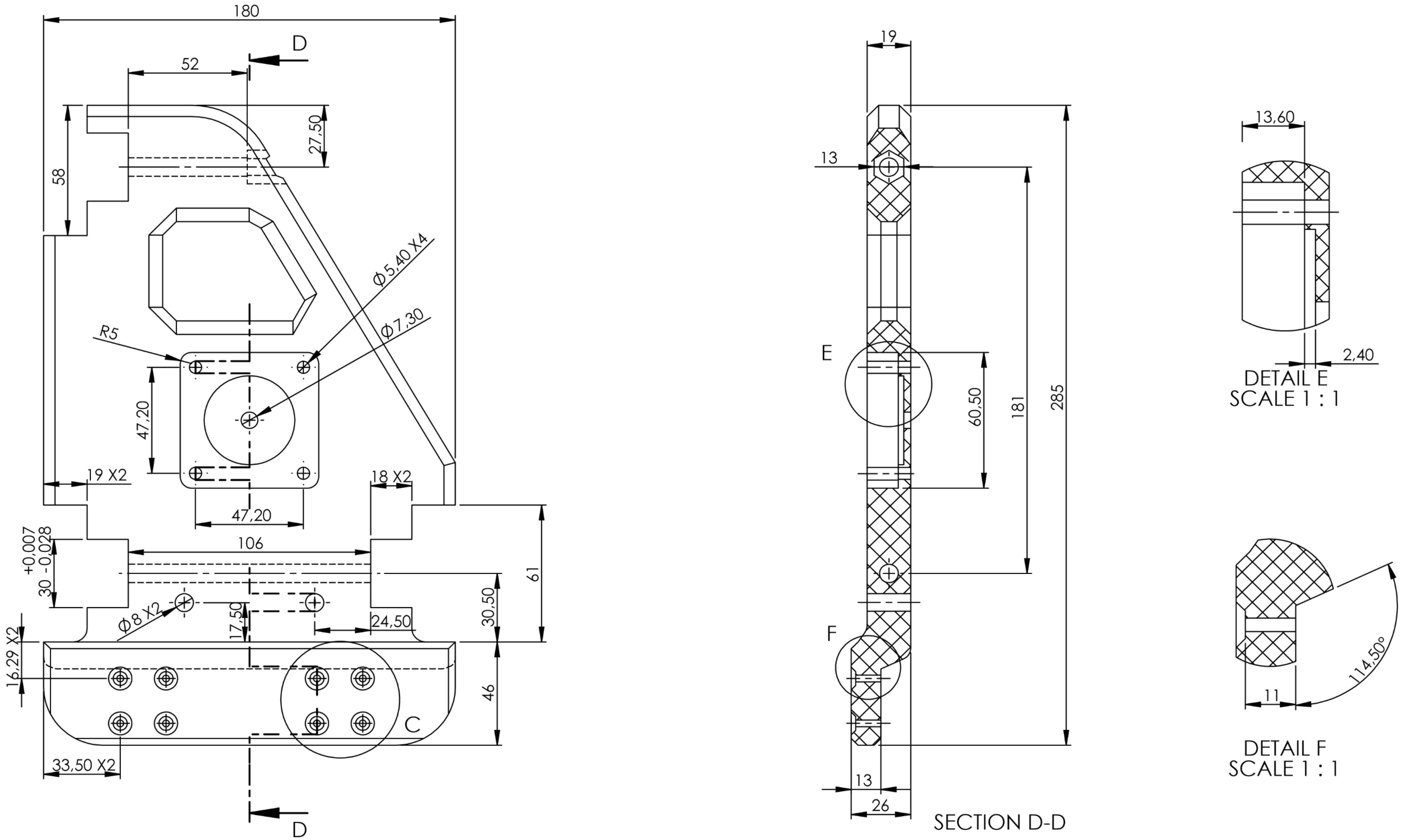
Appendix C

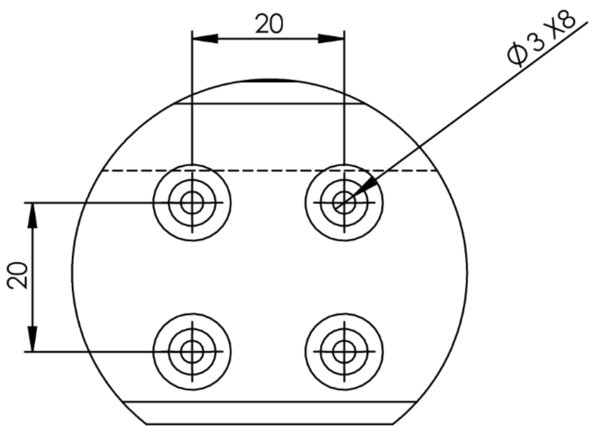
Technical Drawings:





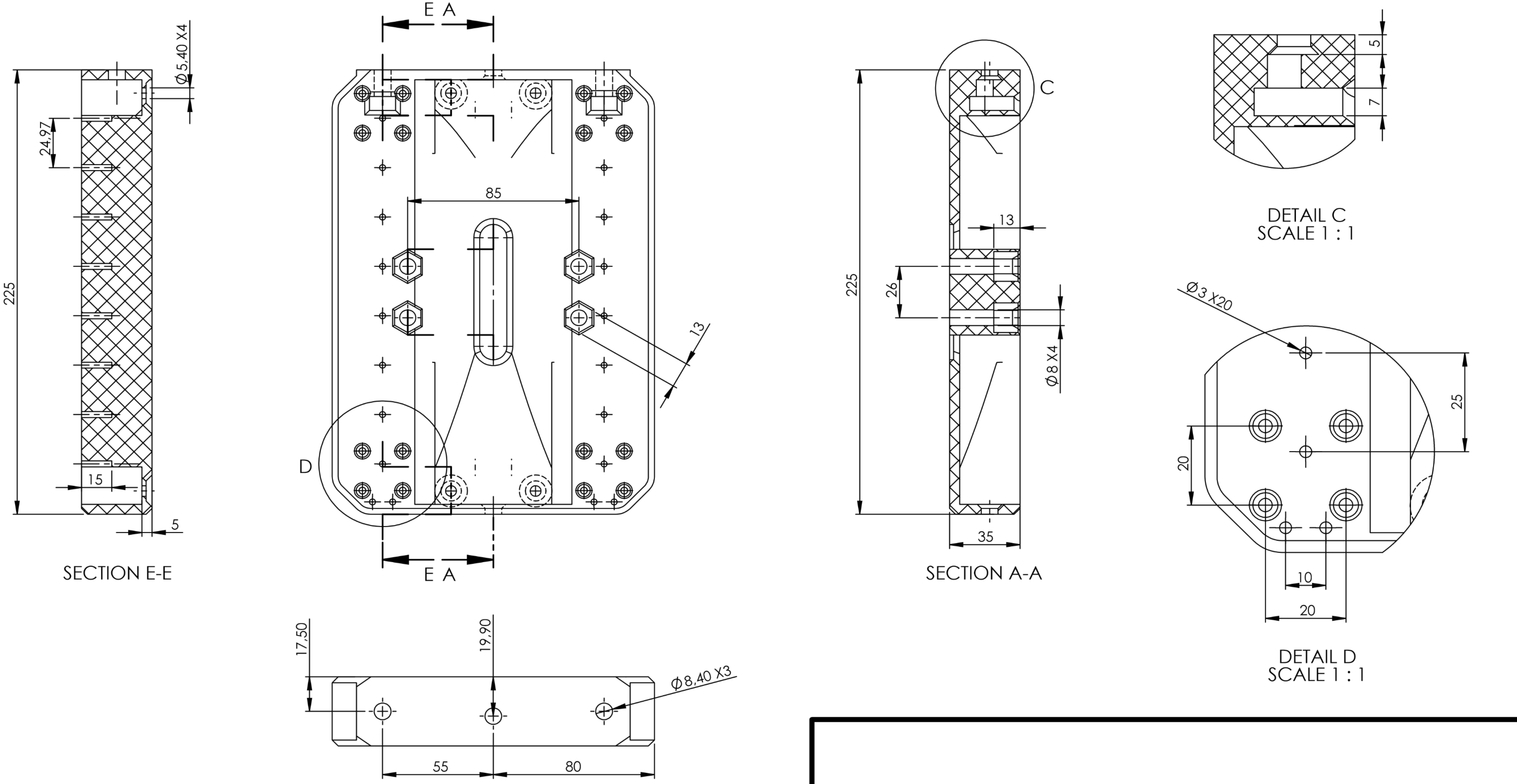
Observações:	Proj. 18/04/22	F.C.T.-U.N.L	André .F.R. Nunes	
	Des. 30/09/22	MIEMc - CNC Router		
	Copiou			
	Visto			
	SCALE: 1:5	CNC ROUTER	S00	
	ISO 2768			





DETAIL C
SCALE 1 : 1

Observações:				
Proj.	18/04/22		F.C.T.-U.N.L	André .F.R. Nunes
Des.	30/09/22		MIEMc - CNC Router	
Copiou				
Visto				
SCALE: 1:2	X_Gantry_RIGHT			P01
ISO 2768				



Observações:

Proj.	18/04/22	
Des.	30/09/22	
Copiou		
Visto		

F.C.T.-U.N.L

MIEMc - CNC Router

André .F.R. Nunes

SCALE: 1:2

ISO 2768

YZ_Gantry

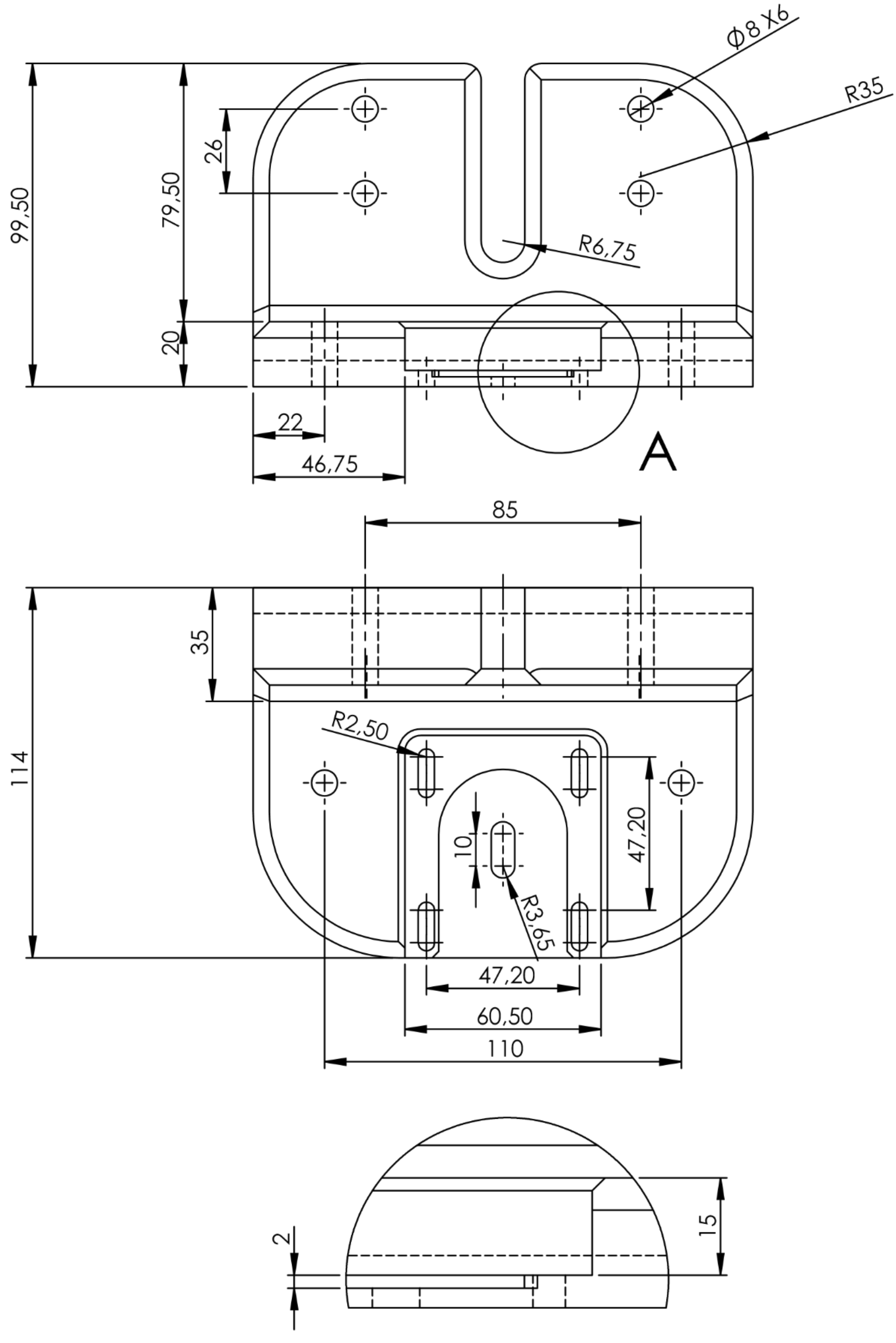
P03

Proj.	18/04/22	
Des.	30/09/22	
Copiou		
Visto		

F.C.T.-U.N.L

MIEMc - CNC Router

André F.R. Nunes
51966

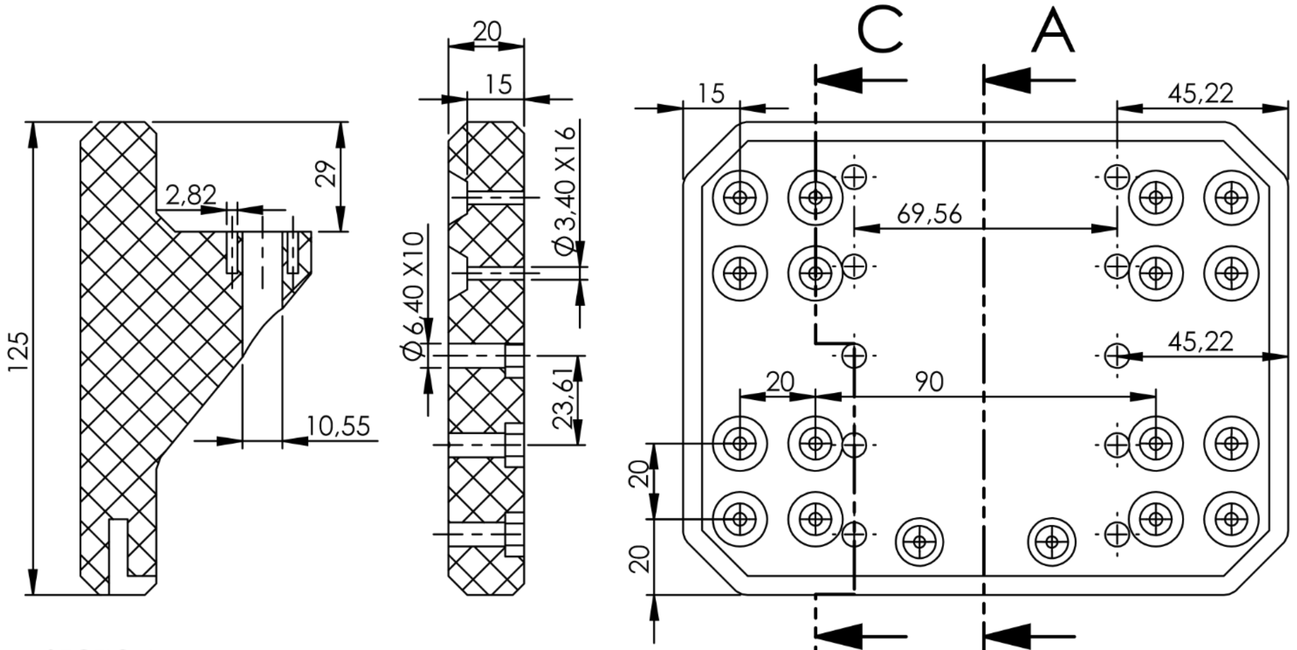


DETAIL A

SCALE 1 : 1

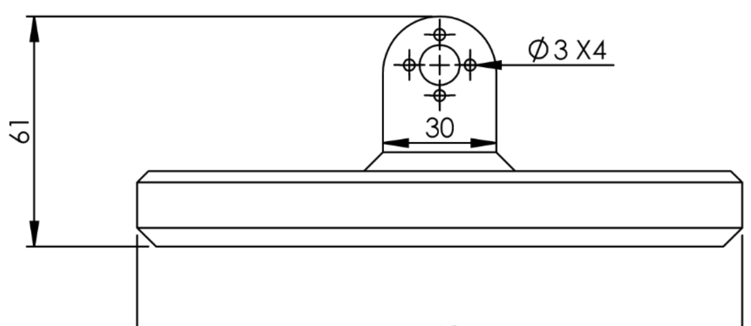
Observações:	1:2 / ISO 2768	**Y_MOTOR_MOUNT**	P04

Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes
Des.	30/09/22		*MIEMc - CNC Router*	51966
Copiou				
Visto				



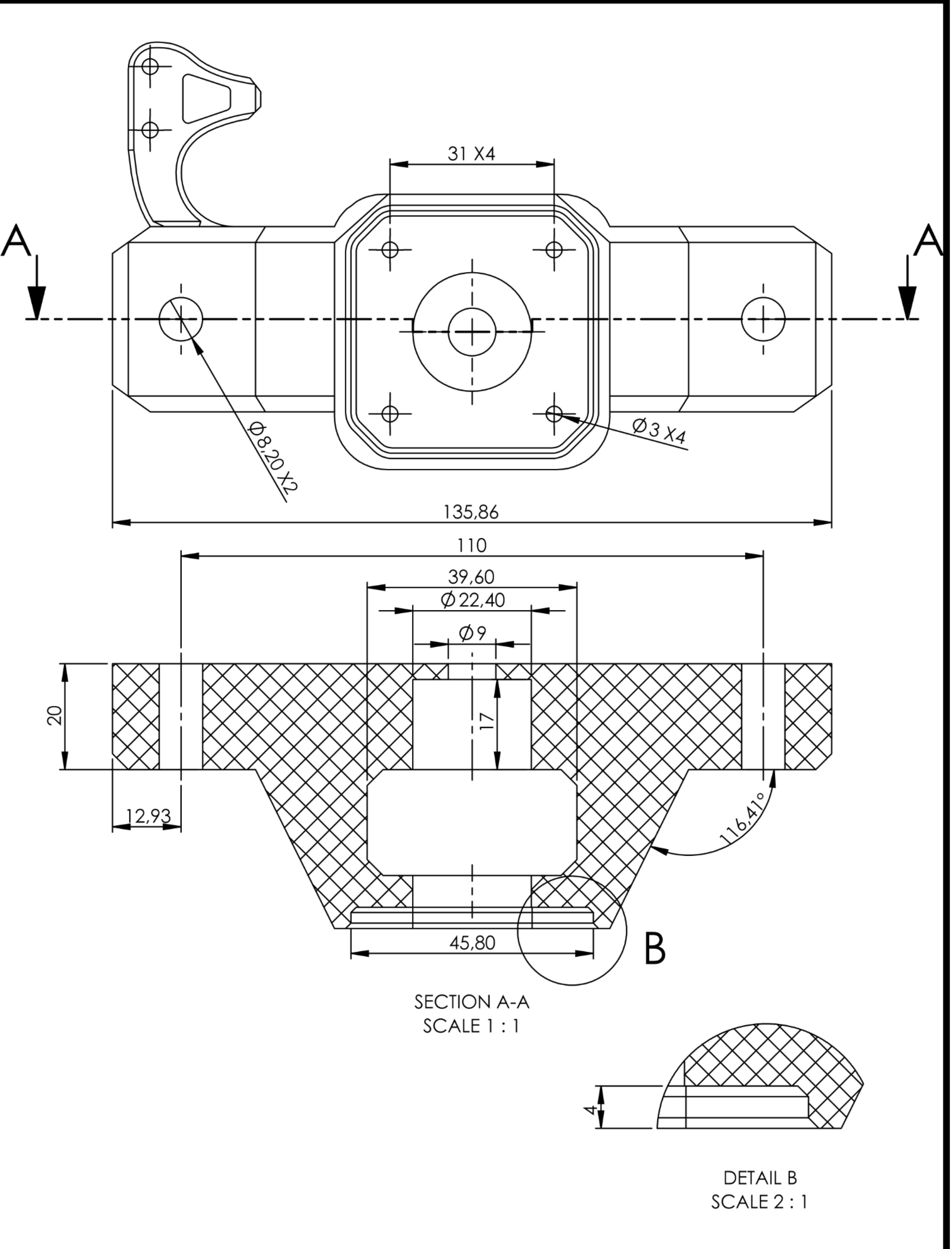
SECTION A-A

SECTION C-C



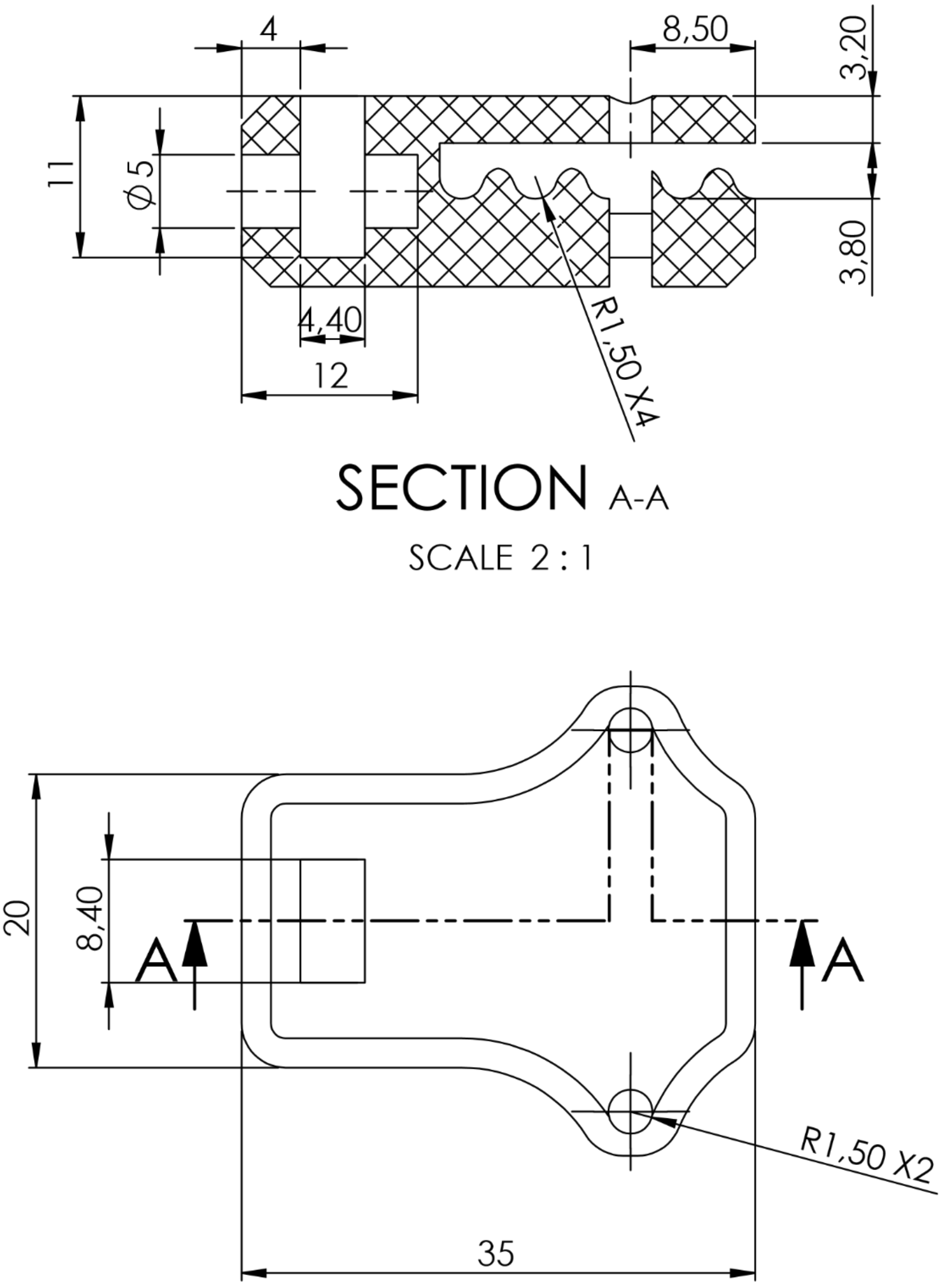
Observações:	1:2	*Z_GANTRY*	*P05*
	ISO 2768		

Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes
Des.	30/09/22		MIEMc - CNC Router	51966
Copiou				
Visto				



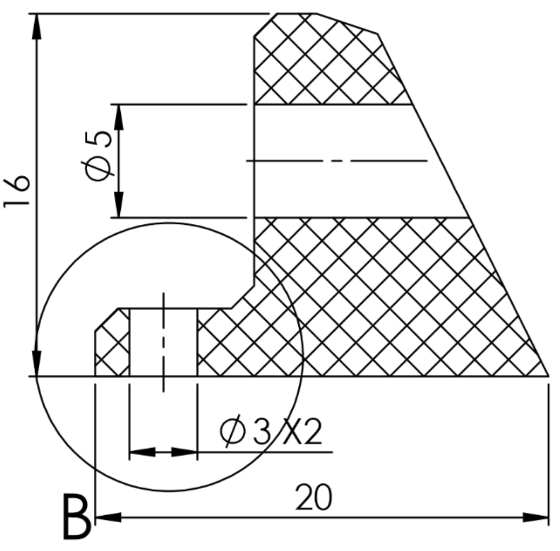
Observações:	1:1	Z_MOTOR_Mount	P06
	ISO 2768		

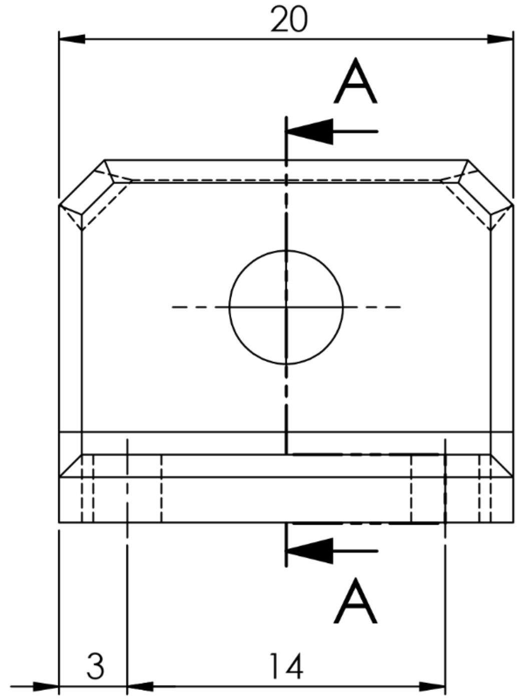
Proj.	*18/04/22*		F.C.T.-U.N.L	*André F.R. Nunes*
Des.	*30/09/22*		*MIEMc - CNC Router*	*51966*
Copiou				
Visto				



Observações:	*2:1*		*P07*
	ISO 2768	***Belt_Clamp_X***	

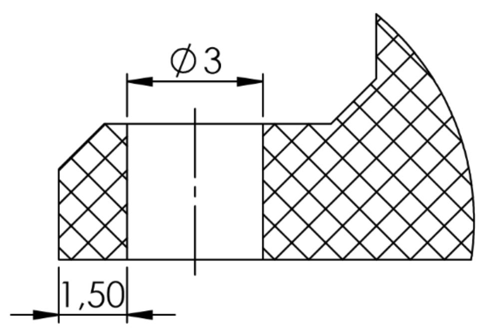
Proj.	18/04/22	F.C.T.-U.N.L	André F.R. Nunes
Des.	30/09/22	MIEMc - CNC Router	51966
Copiou			
Visto			





SECTION A-A

SCALE 3 : 1

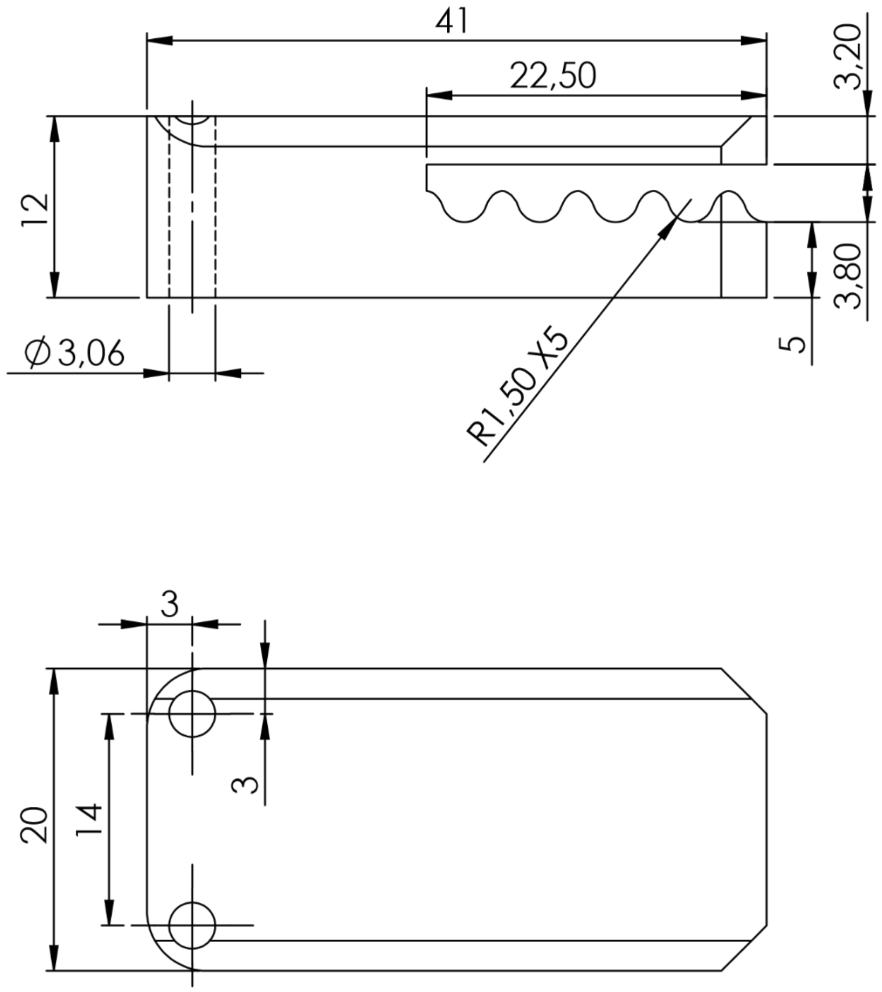


DETAIL B

SCALE 6 : 1

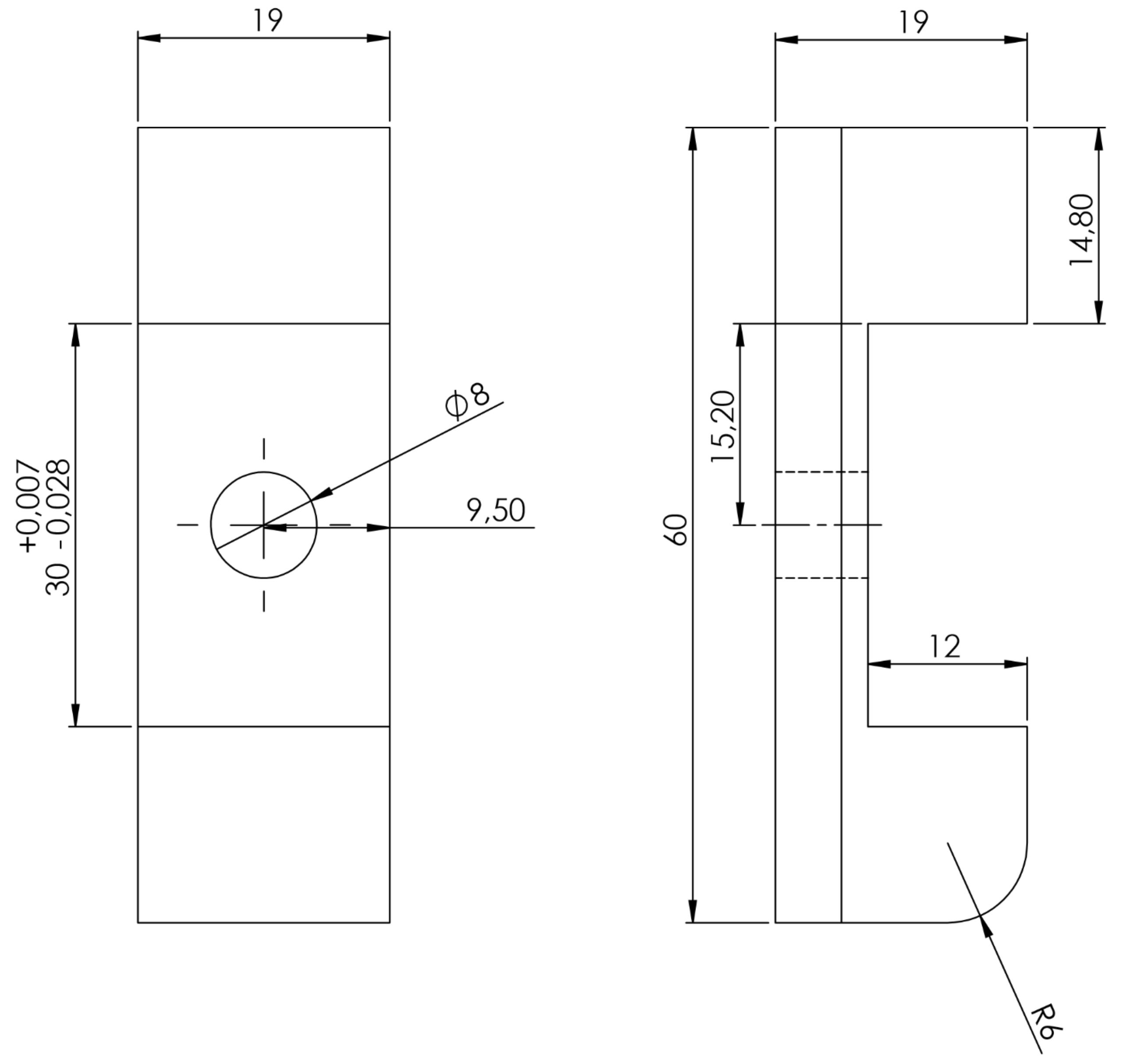
Observações:	3:1	Belt_Tensioner_X	P08
	ISO 2768		

Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes
Des.	30/09/22		MIEMc - CNC Router	51966
Copiou				
Visto				



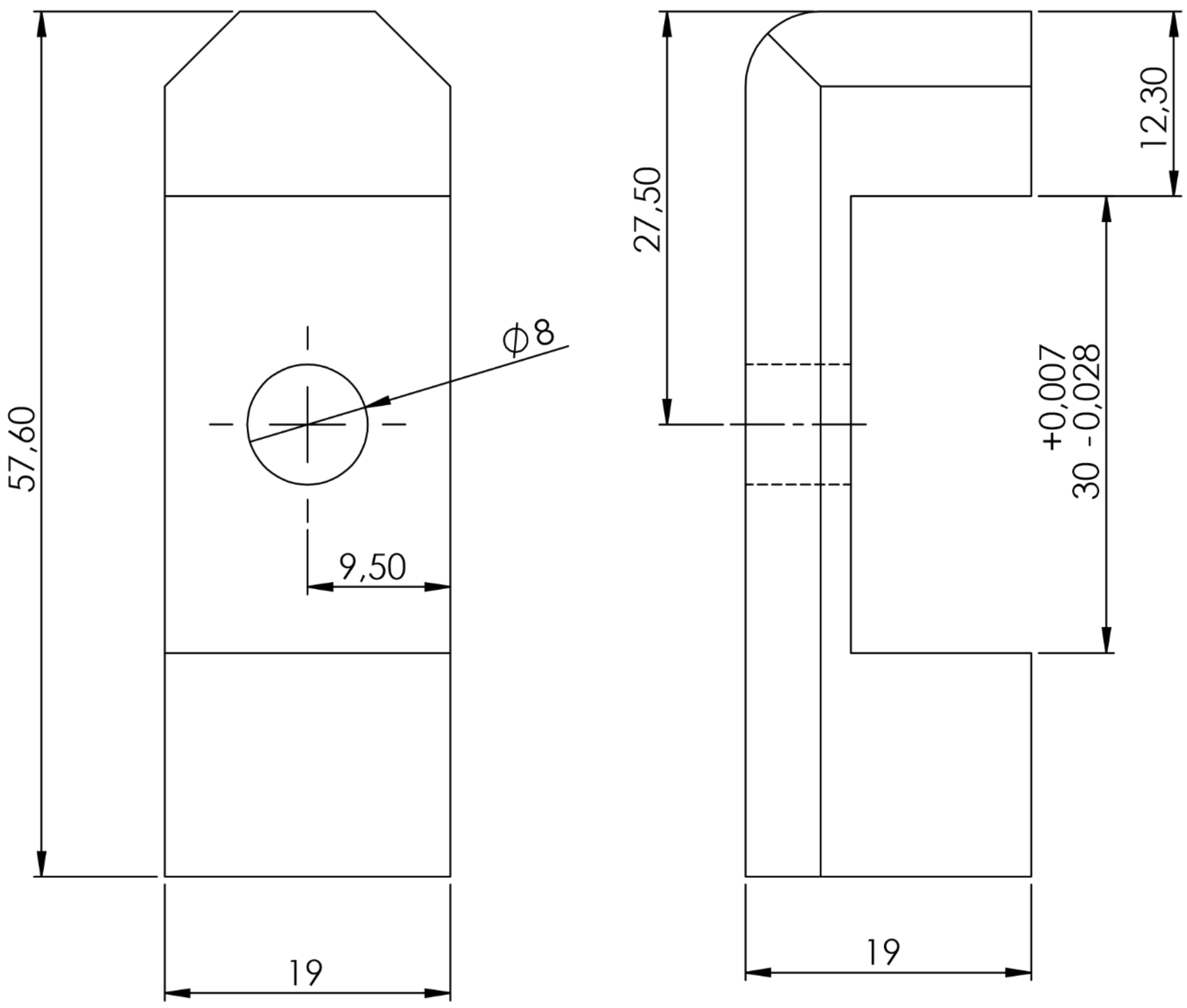
Observações:	2:1	Belt_Clamp_Y	P09
	ISO 2768		

			F.C.T.-U.N.L	André F.R. Nunes
Proj.	18/04/22		MIEMc - CNC Router	51966
Des.	30/09/22			
Copiou				
Visto				



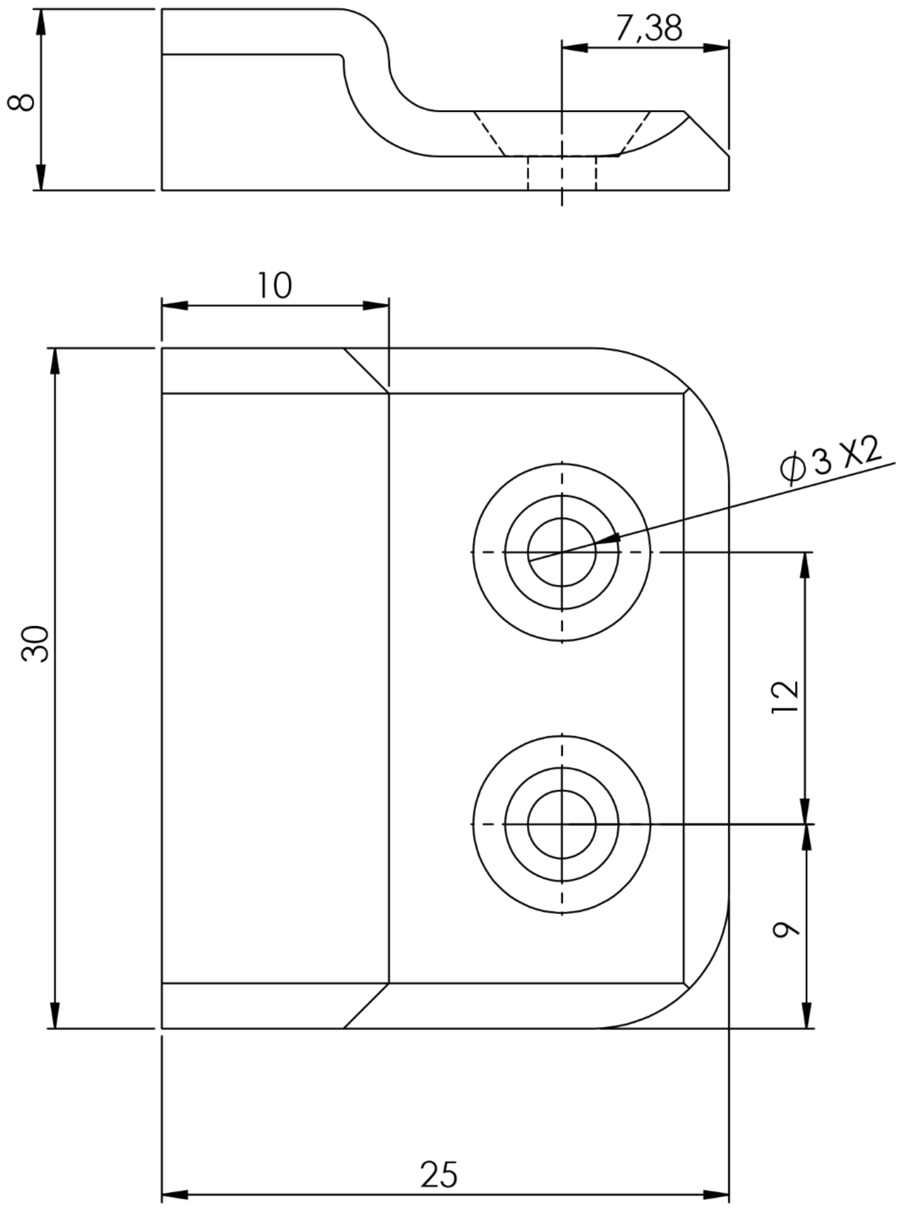
Observações:	3:1	X_Gantry_Clamp_BOT	P10
	ISO 2768		

Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes 51966
Des.	30/09/22		MIEMc - CNC Router	
Copiou				
Visto				



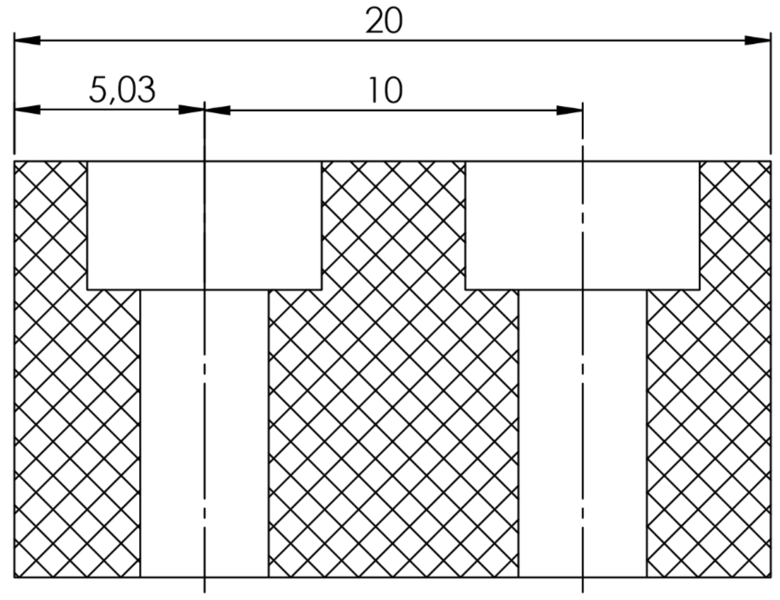
Observações:	3:1	X_Gantry_Clamp_TOP	P11
	ISO 2768		

Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes
Des.	30/09/22		MIEMc - CNC Router	51966
Copiou				
Visto				

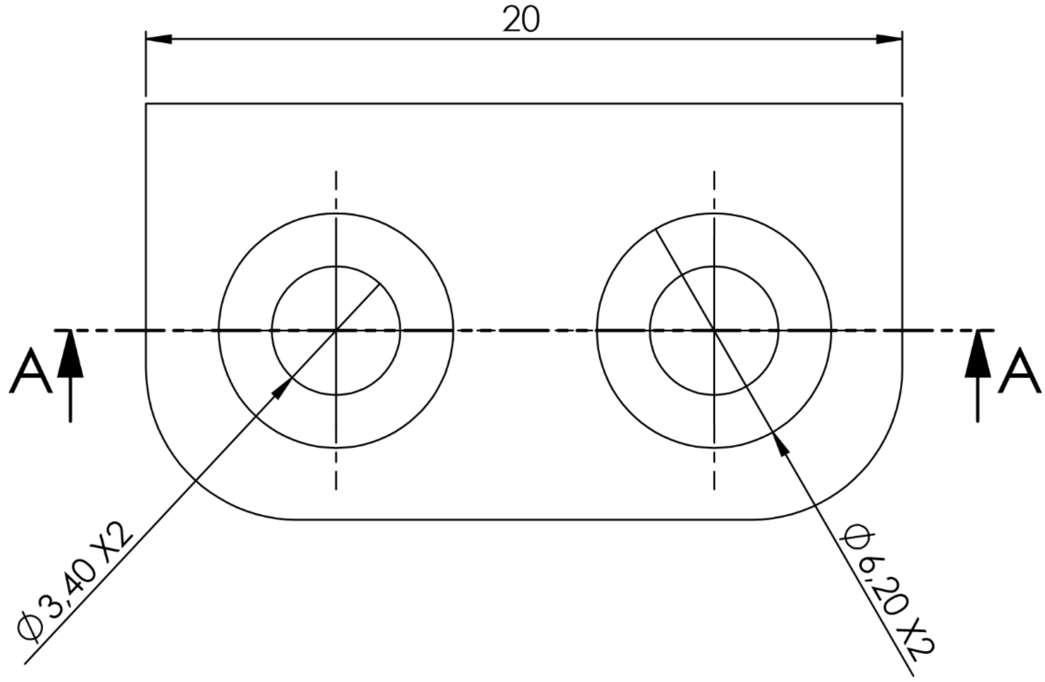


Observações:	3:1	XY_Block_Stopper	P12
	ISO 2768		

Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes 51966
Des.	30/09/22		MIEMc - CNC Router	
Copiou				
Visto				

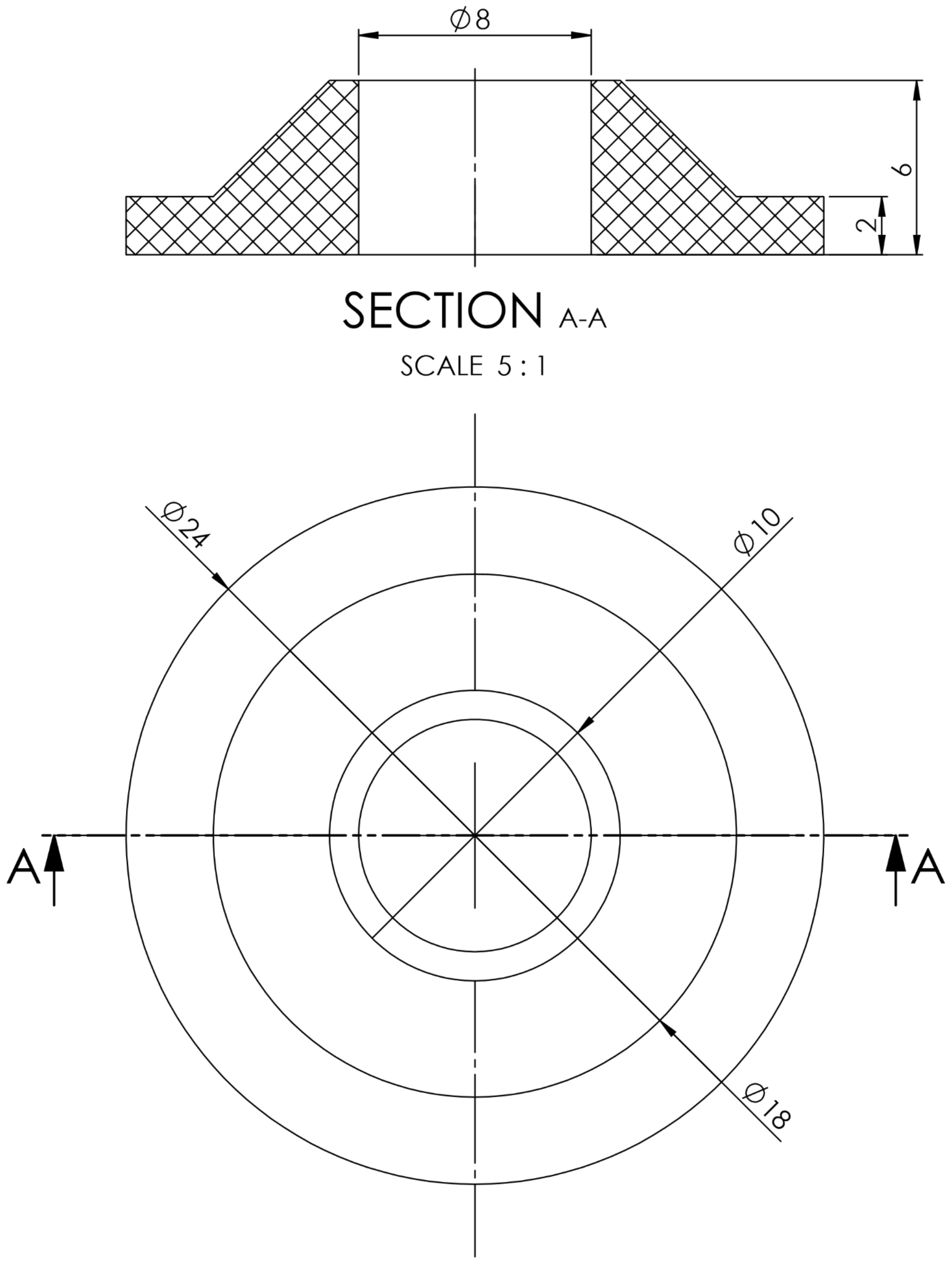


SECTION A-A
SCALE 5 : 1



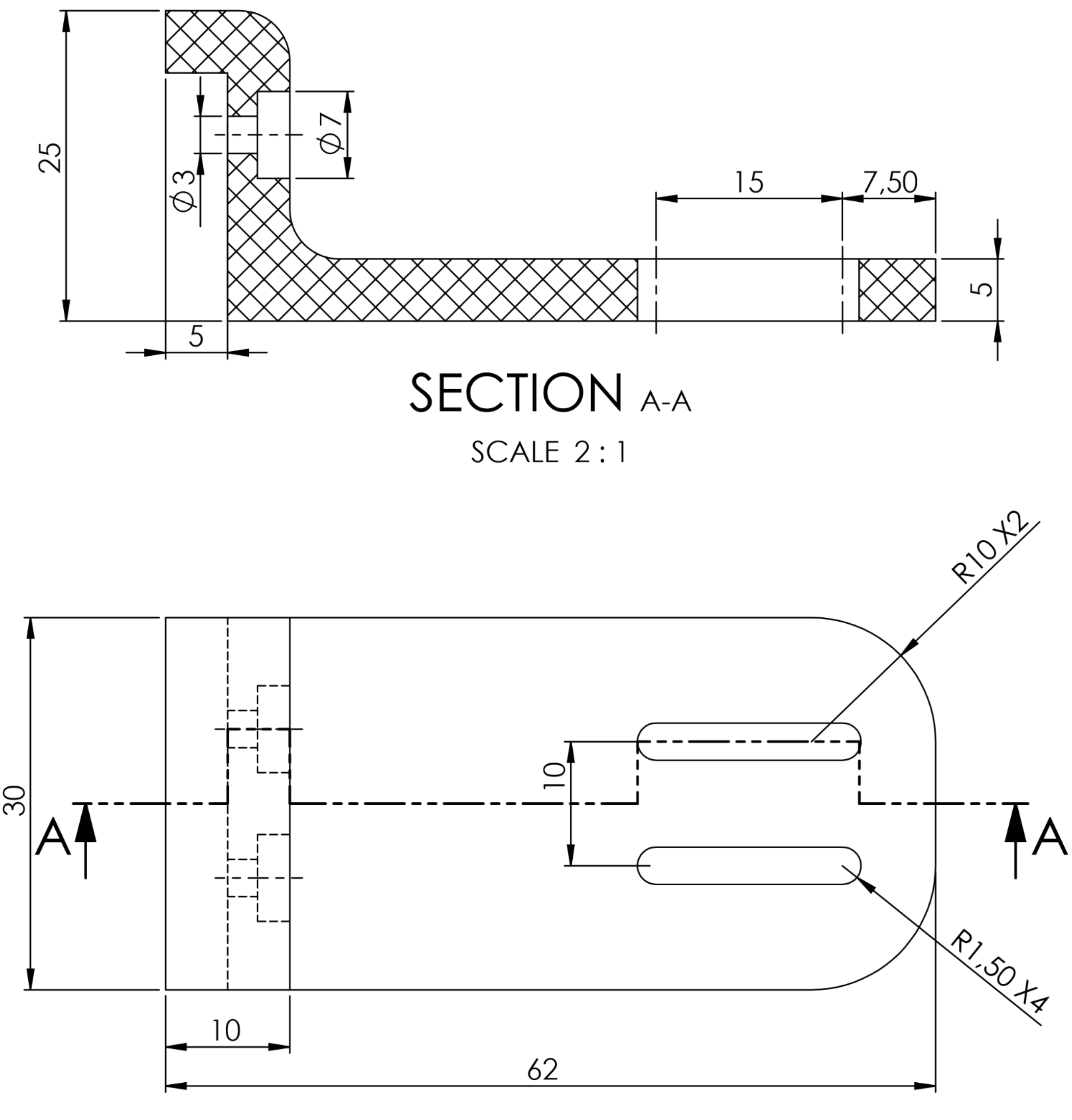
Observações:	5:1 ISO 2768	Z_Block_Stopper	P13

Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes
Des.	30/09/22		MIEMc - CNC Router	51966
Copiou				
Visto				



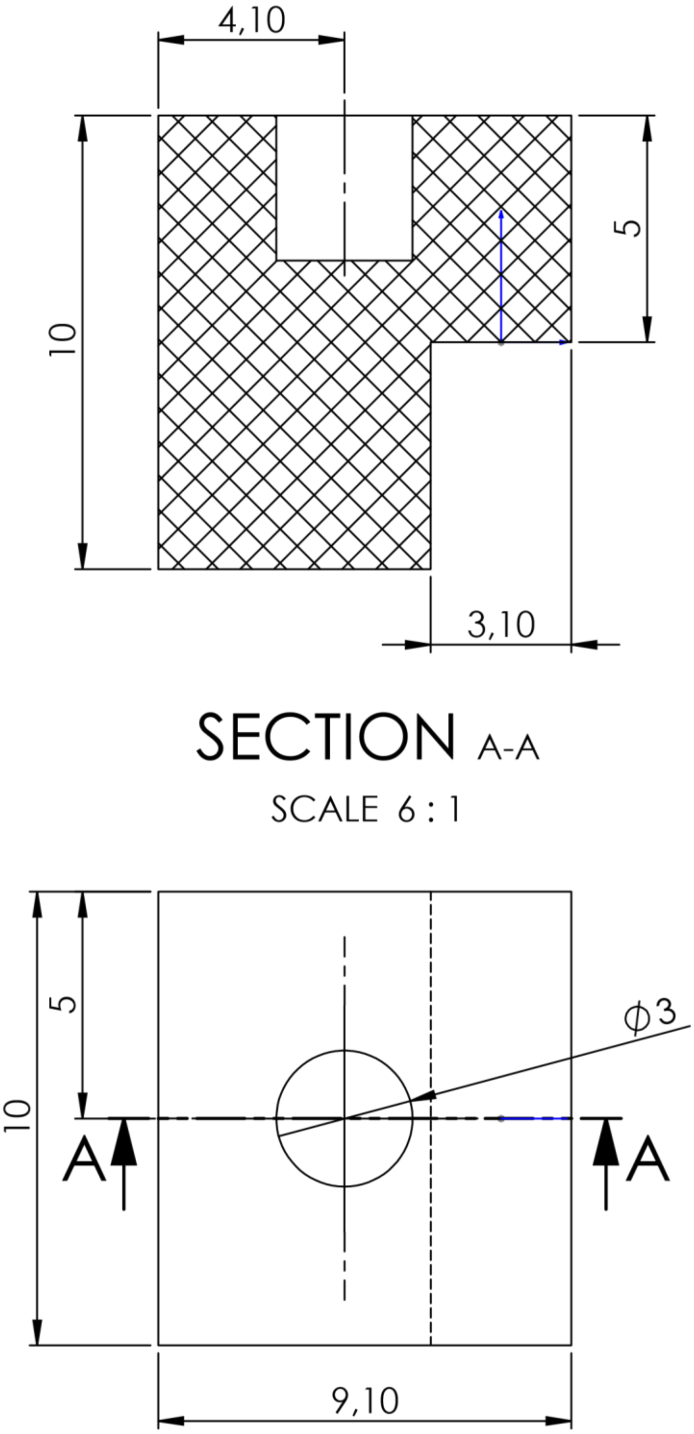
Observações:	5:1	Spacer	P14
	ISO 2768		

			F.C.T.-U.N.L	André F.R. Nunes
Proj.	18/04/22			51966
Des.	30/09/22		*MIEMc - CNC Router*	
Copiou				
Visto				



Observações:	2:1	*CableTrack_holder*	*P15*
	ISO 2768		

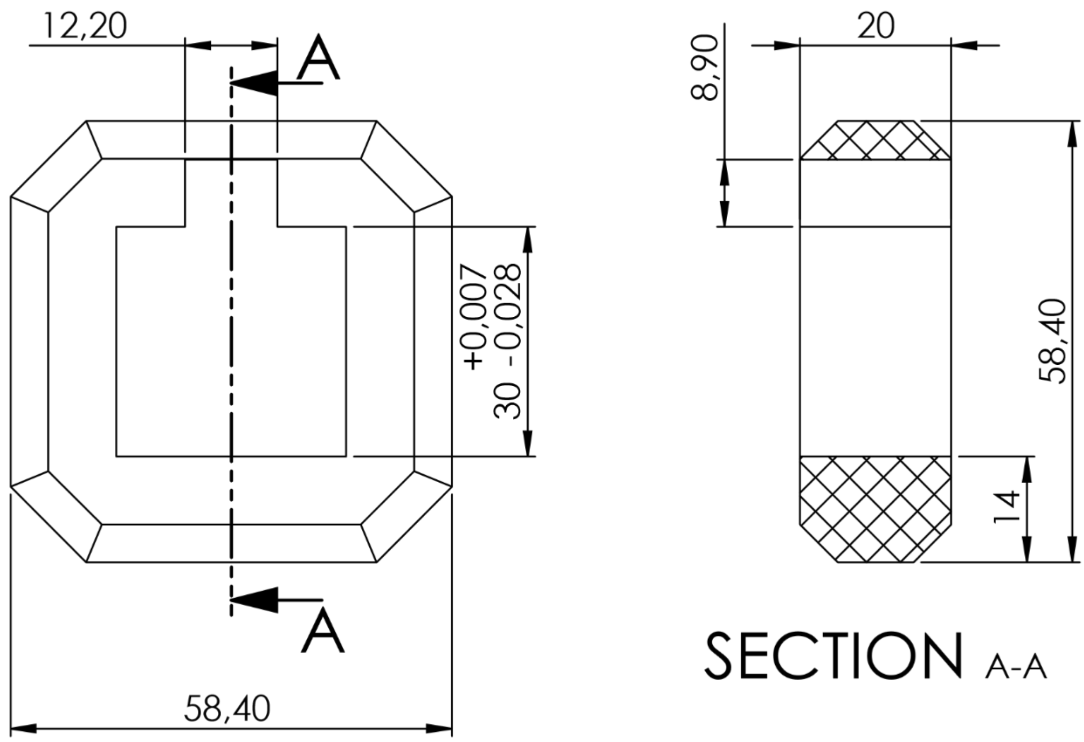
Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes
Des.	30/09/22		MIEMc - CNC Router	51966
Copiou				
Visto				



Observações:	6:1	Magnet_holder	P16
	ISO 2768		

Proj.	18/04/22		F.C.T.-U.N.L
Des.	30/09/22		*MIEMc - CNC Router*
Copiou			
Visto			

André F.R. Nunes
51966



Observações:

1:1

ISO 2768

Rail_Centering_Block

P17

Proj.	18/04/22		
Des.	30/09/22		
Copiou			
Visto			

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MIEMc - CNC Router

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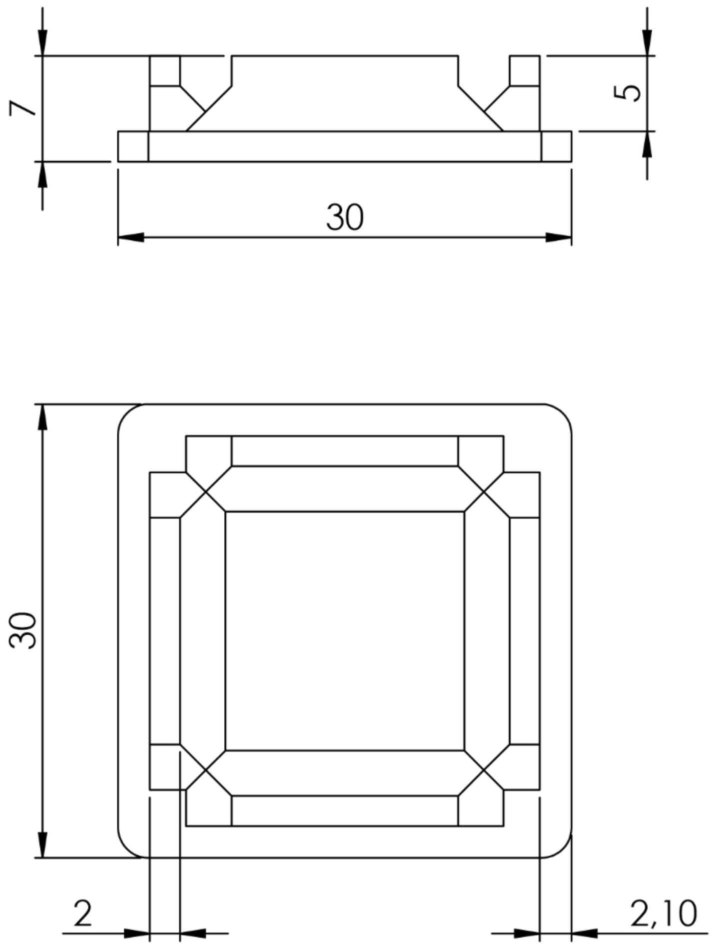
51966



Observações:

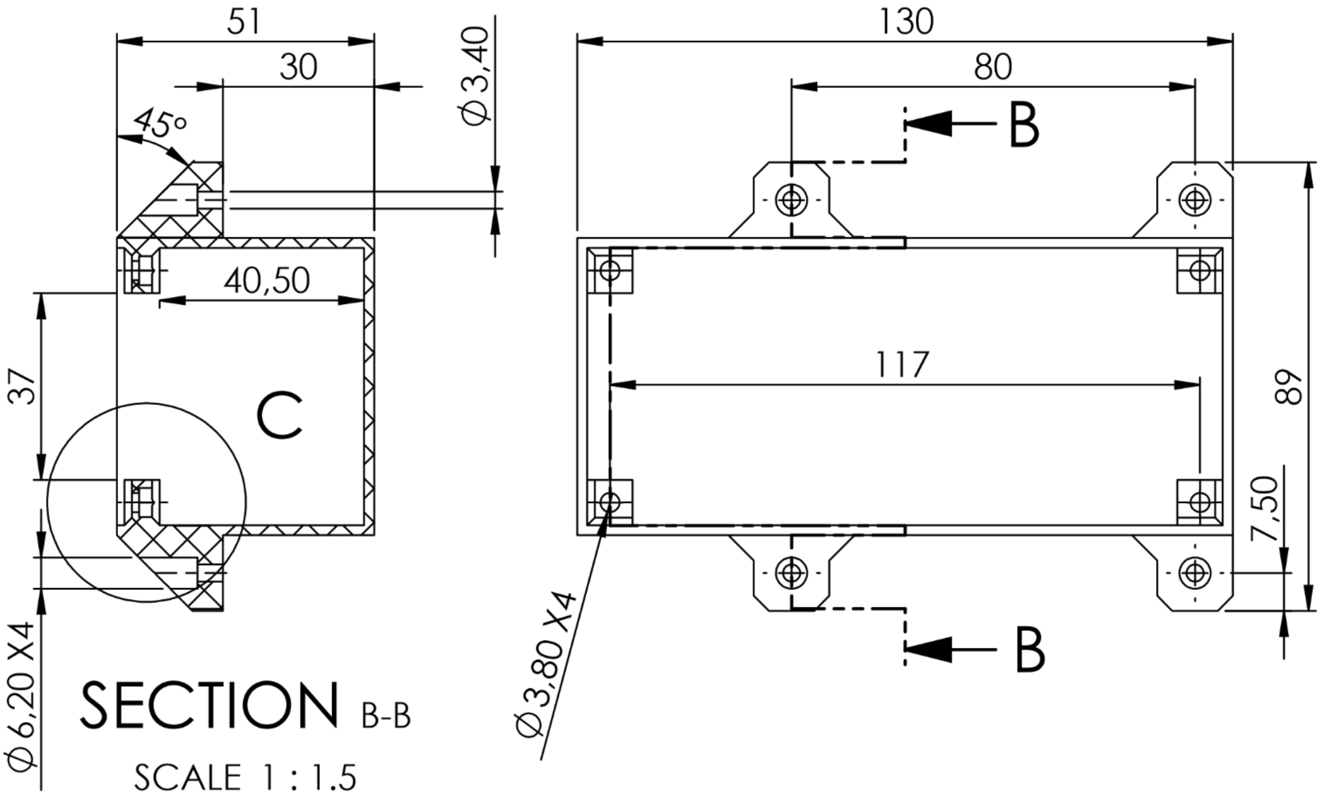
2:1

ISO 2768

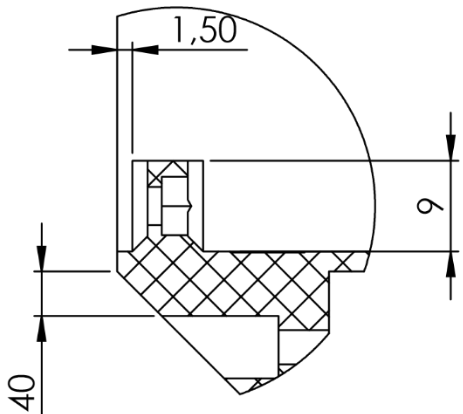
Square_Tube_Lid

P18

			F.C.T.-U.N.L	André F.R. Nunes
Proj.	18/04/22		*MIEMc - CNC Router*	51966
Des.	30/09/22			
Copiou				
Visto				



SECTION B-B
SCALE 1 : 1.5

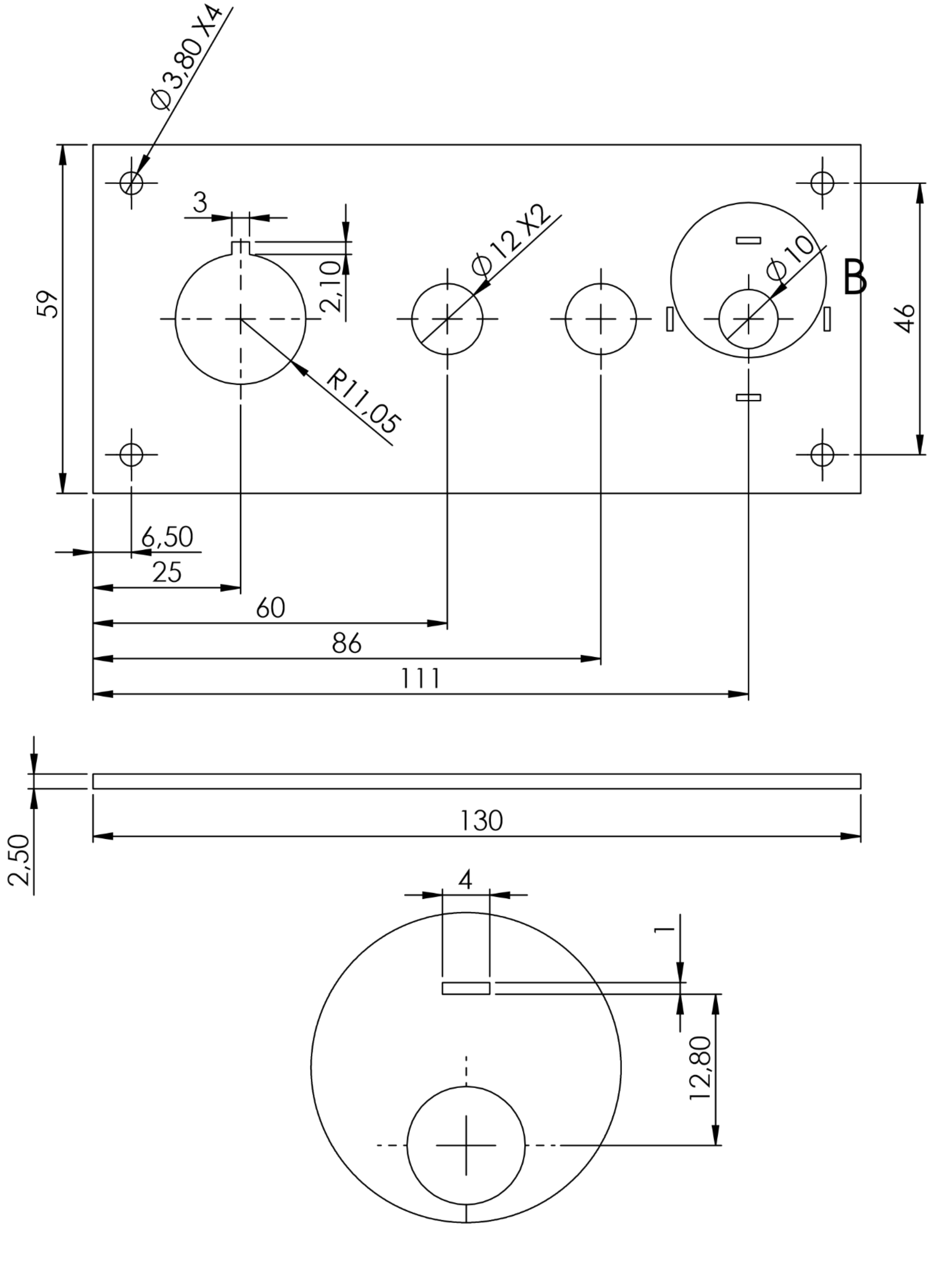


DETAIL C
SCALE 2 : 1.5

Observações:	1:1.5	*Control_Box*	P19
	ISO 2768		

Proj.	18/04/22		F.C.T.-U.N.L
Des.	30/09/22		*MIEMc - CNC Router*
Copiou			
Visto			

André F.R. Nunes
51966



DETAIL B
SCALE 2 : 1

Observações:

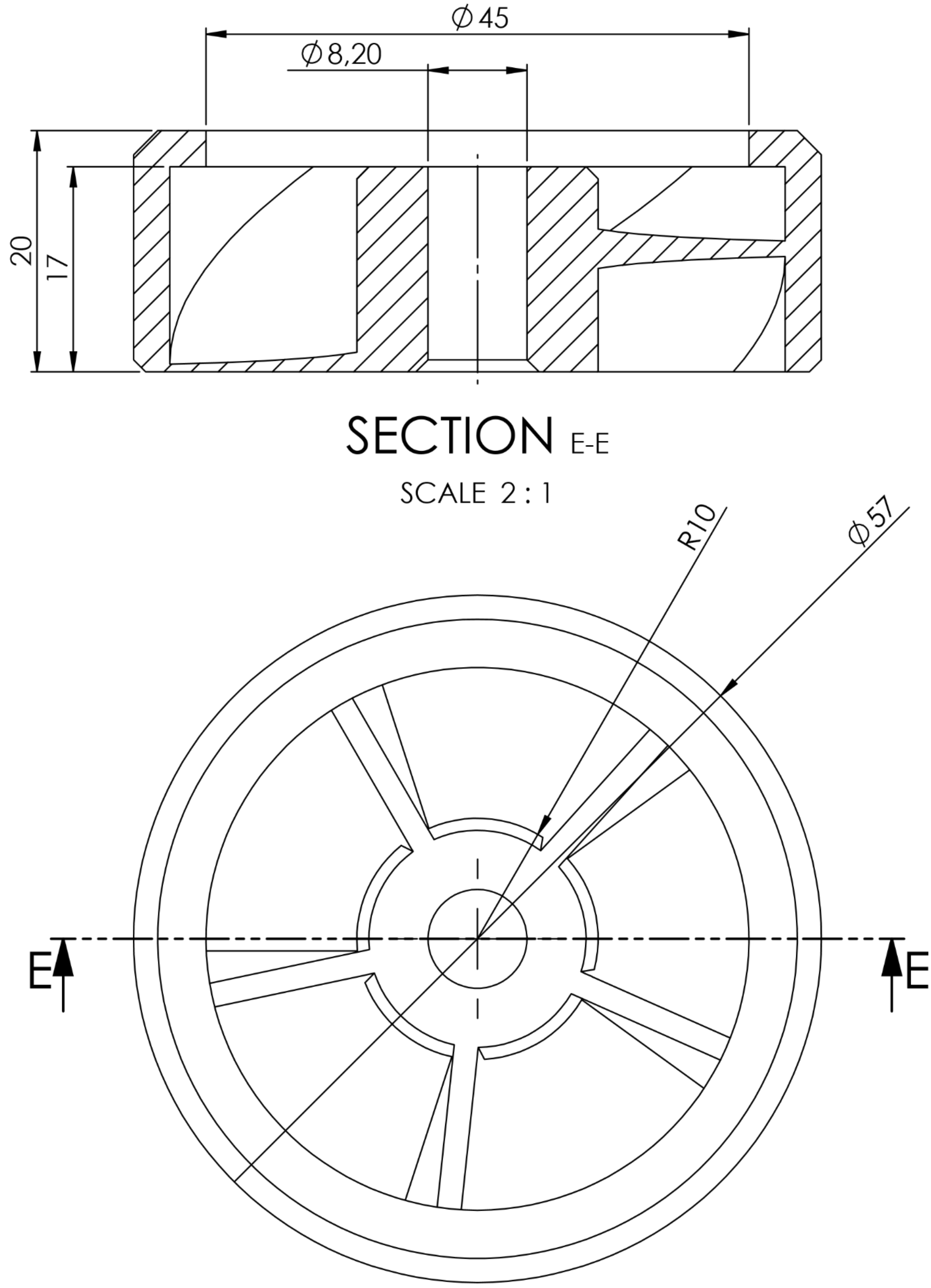
1:1

ISO 2768

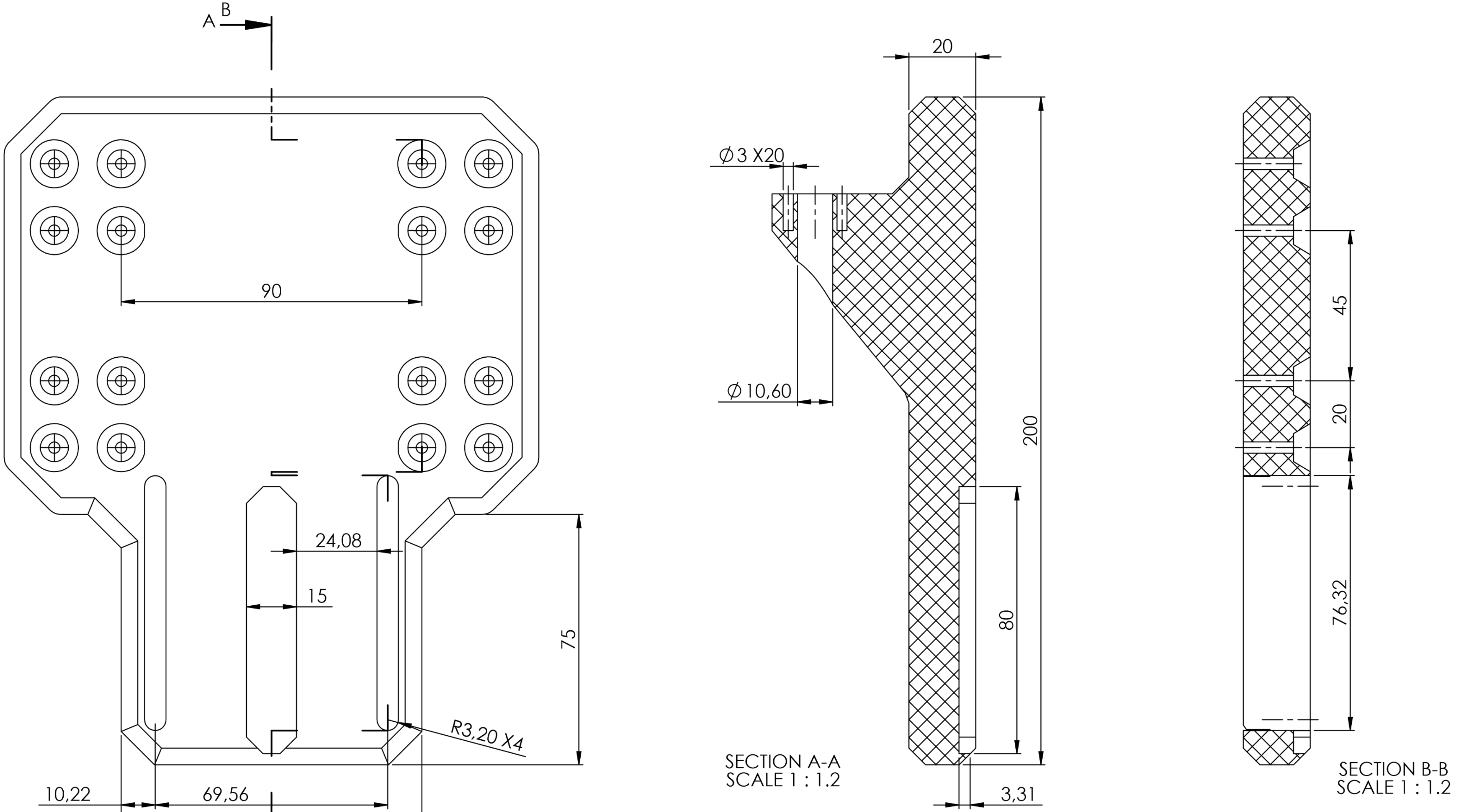
Control_Box_Lid

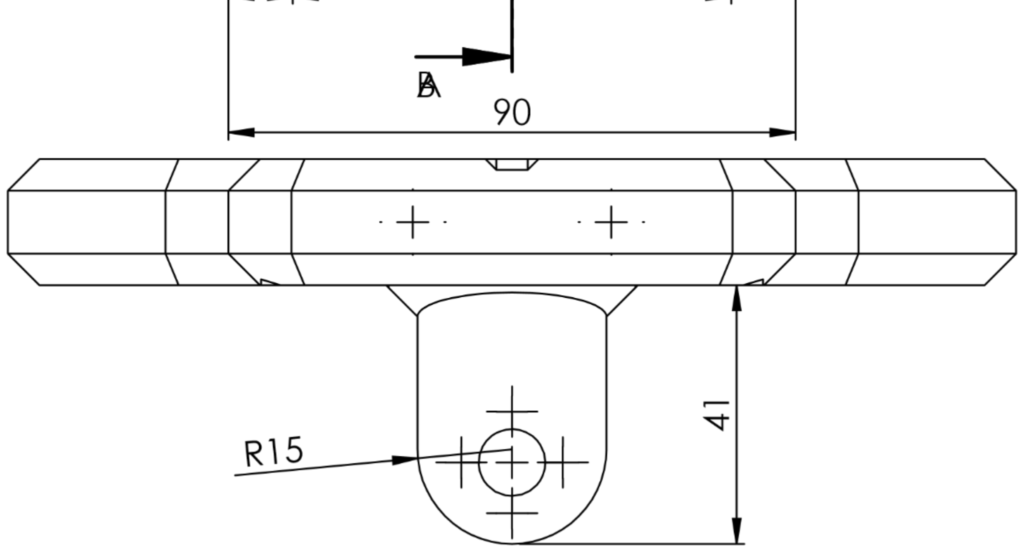
P20

Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes
Des.	30/09/22		MIEMc - CNC Router	51966
Copiou				
Visto				



Observações:	2:1	Spindle_Fan	P21
	ISO 2768		





Observações:

Proj.	18/04/22	
Des.	30/09/22	
Copiou		
Visto		

F.C.T.-U.N.L

MIEMc - CNC Router

André .F.R. Nunes

SCALE: 1:1.2

ISO 2768

Z_Gantry_FourthAxis

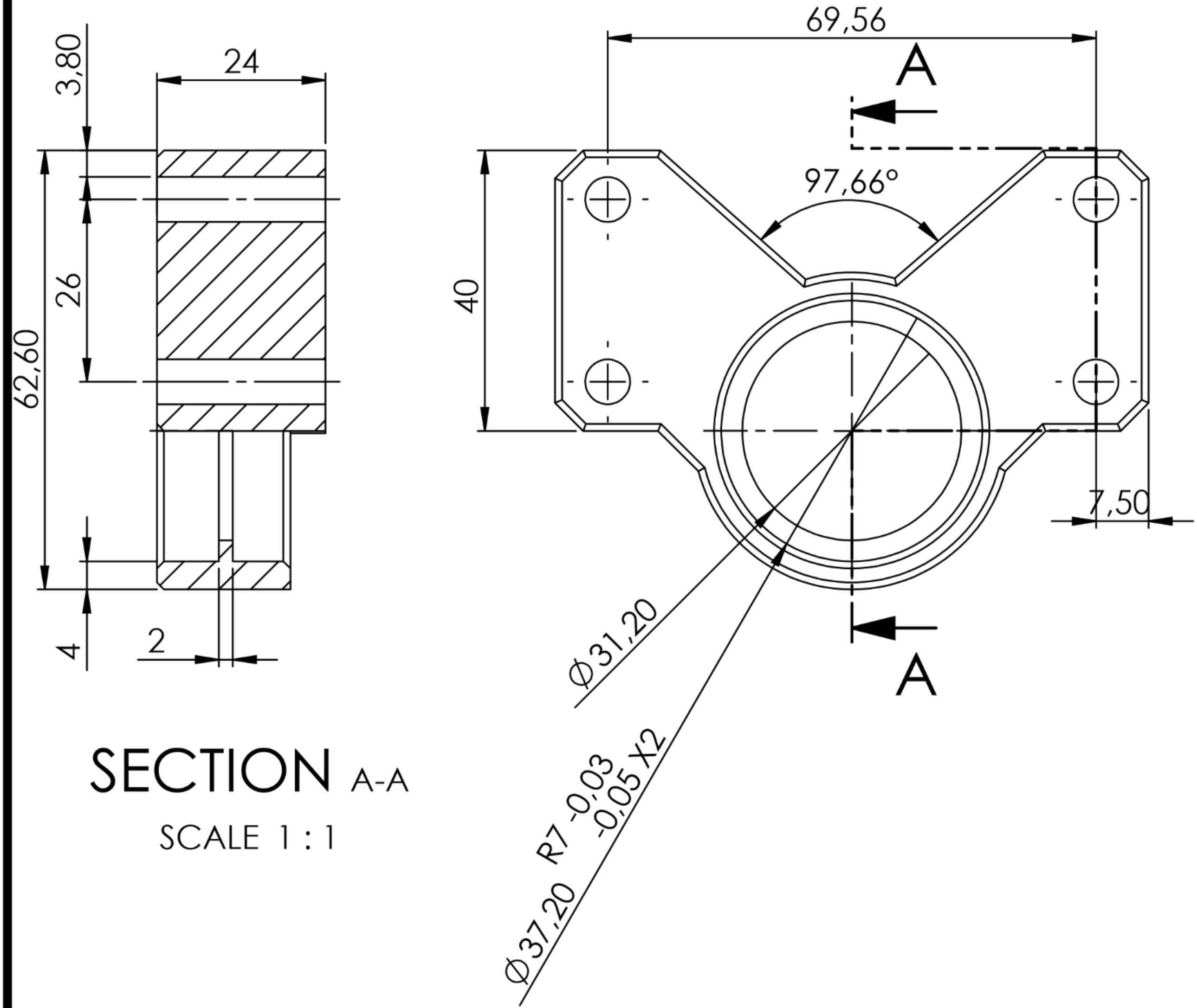
P22

Proj.	18/04/22	
Des.	30/09/22	
Copiou		
Visto		

F.C.T.-U.N.L

MIEMc - CNC Router

André F.R. Nunes
51966



SECTION A-A
SCALE 1 : 1

Observações:

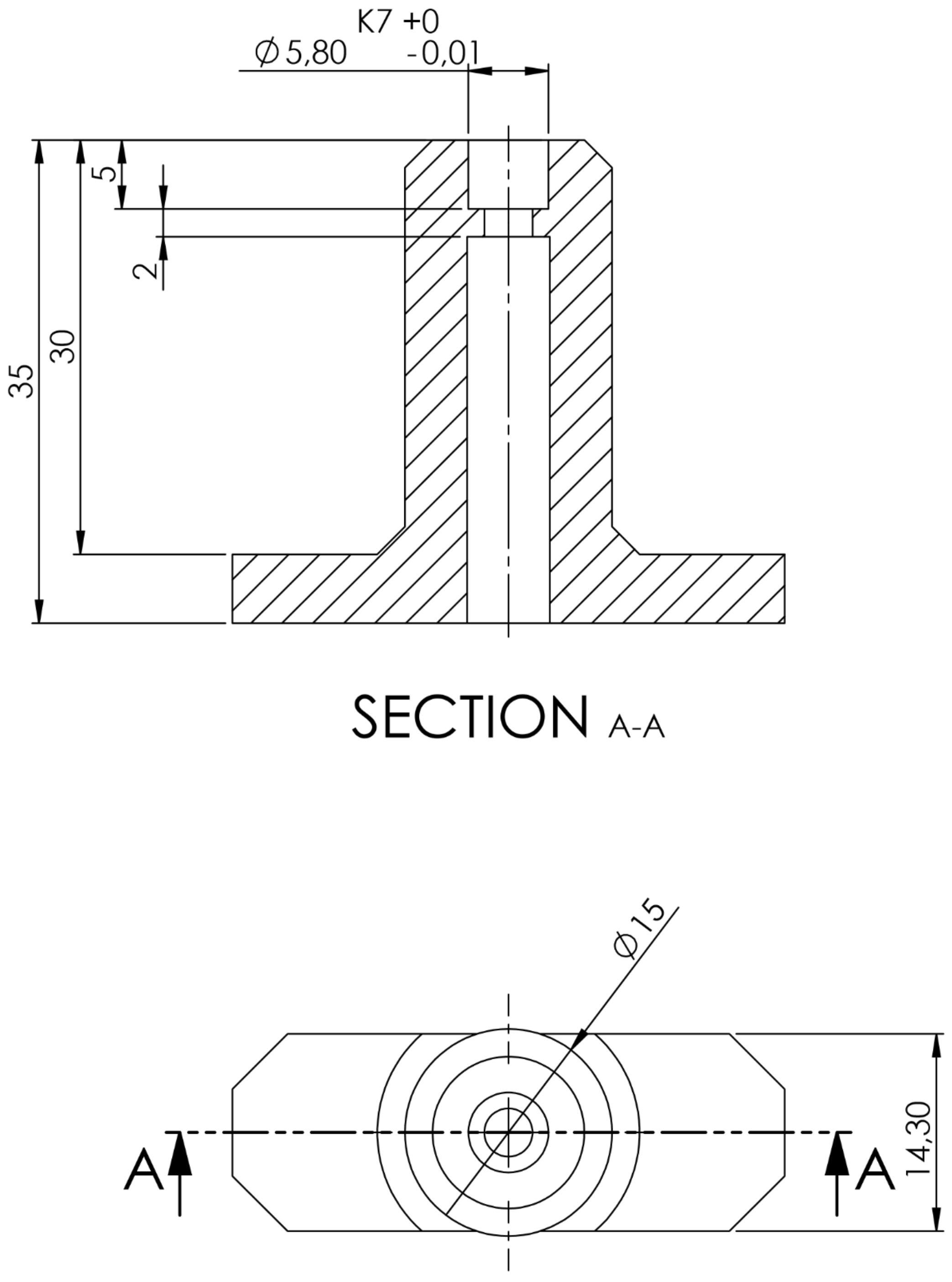
1:1

ISO 2768

Bracket_FourthAxis

P23

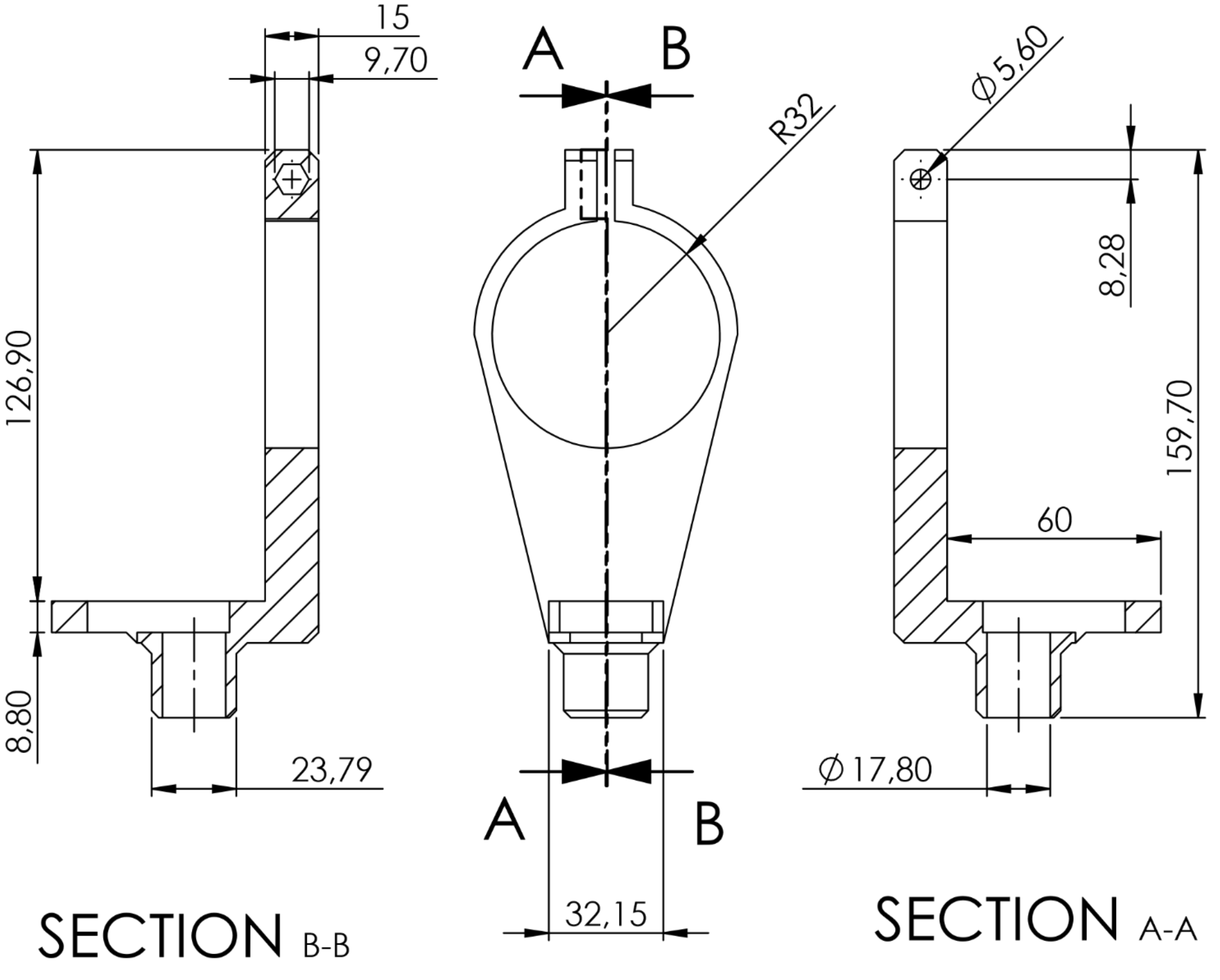
			F.C.T.-U.N.L	André F.R. Nunes
Proj.	18/04/22			51966
Des.	30/09/22		*MIEMc - CNC Router*	
Copiou				
Visto				



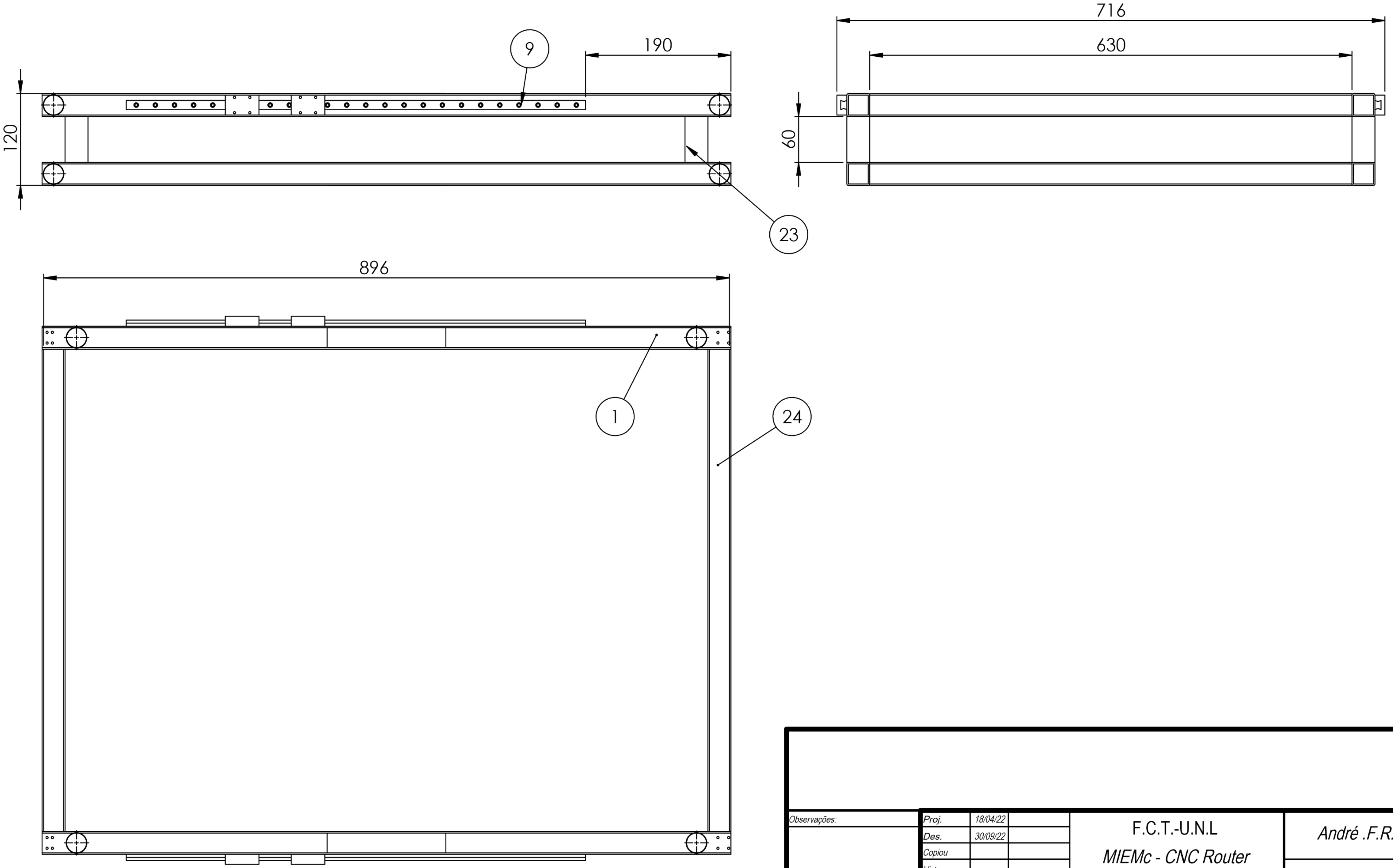
SECTION A-A

Observações:	1:1	*Servo_Shaft_FourthAxis*	P24
	ISO 2768		

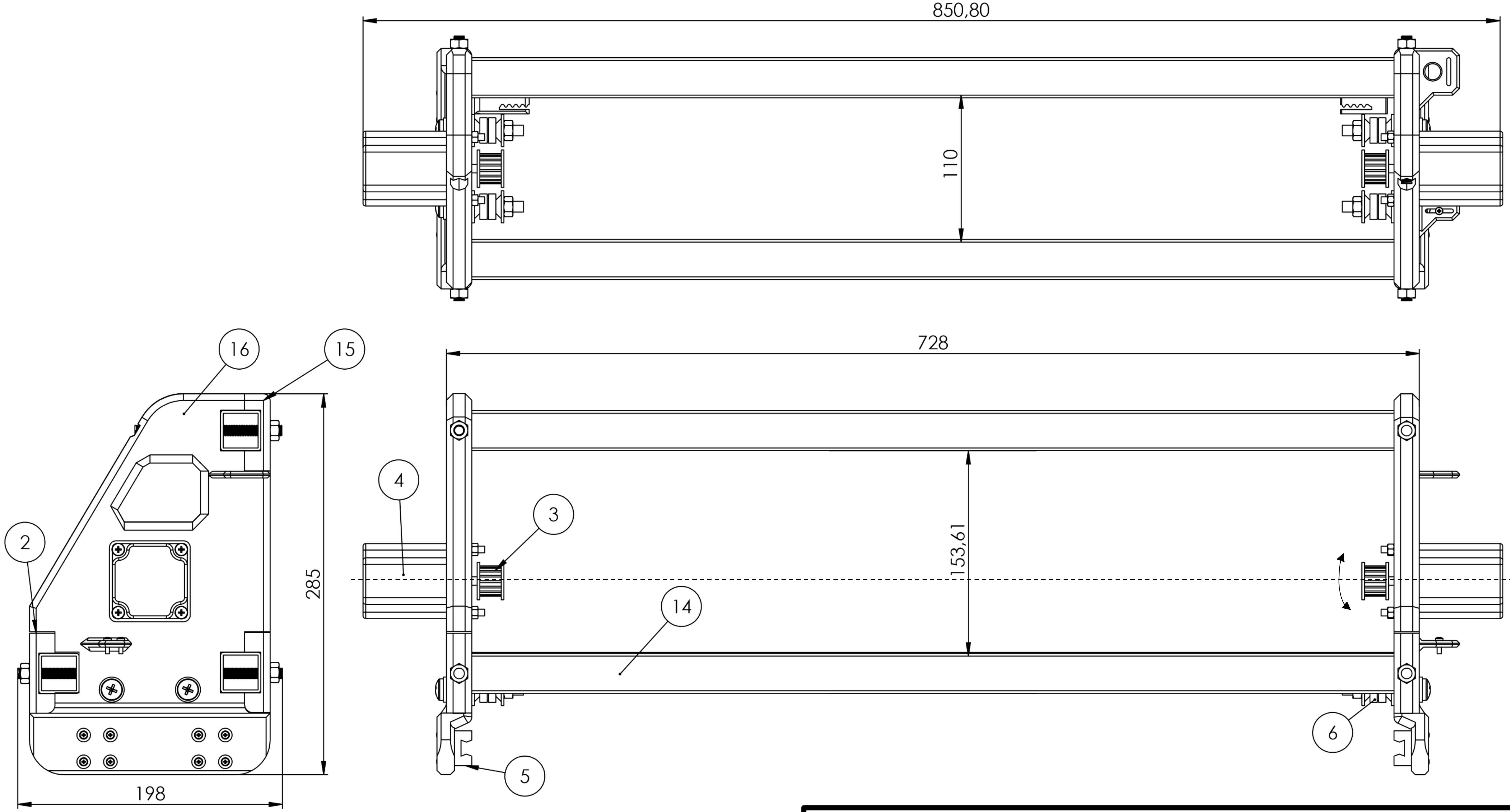
Proj.	18/04/22		F.C.T.-U.N.L	André F.R. Nunes
Des.	30/09/22		MIEMc - CNC Router	51966
Copiou				
Visto				



Observações:	1:2	Router_Holder_FourthAxis	P25
	ISO 2768		

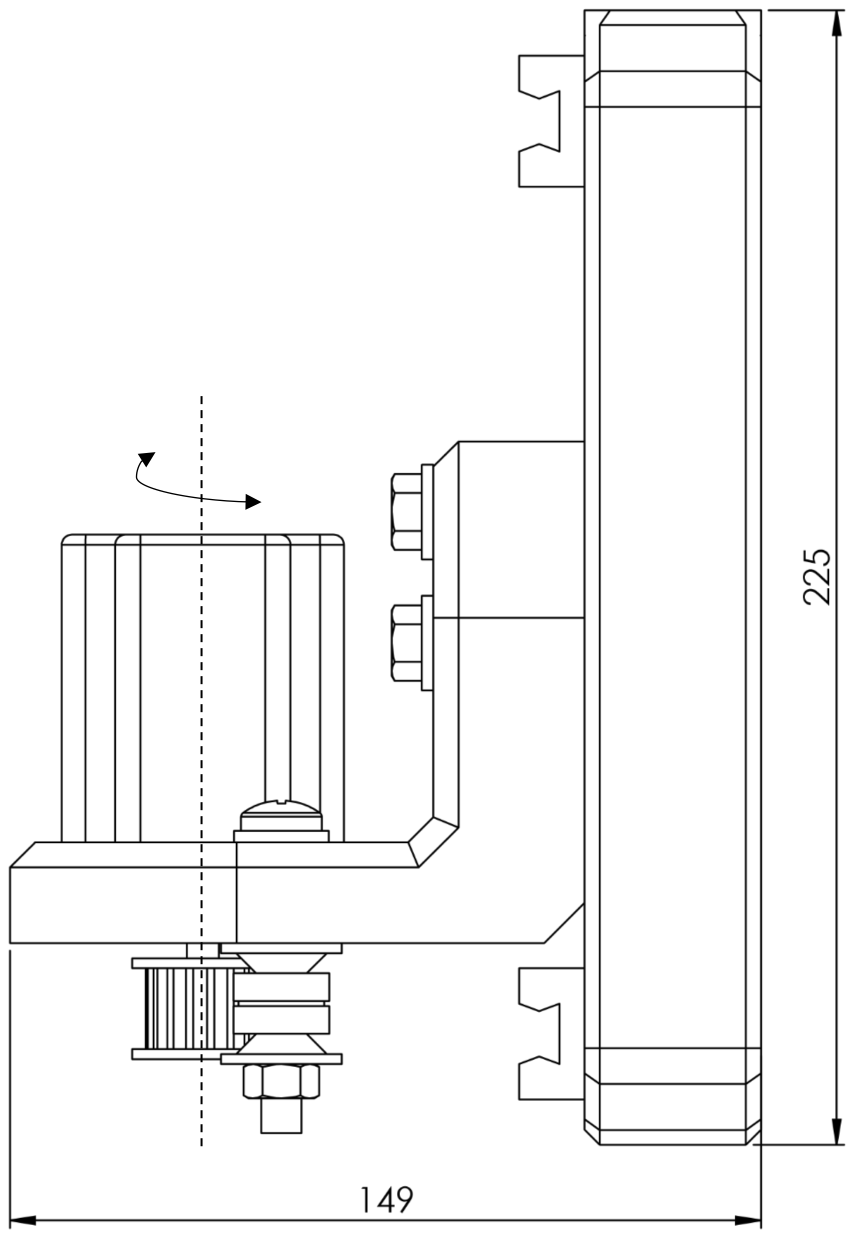


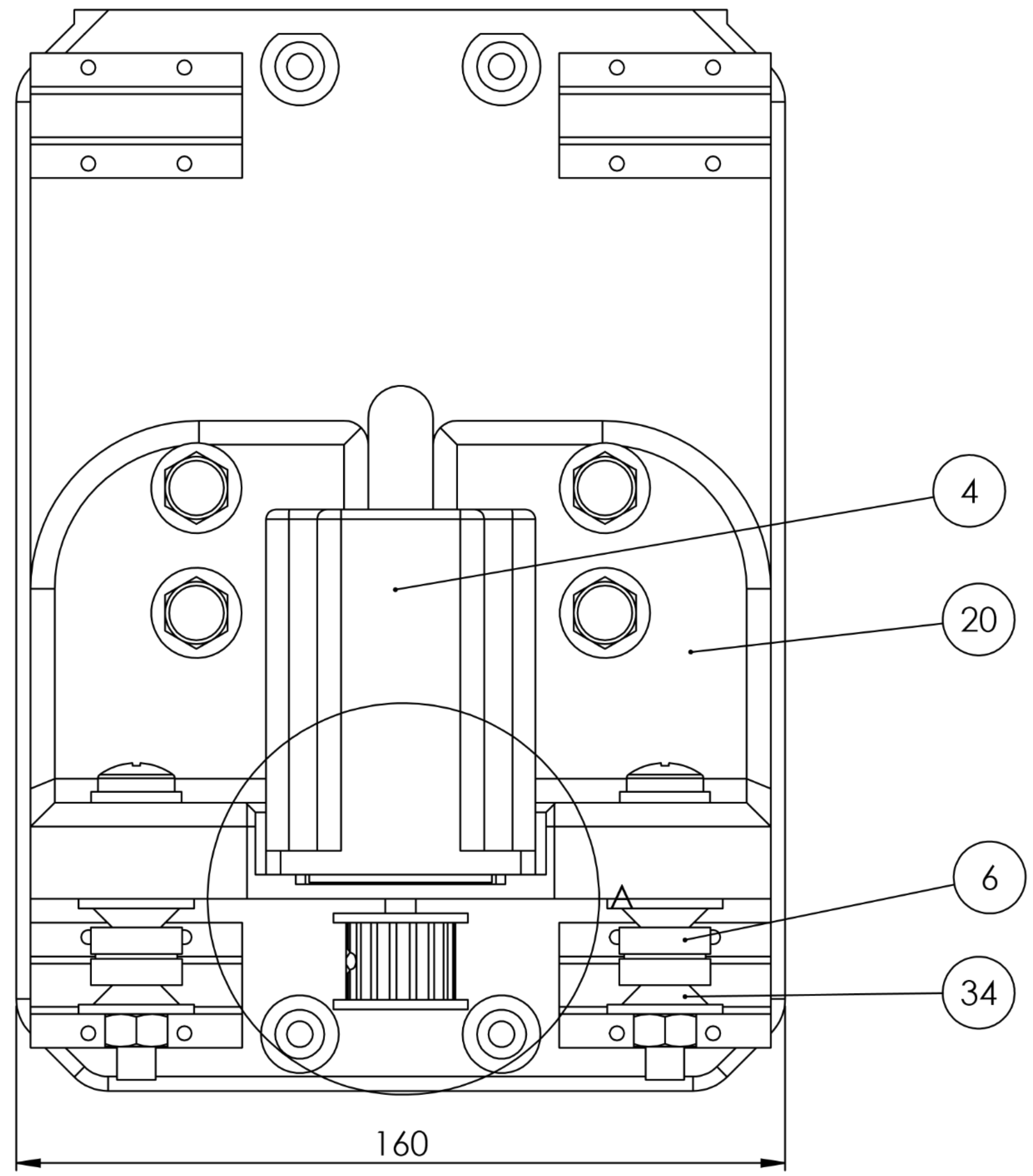
Observações:	Proj.	18/04/22	F.C.T.-U.N.L	André .F.R. Nunes
	Des.	30/09/22	MIEMc - CNC Router	
	Copiou			
	Visto			
	SCALE: 1:5		MainFrame	S01
	ISO 2768			

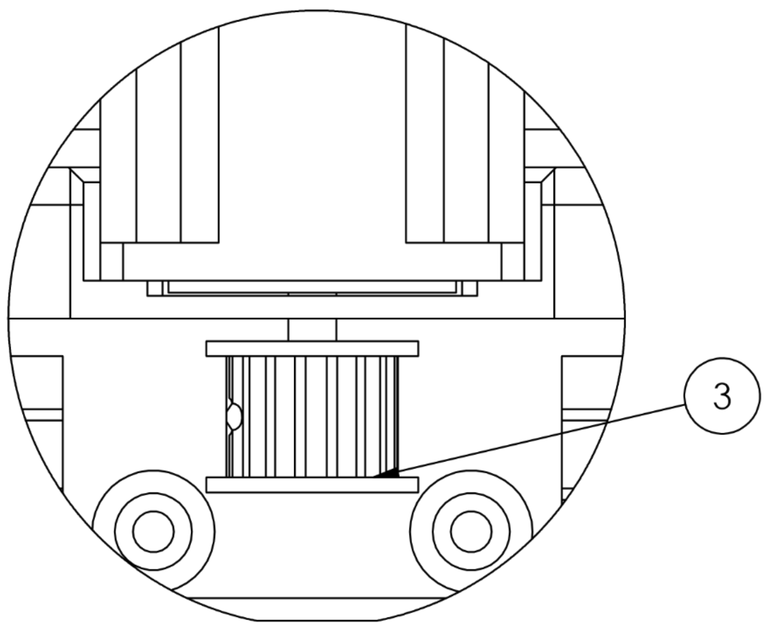


Observações:

Proj.	18/04/22	F.C.T.-U.N.L	André .F.R. Nunes
Des.	30/09/22	MIEMc - CNC Router	
Copiou			
Visto			
SCALE: 1:4	X_Subassembly		S02
ISO 2768			

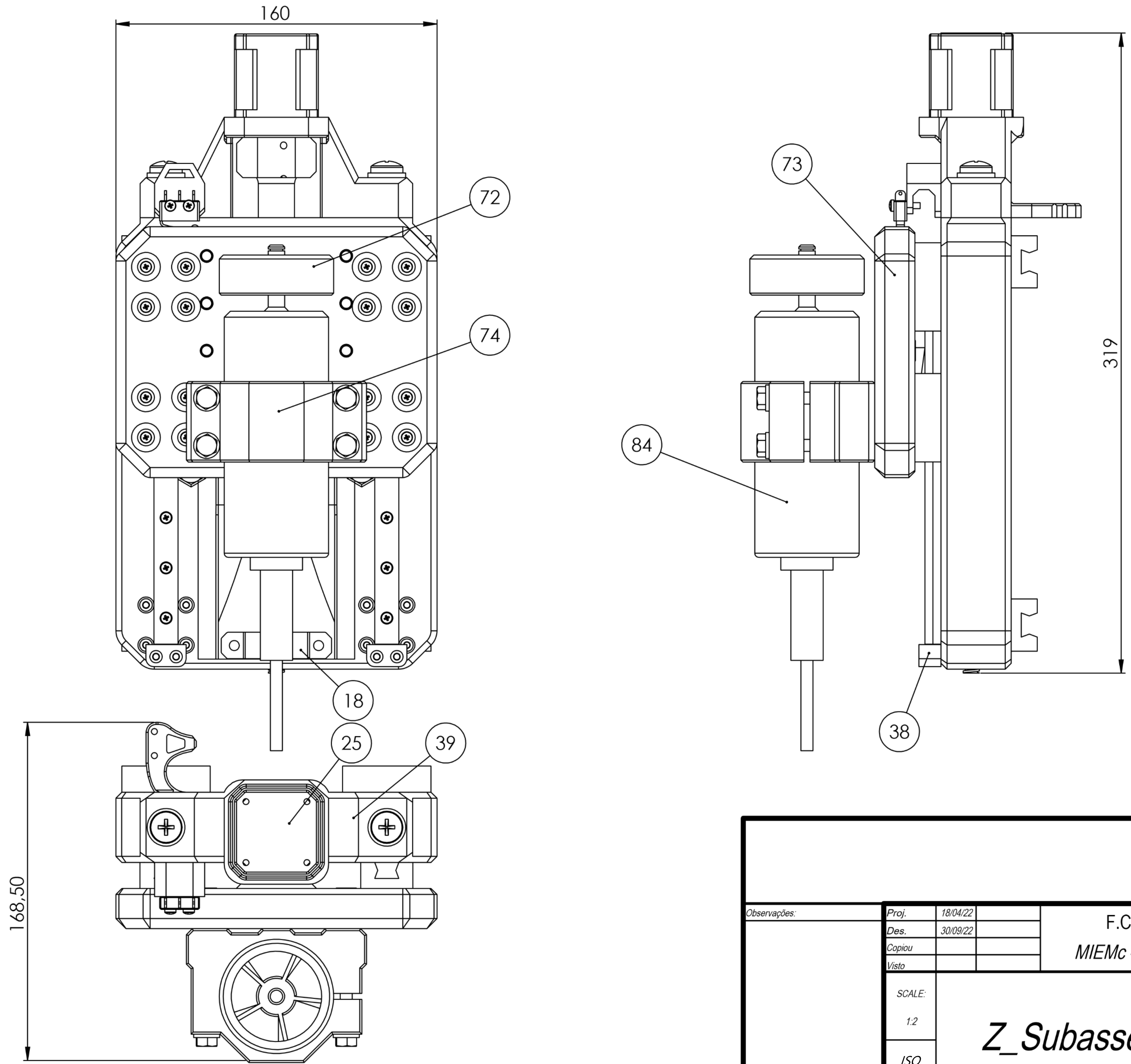






DETAIL A
SCALE 1 : 1

Observações:	Proj.	18/04/22	F.C.T.-U.N.L MIEMc - CNC Router	André .F.R. Nunes
	Des.	30/09/22		
	Copiou			
	Visto			
	SCALE: 1:1.5		Y_Subassembly	S03
	ISO 2768			



Observações:	Proj. 18/04/22		F.C.T.-U.N.L	André .F.R. Nunes
	Des. 30/09/22		MIEMc - CNC Router	
	Copiou			
	Visto			
	SCALE: 1:2	Z_Subassembly		S04
	ISO 2768			

BOM

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Perfil_700		4
2	Aperto_Perfil_XZ_VERSION_2		4
3	HTD5M_Pulley		3
4	Motor_Nema23		3
5	Rail_Block		12
6	Rolamento_Esticador		6
7	Tensionador		2
8	Tensionador_ISOLADO		2
9	Rail_600		4
10	B18.2.3.1M - Hex cap screw, M5 x 0.8 x 30 --16N		2
11	B18.2.4.1M - Hex nut, Style 1, M6 x 1 --D-N		56
12	B18.22M - Plain washer, 6 mm, narrow		32
13	B18.6.7M - M5 x 0.8 x 20 Type I Cross Recessed PHMS --20N		142
14	Perfil_800		3
15	Aperto_Perfil_XZ_VERSION_2_CIMA		2
16	YY_AXIS_LEFT_VERSION_3.STL		1
17	End_STOP		4
18	Lead_SCREW_Bearing		2
19	Lead_Screw		1
20	XX_MOTOR_Mount		1
21	Rail_200		2
22	Perfil_116		4
23	Perfil_690		4
24	Motor_Nema17		1
25	Lead_Screw_COUPLER		1
26	Threaded_ROD_650		4
27	Threaded_ROD_90		4
28	Tensionador_ISOLADO_XX		1
29	Wood_base		1
30	Wood_base_2		3
31	Spacer		12
32	Threaded_ROD_100		2
33	Threaded_ROD_195		2
34	End_STOP_ZZ		2
35	ZZ_MOTOR_Mount		1
36	XX_Gantry		1
37	Eletronics_box		1
38	Arduino		1
39	Main_Power_Supply		1

40	Spindle_Power_Supply		1
41	Eletronics_box_LID		1
42	Magnet_holder		4
43	Gelid Silent 5 frame		1
44	Gelid Silent 5 rotor		1
45	Cable_Chain_holder		1
46	Cable_Chain_Path_Z		1
47	Chain_link1		4
48	Chain_link2		70
49	Cable_Chain_Path		1
50	YY_AXIS_RIGHT_VERSION_mirr orless		1
51	Switch_Box		1
52	Switch_Box_LID		1
53	Lever_Switch		2
54	Emergency_Button		1
55	Tensionador_2_v2		2
56	B18.6.7M - M8 x 1.25 x 60 Indented HHMS --38N		4
57	Spindle_controller		1
58	Limit_Switch_Mount_Left		1
59	YY_Limit_Switch		2
60	Limit_Switch_XX		1
61	Limit_Switch_Mount_ZZ		1
62	Tensionador_XX_1		1
63	Spindle_Fan		1
64	ZZ_GANTRY		1
65	Spindle_holder		1
66	B18.2.3.5M - Hex bolt M6 x 1.0 x 60 --60N		4
67	Z_Limit_Switch		1
68	Lead_Screw_NUT		1
69	Profile_square_cover		6
70	Profile_square_cover_hole		2
71	SPINDLE		1
72	Stock_Material		1

ATTACHMENT I

Tolerancing:

Table I.1- Adjustments.

Ajustes	AJUSTES RECOMENDADOS						TABLA 9 . 8
ESPECIFICACION DE LOS ASIENTOS							
Grado del ajuste	Calidades superficiales	SISTEMA: Agujero único: Agujero	Agujero único: Eje	Eje único: Eje	Eje único: Agujero	ASIENTO: Clase	ASIENTO: Características
PRECISION	▽▽▽▽	H 6	p 5	h 5	P 6	Forzado muy duro	Piezas montadas por dilatación o contracción; no necesitan seguro contra giro.
			n 5		N 6	Forzado duro	Piezas montadas o desmontadas a presión; necesitan seguro contra giro.
			k 5		K 6	Forzado medio	Piezas que han de montarse o desmontarse con gran esfuerzo; seguro para giro y deslizamiento.
	▽▽▽		j 5		J 6	Forzado ligero	Montaje y desmontaje sin gran esfuerzo; necesitan seguro contra giro y deslizamiento.
			h 5		H 6	Deslizante	Piezas lubricadas que se montan y desmontan sin gran trabajo, a mano.
			g 5		G 6	Giratorio	En piezas lubricadas el giro y deslizamiento puede efecturse a mano.
FINO		H 7	s 6	h 6	S 7	Forzado muy duro	Montaje por dilatación o contracción; no necesita seguro contra giro.
			r 6		R 7	Forzado muy duro	Montaje por dilatación o contracción; no necesita seguro contra giro.
	▽▽▽		n 6		N 7	Forzado duro	Montado o desmontado a presión; necesita seguro contra giro.
			k 6		K 7	Forzado medio	Montado y desmontado con gran esfuerzo (mediante martillo de plomo); necesita seguro contra giro y deslizamiento.
			j 6		J 7	Forzado ligero	Montado y desmontado sin gran esfuerzo (mediante mazo de madera); necesita seguro contra giro y desplazamiento.
	▽▽		h 6		H 7	Deslizante	En piezas lubricadas, deslizamiento a mano.
			g 6		G 7	Giratorio	En piezas lubricadas, su juego es apreciable.
			f 7		F 8	Holgado medio	En piezas lubricadas, su juego es más apreciable.
			e 8		E 8	Más holgado	En piezas lubricadas, el juego es muy apreciable.
ESMERADO	▽▽	H 8	j 9	h 9	J 8	Forzado ligero	Piezas que se han de montar y desmontar con facilidad.
			h 9		H 8	Deslizante	Piezas que deben montarse sin esfuerzo y que deben desplazarse en su funcionamiento.
			e 9		E 8	Giratorio	Piezas móviles con juego desde perceptible a amplio.
			d 9		D 8	Holgado	Piezas móviles con juego muy amplio.
POCO ESMERADO	▽▽	H 11	h 11	h 11	H 11	Deslizante	Montaje fácil de gran tolerancia y con pequeño juego.
			d 11		E 11	Giratorio	Piezas móviles con gran tolerancia y juego no excesivo.
	▽		c 11		C 11	Holgado	Piezas móviles con gran tolerancia y juego.
			a 11		A 11	Muy holgado	Piezas móviles con gran tolerancia y mucho juego.

Table I.2- Fundamental Tolerances and Quality.

TOLERÂNCIAS FUNDAMENTAIS[1]

Valores em micra

Cota nominal (mm)		Qualidades e tolerâncias fundamentais																	
		01	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
de	até	IT01	IT0	IT1	IT2	IT3	IT4	IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16
0	1	0,3	0,5	0,8	1,2	2	3	4	6	10	14	25	40	60	—	—	—	—	—
1	3	0,3	0,5	0,8	1,2	2	3	4	6	10	14	25	40	60	100	140	250	400	600
3	6	0,4	0,6	1,0	1,5	2,5	4	5	8	12	18	30	48	75	120	180	300	480	750
6	10	0,4	0,6	1,0	1,5	2,5	4	6	9	15	22	36	58	90	150	220	360	580	900
10	18	0,5	0,8	1,2	2,0	3	5	8	11	18	27	43	70	110	180	270	430	700	1100
18	30	0,6	1,0	1,5	2,5	4	6	9	13	21	33	52	84	130	210	330	520	840	1300
30	50	0,6	1,0	1,5	2,5	4	7	11	16	25	39	62	100	160	250	390	620	1000	1600
50	80	0,8	1,2	2,0	3,0	5	8	13	19	30	46	74	120	190	300	460	740	1200	1900
80	120	1,0	1,5	2,5	4,0	6	10	15	22	35	54	87	140	220	350	540	870	1400	2200
120	180	1,2	2,0	3,5	5,0	8	12	18	25	40	63	100	160	250	400	630	1000	1600	2500
180	250	2,0	3,0	4,5	7,0	10	14	20	29	46	72	115	185	290	460	720	1150	1850	2900
250	315	2,5	4,0	6,0	8,0	12	16	23	32	52	81	130	210	320	520	810	1300	2100	3200
315	400	3,0	5,0	7,0	9,0	13	18	25	36	57	89	140	230	360	570	890	1400	2300	3600
400	500	4,0	6,0	8,0	10,0	15	20	27	40	63	97	155	250	400	630	970	1550	2500	4000

Table I.3- Hole reference deviations.

Cota nominal (mm)		Desvio inferior, *DI* (µm)												Desvio superior, *DS* (µm)									
		Todos os graus de tolerâncias normalizadas												IT6	IT7	IT8	Até IT8 (incl.)	Acima de IT8	Até IT8 (incl.)	Acima de IT8	Até IT8 (incl.)	Acima de IT8	Até IT7 (incl.)
Acima	Até (inc.)	A [1]	B [1]	C	CD	D	E	EF	F	FG	G	H	JS [2]	J			K [3]		M [3,4]		N [3,5]		P a ZC [3]
-	3 [1,6]	+270	+40	+60	+34	+20	+14	+10	+6	+4	+2	0	Desvios = ± IT*n* / 2, sendo *n* o valor numérico de IT	+2	+4	+6	0	0	-2	-2	-4	-4	Valores como para os graus das tolerâncias normalizadas acima de IT7 incrementados de Δ
3	6	+270	+140	+70	+46	+30	+20	+14	+10	+6	+4	0		+5	+6	+10	-1+Δ		-4+Δ	-4	-8+Δ	0	
6	10	+280	+150	+80	+56	+40	+25	+18	+13	+8	+5	0		+5	+8	+12	-1+Δ		-6+Δ	-6	-10+Δ	0	
10	14	+290	+150	+95		+50	+32		+16		+6	0		+6	+10	+15	-1+Δ		-7+Δ	-7	-12+Δ	0	
14	18																						
18	24	+300	+160	+110		+65	+40		+20		+7	0		+8	+12	+20	-2+Δ		-8+Δ	-8	-15+Δ	0	
24	30																						
30	40	+310	+170	+120		+80	+50		+25		+9	0		+10	+14	+24	-2+Δ		-9+Δ	-9	-17+Δ	0	
40	50	+320	+180	+130																			
50	65	+340	+190	+140		+100	+60		+30		+10	0		+13	+18	+28	-2+Δ		-11+Δ	-11	-20+Δ	0	
65	80	+360	+200	+150																			
80	100	+380	+220	+170		+120	+72		+36		+12	0		+16	+22	+34	-3+Δ		-13+Δ	-13	-23+Δ	0	
100	120	+410	+240	+180																			
120	140	+460	+260	+200		+145	+85		+43		+14	0		+18	+26	+41	-3+Δ		-15+Δ	-15	-27+Δ	0	
140	160	+520	+280	+210																			
160	180	+580	+310	+230																			
180	200	+660	+340	+240		+170	+100		+50		+15	0		+22	+30	+47	-4+Δ		-17+Δ	-17	-31+Δ	0	
200	225	+740	+380	+260																			
225	250	+820	+420	+280																			
250	280	+920	+480	+300		+190	+110		+56		+17	0		+25	+36	+55	-4+Δ		-20+Δ	-20	-34+Δ	0	
280	315	+1050	+540	+330																			
315	355	+1200	+600	+360		+210	+125		+62		+18	0		+29	+39	+60	-4+Δ		-21+Δ	-21	-37+Δ	0	
355	400	+1350	+680	+400																			
400	450	+1500	+760	+440		+230	+135		+68		+20	0		+33	+43	+66	-5+Δ		-23+Δ	-23	-40+Δ	0	
450	500	+1650	+840	+480																			
500	560					+260	+145		+76		+22	0					0		-26		-44		
560	630																						
630	710					+290	+160		+80		+24	0					0		-30		-50		
710	800																						

Cota nominal (mm)		Desvio superior, *DS* (µm)												Valores para Δ					
		Graus de tolerâncias normalizadas acima de IT7												Graus de tolerâncias normalizadas					
Acima	Até (inc.)	P	R	S	T	U	V	X	Y	Z	ZA	ZB	ZC	IT3	IT4	IT5	IT6	IT7	IT8
-	3	-6	-10	-14		-18		-20		-26	-32	-40	-60	0	0	0	0	0	0
3	6	-12	-15	-19		-23		-28		-35	-42	-50	-80	1	1,5	1	3	4	6
6	10	-15	-19	-23		-28		-34		-42	-52	-67	-97	1	1,5	2	3	6	7
10	14	-18	-23	-28		-33		-40		-50	-64	-90	-130	1	2	3	3	7	9
14	18						-39	-45		-60	-77	-108	-150						
18	24	-22	-28	-35		-41	-47	-54	-63	-73	-98	-136	-188	1,5	2	3	4	8	12
24	30				-41	-48	-55	-64	-75	-88	-118	-160	-218						
30	40	-26	-34	-43	-48	-60	-68	-80	-94	-112	-148	-200	-274	1,5	3	4	5	9	14
40	50				-54	-70	-81	-97	-114	-136	-180	-242	-325						
50	65	-32	-41	-53	-66	-87	-102	-122	-144	-172	-226	-300	-405	2	3	5	6	11	16
65	80		-43	-59	-75	-102	-120	-146	-174	-210	-274	-360	-480						
80	100	-37	-51	-71	-91	-124	-146	-178	-214	-258	-335	-445	-585	2	4	5	7	13	19
100	120		-54	-79	-104	-144	-172	-210	-254	-310	-400	-525	-690						
120	140	-43	-63	-92	-122	-170	-202	-248	-300	-365	-470	-620	-800	3	4	6	7	15	23
140	160		-65	-100	-134	-190	-228	-280	-340	-415	-535	-700	-900						
160	180		-68	-108	-146	-210	-252	-310	-380	-465	-600	-780	-1000						
180	200	-50	-77	-122	-166	-236	-284	-350	-425	-520	-670	-880	-1150	3	4	6	9	17	26
200	225		-80	-130	-180	-258	-310	-385	-470	-575	-740	-960	-1250						
225	250		-84	-140	-196	-284	-340	-425	-520	-640	-820	-1050	-1350						
250	280	-56	-94	-158	-218	-315	-385	-475	-580	-710	-920	-1200	-1550	4	4	7	9	20	29
280	315		-98	-170	-240	-350	-425	-525	-650	-790	-1000	-1300	-1700						
315	355	-62	-108	-190	-268	-390	-475	-590	-730	-900	-1150	-1500	-1900	4	5	7	11	21	32
355	400		-114	-208	-294	-435	-530	-660	-820	-1000	-1300	-1650	-2100						
400	450	-68	-126	-232	-330	-490	-595	-740	-920	-1100	-1450	-1850	-2400	5	5	7	13	23	34
450	500		-132	-252	-360	-540	-660	-820	-1000	-1250	-1600	-2100	-2600						
500	560	-78	-150	-280	-400	-600													
560	630		-155	-310	-450	-660													
630	710	-88	-175	-340	-500	-740													
710	800		-185	-380	-560	-840													

Table I.4- Shaft reference deviations.

Cota nominal (mm)		Desvio superior, ds (µm)												Desvio inferior, di (µm)																		
		Todos os graus de tolerâncias normalizadas												IT5 e IT6	IT7	IT8	IT4 a IT7	Até IT3 (incl.) e acima de IT7	Todos os graus de tolerâncias normalizadas													
Acima	Até (inc.)	a [1]	b [1]	c	cd	d	e	ef	f	fg	g	h	js [2]	j			k		m	n	p	r	s	t	u	v	x	y	z	za	zb	zc
-	3 [1]	- 270	- 140	- 60	- 34	- 20	- 14	- 10	- 6	- 4	- 2	0	Desvios = ± ITn / 2, sendo n o valor numérico de IT	- 2	- 4	- 6	0	0	+ 2	+ 4	+ 6	+ 10	+ 14		+ 18		+ 20		+ 26	+ 32	+ 40	+ 60
3	6	- 270	- 140	- 70	- 46	- 30	- 20	- 14	- 10	- 6	- 4	0		- 2	- 4		+ 1	0	+ 4	+ 8	+ 12	+ 15	+ 19		+ 23		+ 28		+ 35	+ 42	+ 50	+ 80
6	10	- 280	- 150	- 80	- 56	- 40	- 25	- 18	- 13	- 8	- 5	0		- 2	- 5		+ 1	0	+ 6	+ 10	+ 15	+ 19	+ 23		+ 28		+ 34		+ 42	+ 52	+ 67	+ 97
10	14	- 290	- 150	- 95		- 50	- 32		- 16		- 6	0		- 3	- 6		+ 1	0	+ 7	+ 12	+ 18	+ 23	+ 28		+ 33		+ 40		+ 50	+ 64	+ 90	+ 130
14	18																									+ 39	+ 45		+ 60	+ 77	+ 108	+ 150
18	24	- 300	- 160	- 110		- 65	- 40		- 20		- 7	0		- 4	- 8		+ 2	0	+ 8	+ 15	+ 22	+ 28	+ 35		+ 41	+ 47	+ 54	+ 63	+ 73	+ 98	+ 136	+ 188
24	30																							+ 41	+ 48	+ 55	+ 64	+ 75	+ 88	+ 118	+ 160	+ 218
30	40	- 310	- 170	- 120		- 80	- 50		- 25		- 9	0		- 5	- 10		+ 2	0	+ 9	+ 17	+ 26	+ 34	+ 43	+ 48	+ 60	+ 68	+ 80	+ 94	+ 112	+ 148	+ 200	+ 274
40	50	- 320	- 180	- 130																				+ 54	+ 70	+ 81	+ 97	+ 114	+ 136	+ 180	+ 242	+ 325
50	65	- 340	- 190	- 140		- 100	- 60		- 30		- 10	0		- 7	- 12		+ 2	0	+ 11	+ 20	+ 32	+ 41	+ 53	+ 66	+ 87	+ 102	+ 122	+ 144	+ 172	+ 226	+ 300	+ 405
65	80	- 360	- 200	- 150																		+ 43	+ 59	+ 75	+ 102	+ 120	+ 146	+ 174	+ 210	+ 274	+ 360	+ 480
80	100	- 380	- 220	- 170		- 120	- 72		- 36		- 12	0		- 9	- 15		2	0	+ 13	+ 23	+ 37	+ 51	+ 71	+ 91	+ 124	+ 146	+ 178	+ 214	+ 258	+ 335	+ 445	+ 585
100	120	- 410	- 240	- 180																		+ 54	+ 79	+ 104	+ 144	+ 172	+ 210	+ 254	+ 310	+ 400	+ 525	+ 690
120	140	- 460	- 260	- 200		- 145	- 85		- 43		- 14	0		- 11	- 18		3	0	+ 15	+ 27	+ 43	+ 63	+ 92	+ 122	+ 170	+ 202	+ 248	+ 300	+ 365	+ 470	+ 620	+ 800
140	160	- 520	- 280	- 210																		+ 65	+ 100	+ 134	+ 190	+ 228	+ 280	+ 340	+ 415	+ 535	+ 700	+ 900
160	180	- 580	- 310	- 230																		+ 68	+ 108	+ 146	+ 210	+ 252	+ 310	+ 380	+ 465	+ 600	+ 780	+ 1000
180	200	- 660	- 340	- 240		- 170	- 100		- 50		- 15	0		- 13	- 21		3	0	+ 17	+ 31	+ 50	+ 77	+ 122	+ 166	+ 236	+ 284	+ 350	+ 425	+ 520	+ 670	+ 880	+ 1150
200	225	- 740	- 380	- 260																		+ 80	+ 130	+ 180	+ 258	+ 310	+ 385	+ 470	+ 575	+ 740	+ 960	+ 1250
225	250	- 820	- 420	- 280																		+ 84	+ 140	+ 196	+ 284	+ 340	+ 425	+ 520	+ 640	+ 820	+ 1050	+ 1350
250	280	- 920	- 480	- 300		- 190	- 110		- 56		- 17	0		- 16	- 26		4	0	+ 20	+ 34	+ 56	+ 94	+ 158	+ 218	+ 315	+ 385	+ 475	+ 580	+ 710	+ 920	+ 1200	+ 1550
280	315	- 1050	- 540	- 330																		+ 98	+ 170	+ 240	+ 350	+ 425	+ 525	+ 650	+ 790	+ 1000	+ 1300	+ 1700
315	355	- 1200	- 600	- 360		- 210	- 125		- 62		- 18	0		- 18	- 28		4	0	+ 21	+ 37	+ 62	+ 108	+ 190	+ 268	+ 390	+ 475	+ 590	+ 730	+ 900	+ 1150	+ 1500	+ 1900
355	400	- 1350	- 680	- 400																		+ 114	+ 208	+ 294	+ 435	+ 530	+ 660	+ 820	+ 1000	+ 1300	+ 1650	+ 2100
400	450	- 1500	- 760	- 440		- 230	- 135		- 68		- 20	0		- 20	- 32		5	0	+ 23	+ 40	+ 68	+ 126	+ 232	+ 330	+ 490	+ 595	+ 740	+ 920	+ 1100	+ 1450	+ 1850	+ 2400
450	500	- 1650	- 840	- 480																		+ 132	+ 252	+ 360	+ 540	+ 660	+ 820	+ 1000	+ 1250	+ 1600	+ 2100	+ 2600
500	560					- 260	- 145		- 76		- 22	0					0	0	+ 26	+ 44	+ 78	+ 150	+ 280	+ 400	+ 600							
560	630																					+ 155	+ 310	+ 450	+ 660							
630	710					- 290	- 160		- 80		- 24	0					0	0	+ 30	+ 50	+ 88	+ 175	+ 340	+ 500	+ 740							
710	800																					+ 185	+ 380	+ 560	+ 840							
800	900					- 320	- 170		- 86		- 26	0					0	0	+ 34	+ 56	+ 100	+ 210	+ 430	+ 620	+ 940							
900	1000																					+ 220	+ 470	+ 680	+ 1050							
1000	1120					- 350	- 195		- 98		- 28	0					0	0	+ 40	+ 66	+ 120	+ 250	+ 520	+ 780	+ 1150							
1120	1250																					+ 260	+ 580	+ 840	+ 1300							
1250	1400					- 390	- 220		- 110		- 30	0					0	0	+ 48	+ 78	+ 140	+ 300	+ 640	+ 960	+ 1450							
1400	1600																					+ 330	+ 720	+ 1050	+ 1600							
1600	1800					- 430	- 240		- 120		- 32	0					0	0	+ 58	+ 92	+ 170	+ 370	+ 820	+ 1200	+ 1850							
1800	2000																					+ 400	+ 920	+ 1350	+ 2000							
2000	2240					- 480	- 260		- 130		- 34	0					0	0	+ 68	+ 110	+ 195	+ 440	+ 1000	+ 1500	+ 2300							
2240	2500																					+ 460	+ 1100	+ 1650	+ 2500							
2500	2800					- 520	- 290		- 145		- 38	0					0	0	+ 76	+ 135	+ 240	+ 550	+ 1250	+ 1900	+ 2900							
2800	3150																					+ 580	+ 1400	+ 2100	+ 3200							