

UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías

**Universal Automatic Mechanism for the Operation of
CNC Lathe Chucks**

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Ingeniería Mecánica

Trabajo de integración curricular presentado como requisito
para la obtención del título de
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Quito, 23 de diciembre de 2019

UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ
COLEGIO DE CIENCIAS E INGENIERIAS

**HOJA DE CALIFICACIÓN
DE TRABAJO DE INTEGRACIÓN CURRICULAR**

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Chucks**

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RESUMEN

En el Ecuador actualmente no existe la manufactura de partes y piezas de acero mediante forjado o moldeo. La industria acerera ecuatoriana está mayormente concentrada en la creación de elementos estructurales y como tal solo se dedica a la fabricación de varillas de acero a partir de acero reciclado o a la elaboración de perfiles de acero mediante procesos de soldadura y doblado. Esto ha llevado a que la mayoría de las piezas que se necesitan en el mercado local tengan que ser importadas o si se desean hacer en el país estas deben ser maquinadas.

Al ser el maquinado el mayor proceso local de manufactura, muchas empresas y talleres comenzaron con la compra de tornos y maquinaria CNC (Control Numérico Computarizado). Gracias a la apertura y accesibilidad de estas máquinas dentro del mercado en los últimos años. Sin embargo, muchos de estos talleres o fábricas no cuentan con equipos CNC autosustentables, ya que estos dependen de un operador para su alimentación y por ende no logran sacar el mayor provecho de la maquinaria CNC la cual es manufacturar un gran número de piezas, acción que ayuda a igualar su costo frente a tornos regulares más económicos. Este proyecto busca sentar el primero de los pasos necesarios para el desarrollo de un sistema de alimentación de barras completamente universal y autónomo. Siendo este paso el idear y diseñar un prototipo que opere automáticamente el mandril de cualquier torno CNC.

El prototipo de concepto se realizó utilizando diferentes métodos de manufactura, en su mayoría manufactura aditiva en forma de impresión 3D. Gracias a esta herramienta se logró realizar diferentes iteraciones del diseño y mejorarlo a medida que se diseñaba. También se utilizaron de piezas maquinadas a la medida debido a la falta de ciertos componentes en el mercado local. Con el prototipo de concepto se puede visualizar la apertura y clausura de un mandril de torno CNC. Se realizaron, además, cálculos y la programación necesaria para la futura implementación de una máquina que utilice el concepto aquí desarrollado para la implementación de un sistema de apertura de mandril de tornos CNC que, al unirse con un alimentador de barras, se convertirá en un sistema que completamente automatice los tornos CNC.

Palabras clave: CNC, maquinado, torno, mandril, automatización

ABSTRACT

In Ecuador there is currently no manufacturing of steel parts and pieces by forging or molding. The Ecuadorian steel industry is focused on the creation of structural elements and as such is only dedicated to the manufacturing of steel rods from recycled steel or on the preparation of steel profiles using welding and bending processes. This has led to the current state where most of the parts that are needed in the local market must be imported or machined if importing is not a possibility.

Since machining is by far the largest manufacturing process in the country, many companies and workshops started purchasing CNC (Computer Numerical Control) machinery such as lathes and mills. This shift is due to the opening and accessibility of these machines within the market in recent years. However, many of these workshops or factories do not have self-sustaining CNC equipment, since these depend on an operator for their feeding and function and therefore fail to make the most of the true purpose of CNC machinery, which is to manufacture a large number of parts, an action which helps to equalize its cost against more economic NC (Numeric Control) or traditional, non-computerized, lathes. This project seeks to establish the first of the necessary steps for the development of a completely universal and autonomous bar feeding system. This step being the design and design of a prototype that automatically operates the chuck of any CNC lathe.

The concept prototype was made using different manufacturing methods, mostly additive manufacturing in the form of 3D printing. Thanks to this tool, different iterations of the design were made and improved as the design went along. Custom machined parts were also used due to the lack of certain components in the local market. With the concept prototype you can visualize the opening and closing of a CNC lathe chuck. Together with the design of a concept prototype, design calculations were made, together with the necessary programming for the future implementation of a machine that uses the concept here developed. This future iteration of the chuck opening mechanism should be joined with a bar feeder design that aims to finally create a completely autonomous CNC lathe system.

Key words: CNC, lathe, chuck, machining, automatization

Table of Contents

| | |
|---|-----------|
| Introduction | 9 |
| Problem Definition | 9 |
| Need Identification | 13 |
| Design Concept..... | 13 |
| Concept Evaluation and Selection | 15 |
| Project Management | 19 |
| Budget..... | 20 |
| Materials..... | 20 |
| Tool Material..... | 20 |
| Housing Material | 26 |
| Component Selection | 31 |
| Prototype Design | 32 |
| Engineering Experiment..... | 36 |
| Design Report | 37 |
| Discussion | 43 |
| safety through design..... | 43 |
| Executive summary | 44 |
| Bibliography..... | 46 |
| Anexo A: Plano explosivo..... | 47 |
| Anexo B: Provisional Arduino Code | 48 |
| Anexo C: Individual piece Drawings | 51 |

ÍNDICE DE TABLAS

| | |
|---|----|
| Table 1: Weighted matrix for Chuck Operation (the lower the better) | 16 |
| Table 2: Weighted matrix for movement Mechanism..... | 17 |
| Table 3: Weighted matrix for Tool Alignment (the lower the better) | 18 |
| Table 4: Gantt Diagram for the project | 19 |
| Table 5: Budget | 20 |
| Table 6: AISI 1018 CD Mechanical Properties..... | 22 |
| Table 7: S_e Calculations: Tool with AISI 1018 | 23 |
| Table 8: AISI 4041 Steel Properties | 25 |
| Table 9: S_e Calculations: Tool with AISI 4340 | 25 |
| Table 10: AISI 1018 HR Steel Properties | 28 |
| Table 11: S_e Calculations: Housing with AISI 1018 HR | 28 |
| Table 12: Fastening Torque Tries in (Nm)..... | 36 |
| Table 13: Code Variable definitions..... | 41 |

ÍNDICE DE FIGURAS

| | |
|--|----|
| Figure 1:Automatic Lathe (notice bar feeder) | 11 |
| Figure 2: Bar Feeding mechanism from the Polytechnic of Porto (Silva et al., 2018)... | 12 |
| Figure 3: Chuck Diagram | 13 |
| Figure 4:Design Concepts Diagram | 14 |
| Figure 5: Tool, Orthogonal View | 21 |
| Figure 6: Tool, Dimensions for calculations | 21 |
| Figure 7: Housing: Motor Fastening | 26 |
| Figure 8: Housing: Static Stress Analysis. Von Mises Criterion. | 29 |
| Figure 9: Housing: Static Stress Analysis Critical point. Von Mises Criterion. | 29 |
| Figure 10: Housing: Static Stress Analysis Critical point. Von Mises Criterion)..... | 30 |
| Figure 11: Housing: Fatigue Analysis Critical Point. Maximum Normal Stress. | 30 |
| Figure 12: Chuck and Device, Side view | 32 |
| Figure 13: Chuck and Device, Orthogonal-front view | 33 |
| Figure 14:Main Rail | 34 |
| Figure 15: Rail for Rack | 34 |
| Figure 16: Main housing, Orthogonal view | 35 |
| Figure 17: Housing top View | 35 |
| Figure 18: Left image, torque meter with attachment being placed on lathe wrench. Right image, torque applied..... | 36 |
| Figure 19: Torque meter wrench model specs..... | 37 |
| Figure 20: The three iterations of the housing and rail rack design. On the left, the initial design; on the right, the final design..... | 39 |
| Figure 21: Right, final iteration. Left, second iteration | 40 |
| Figure 22: Final Iteration..... | 40 |
| Figure 23: Final Prototype, assembled | 41 |
| Figure 24: PLC code..... | 42 |

INTRODUCTION

PROBLEM DEFINITION

Ecuador began the first decade of the 21st century with an important challenge: to change the “production matrix” of the country. This change in production was proposed in order to balance the imports and exports of the country. However, as time has passed this has not happened. According to a report of the Latin American Association of Steel (ALACERO) Ecuador only produces 30% of the steel it consumes (Redacción Líderes, 2016). It is widely known that the cause for this is that all steel production is focused on the production of steel rods for concrete reinforcement, this is backed up by the World Steel Association who published that the 576 tons of steel produced in Ecuador were in continuously cast semis form, referring to billets and slabs, having no steel be produced for casting or as ingots for material removal manufacturing (World Steel Association, 2018). On this same report we can find that 710 tons of hot rolled products are produced in Ecuador referring to steel rods for concrete reinforcement.

Ecuador imports 1096 tons of steel, 850 tons of which is laminated steel (World Steel Association, 2018). Local companies such as Kubiec or Sedemi use this steel to make tubes, beams and other finished products via cold deformation and welding. This means that a minor amount of steel is used in other applications. Since no casting is done in country, this leaves chip removal processes as the only manufacturing option to produce complex steel pieces. For this reason, changes introduced in the machining industry could show the fastest results when aiming to improve Ecuadorian manufacturing, as it is already established in the country.

Today workshops and factories of all sizes operate machining tools, many of them have made the investment of purchasing CNC (Computer Numeric Control) machines. It

is widely known by all engineers that the precision of these machines is unparalleled and that the finished products are much easier to be standardized and maintain uniformity, since a computer program keeps the piece way above human tolerances.

A 1983 study done in Germany however, points out something obvious and that has not changed throughout the years, the higher cost of CNC machines must be offset with higher production numbers (Bussmann, Granow, & Hammer, 1983). Purchasing a CNC lathe is a lifechanging purchase for a small shop, and a big investment for a factory. Bussmann et al studied the benefits of a conventional hand lathe, a CNC non automatic machine and an Automatic CNC lathe, and a very interesting point was drawn up. A non-automatic CNC lathe has a major advantage in production time and precision over a conventional lathe, however in both an operator must be present throughout operation, in one case a machinist is operating the machine, in the other, an operator is loading and unloading parts, running the program, and supervising the process. This means that both lathes are tied to human work hours and shifts. In the case of a small workshop, who only operates one shift, the CNC lathe will only be productive for a maximum of 8 hours a day, although higher production will be achieved, return of investment time is not that fast, taking into consideration the expensive cost of a CNC machine. Below, in Figure 1, one can appreciate a CNC lathe that has been fitted with a Bar Feeder attachment. The purpose and functions of such attachments is explained in the following paragraph.



Figure 1:Automatic Lathe (notice bar feeder)

Automatic lathes are CNC lathes that can operate only under supervision, and that change parts for machining automatically through bar feeding mechanisms and self-fastening chuck jaws. A bar feeder, as the name implies, is a machine that automatically “feeds” or inputs raw material into the CNC lathe. For this machine to make any sense, it must be paired with a self-fastening chuck, for it would not make sense to have the machine save time by pushing a bar automatically, only for this saved time to be wasted by the opening and closing of chuck jaws by an operator. However, these machines, the bar-feeder and the chuck opener, are expensive, costing around 20,000 USD (2,000 to 4,000 for the hydraulic chucks and 17,000 for the bar feeder) as of December 2019 without tax or import cost. A novel universal design for a bar feeder has been made already, unlike a machine for opening lathe chucks externally. This design which was made by engineers of the Polytechnic of Porto School of Engineers and is to be made

adaptable with most kinds of CNC lathes. The design presented in this paper is shown below.

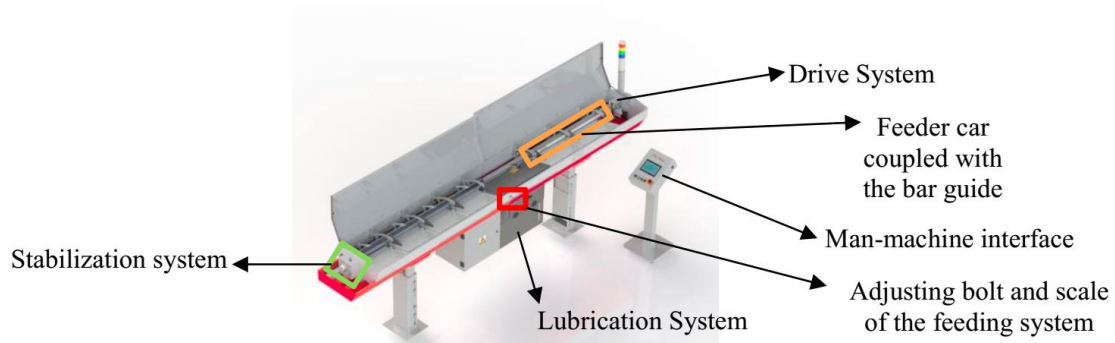


Figure 2: Bar Feeding mechanism from the Polytechnic of Porto (Silva et al., 2018)

This design can be made to work with any kind of controller, so adapting it to a PLC controller that manages both it and the chuck opening device seems plausible. Once the design of a bar feeder has been taken into consideration. One must also take into consideration taking into consideration that not all CNC lathes are compatible with all chucks or CNC lathes, the prices above being for a HASS bar feeder, which is only compatible with HASS machines, and a different assortment of chucks sold by catalogue. Herein lies the problem to be solved by this project. How to open and close the chuck jaws of any CNC lathe, even those that have no pneumatic attachment for their chuck Operation.

NEED IDENTIFICATION

The client, BKB maquinaria industrial, has identified the need for a chuck opening and closing mechanism that is universal, meaning it can be adapted to any CNC lathe and automatic, needing no human interaction after setting parameters of work. Their needs are listed as the following

- The machine must open and close a manual Chuck of either 8 or 10 inches with a mechanism of its own
- It can use pneumatic or electric actuators (120 o 220 AC)
- It must have a controller that receives signals from the CNC itself.

Going further than the requested specs, the machine needs to be rugged and to withstand the rigors of industrial life.

DESIGN CONCEPT

Taking into consideration the needs of the machine, the following concept has been formed as is shown in Figure 3. In order to understand the Design Concept Outline, figure 2: Chuck Diagram, (to the right) must be viewed. The crossed-out concepts were not utilized. This is explained by the weighted decision matrixes that follow the diagram.

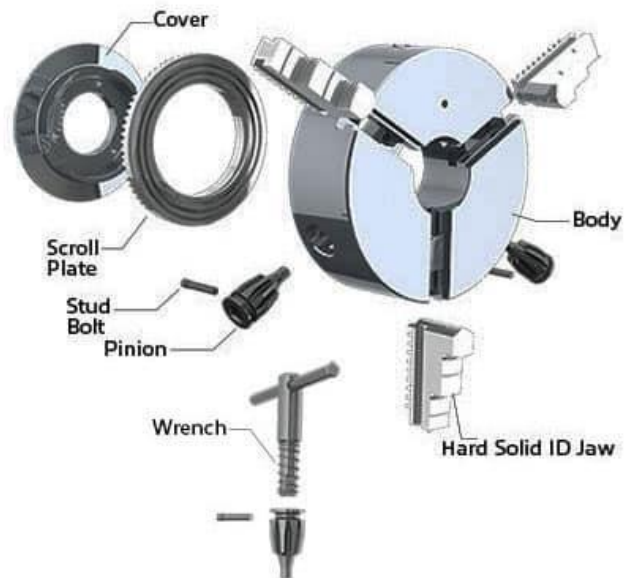


Figure 3: Chuck Diagram

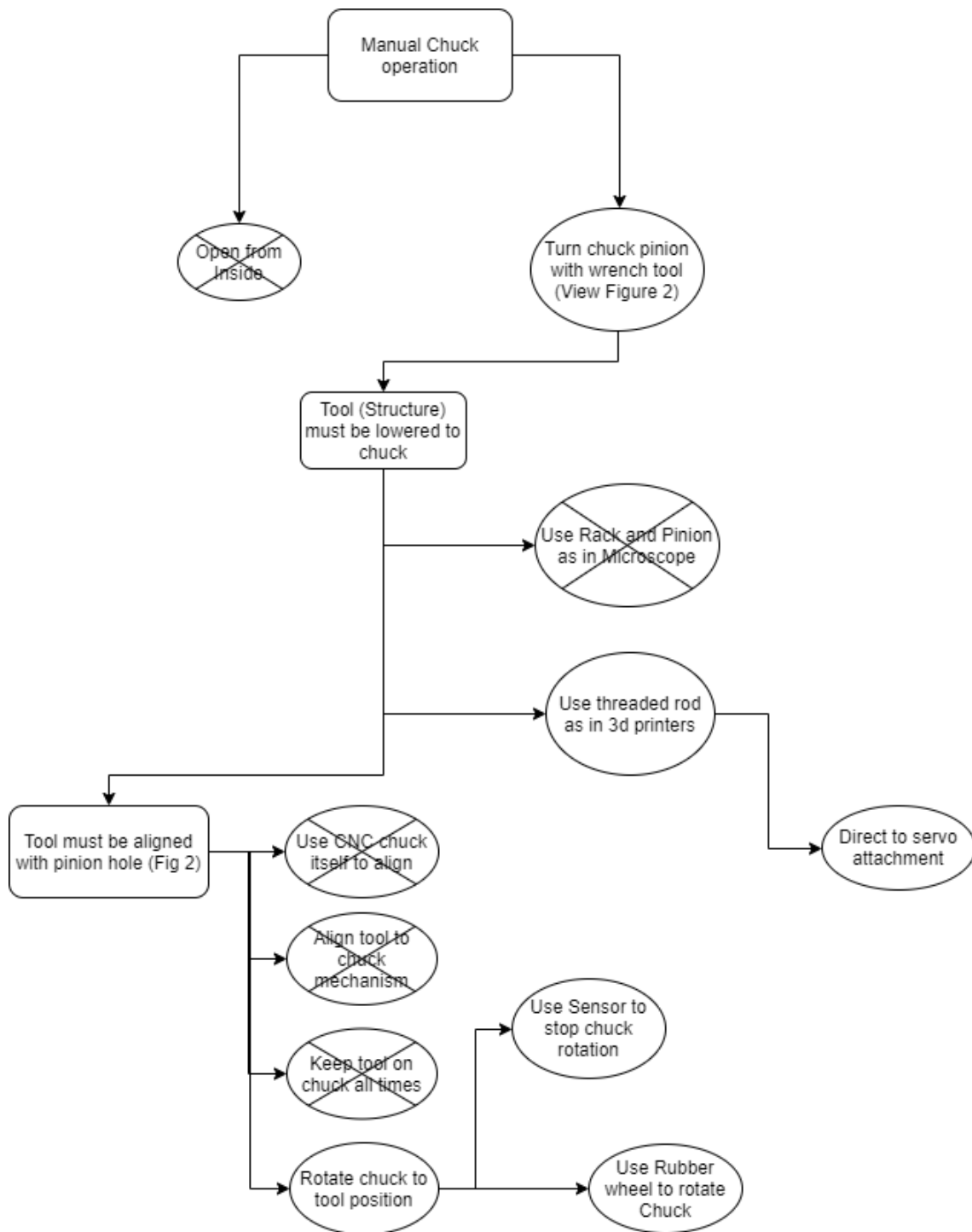


Figure 4: Design Concepts Diagram

CONCEPT EVALUATION AND SELECTION

The need to operate the manual chuck with a universal equipment that can withstand the rigors of continuous manufacturing, and for a low cost gives the following criteria for the selection of concept ideas: **Complexity, Universality, Ruggedness, and Cost.**

These are explained in further detail below

- **Complexity** takes into consideration:
 - Number of parts
 - Alterations made on the existing CNC lathe
 - Difficulty of applying the concept
- **Universality** considers:
 - Applicability to all models of CNC lathes
 - Size considerations
 - Differences in complexity of lathes
 - Age of the lathes
- **Ruggedness** considers:
 - Ability to bear a load
 - Propensity of system to fail (Related to number of parts as well)
 - Dependence on electric systems
- **Cost** considers:
 - Price of parts existing in market
 - Amount of custom parts to be machined

With these considerations in mind the following weighted matrices were constructed based on the concepts previously shown in Figure 3.

The machine must operate a manual chuck that is installed on a CNC lathe. In order to do so, two concepts or ideas were developed to accomplish this action. Concept 1 consists of somehow getting inside the chuck and opening the jaws. This although the best option for an individual solution, is not possible as intervening with the chuck itself could prove very complex, plus the process derived from this would prove to only work on one model of chuck making void the universality criteria of the evaluation. The risk of damaging the chuck that is being intervened is also very real and therefore the only real option is to use a wrench tool to turn the chuck pinion, which is Concept 2. This is universal and does not require tampering with the chuck mechanism itself, making it a lot less complex in comparison, but also maintaining some complexity as a mechanism to recreate this action must now be created. Therefore Concept 2 is chosen with a lower valuation of 2, as can be seen in Table 1.

| Need | Concept 1 | Concept 2 | |
|-------------------------|-------------------------|--|-----------------|
| Operate Manual Chuck | <i>Open from Inside</i> | <i>Turn chuck pinions with a wrench tool</i> | Criteria |
| | 5 | 3 | Complexity |
| | 5 | 1 | Universality |
| Total | 10 | 2 | |

Table 1: Weighted matrix for Chuck Operation (the lower the better)

The tool that is to operate the chuck must be lowered or moved toward the pinion hole. Two concept ideas were evaluated in order to do so. The first concept consists of a rack and pinion, similar to the way a microscope is moved. This concept is much more rugged when compared to a threaded rod mechanism, concept 2, as used in a 3D printer, this is due to the relative simplicity of a rack and pinion system, not only when manufacturing but also universally. This universality is seen as the rack and pinion system can be easily adapted to different motors and can also serve as a way to increase the torque output of

the motor, whereas the threaded rod design utilizes the raw torque of the actuator that is attached to it. Finally, cost was analyzed, and a rack and pinion outshine to threaded rod as it is easy to be manufactured in country, whereas most quality threaded rods must be imported. These choices are weighted in Table 2 below, where a rack and pinion system are chosen with a lower point average of 7 compared to the threaded rods 9

| Need | Concept 1 | Concept 2 | |
|---|------------------------|---------------------|-----------------|
| Tool (and or structure/ table) must be Lowered to Chuck | <i>Rack and Pinion</i> | <i>Threaded Rod</i> | Criteria |
| | 1 | 4 | Ruggedness |
| | 4 | 2 | Complexity |
| | 2 | 3 | Cost |
| Total | 7 | 9 | |

Table 2: Weighted matrix for movement Mechanism

The movement of the wrench tool however must be regulated by the position of the pinion hole on the chuck. The concepts for aligning the chuck and the tool are shown below in Table 3. The first concept to be explored was the obvious solution. Since the chuck is a moving part why not use that same movement to align with the tool. This choice would almost be the best in every criterion as it requires no investment, uses the very rugged system of a chuck and would just be down to programing. However, it is impossible to use the chuck itself for alignment in every CNC lathe, as only 5 Axis CNC lathe and mill combos have the option of precise chuck movement, most of these machines also already count with an automatic chuck. All CNC lathes use conventional electric motors for the spinning of the chuck and therefore lack the ability to accurately position it. Instead the chuck moves with the spindle command and stops in random positions.

The other concepts that where therefore taken into consideration for tool alignment where analyzed. Both concepts 2 and 3 where deemed too complex and non-rugged. These concepts are as follows. Concept 2, Align Tool, consist in moving the tool itself around a stopped chuck in order to find the pinion hole. This however would imply

either a form of a robotic arm or 360° tracks around the chuck. These are both complex and expensive in their execution, apart from having a large amount of parts which as is obvious would give many places where the design could fail. Concept 3, Keep on Chuck, relies on a way to keep an actuator on the chuck while it rotates. This however was deemed way too complex as it requires a way to stay attached to the spindle, which rotates at many rpm, while keeping its feeding, be it electric or pneumatic, from tangling up and breaking. This concept would also not be rugged or safe in the least as tools from the CNC lathes tool holder would collide with it if they are long, which is something that the client has warned about.

For these reasons it was determined that Concept 4, Rotate Chuck, which requires the chuck to be rotated externally to an alignment point with a rubber wheel, was the best choice of them all. A rubber wheel that can be moved and held in place on the chuck is relatively inexpensive, makes use of the least amount of parts and can be moved out of the way in an emergency, or when the tools exceed the length of the chuck.

| Need | Concept 1 | Concept 2 | Concept 3 | Concept 4 | |
|---------------------------------------|-------------------|-------------------|----------------------|---------------------|-----------------|
| Tool must be aligned with pinion hole | <i>Chuck code</i> | <i>Align tool</i> | <i>Keep on chuck</i> | <i>Rotate chuck</i> | Criteria |
| | 1 | 4 | 4 | 2 | Ruggedness |
| | 1 | 4 | 5 | 2 | Complexity |
| | 5 | 1 | 1 | 1 | Universality |
| | 1 | 3 | 4 | 2 | Cost |
| Total | 8 | 12 | 14 | 7 | |

Table 3: Weighted matrix for Tool Alignment (the lower the better)

PROJECT MANAGEMENT

The Project was managed by Mauro Rivadeneira, and Nicolas Viñas and was supervised and financed by Martin Gandara of BKB Maquinaria Industrial. The following Timetable was agreed upon

| Activities | 13/09 | 13/09 – 04/10 | 04/10/2019 | 04/10-22/10 | 22/10/2019 | 22/10-12/11 | 12/11/2019 |
|--------------------------------------|-------|---------------|------------|-------------|------------|-------------|------------|
| Project Proposal | | | | | | | |
| CAD Design | | | | | | | |
| Material and Controller Selection | | | | | | | |
| Prototype of Machine | | | | | | | |
| Check and testing | | | | | | | |
| User Manual Created and Final Report | | | | | | | |

Table 4: Gantt Diagram for the project

BUDGET

The costs stated in Table 5 relate to the concept prototype designed. However, an initial budget of more than 2000 USD was proposed for a further functional design. This included an industrial grade control system such as a PLC rather than an arduino.

| | |
|---|-------------------------|
| Arduino Mega | 20.00 |
| Electric <ul style="list-style-type: none"> • 3 TB6600 Drivers • 3 Nema 17 Stepper motors • 12V 30 A Power Source • Hall Sensor for PLC | 187.30 |
| Physical Parts and Pieces <ul style="list-style-type: none"> • PETg 3D Printing Filament • 2 Nylon 6 sheets • 1 steel axis • 1 Nylon 6 Axis • 1 Rubber wheel | 52.50 |
| Machining Cost | 110.00 |
| | Total 369.80 USD |

Table 5: Budget

MATERIALS

TOOL MATERIAL

Experimentation showed that the machine for future development must be manufactured in such a way as to resist an input torque of around 85 N-m. in order to properly secure pieces to be machined. These experiments are detailed below in the experimentation section of the report. With these 85 N-m. of input the following calculations were made in order to correctly select a material. The calculations follow use formulas and the criteria from the book: “Shigley’s Mechanical Engineering Design”.

The tool to be used in the future machine is to be analyzed as it is considered to be a critical part for it is the only way that the input torque enters the machine. The tool and the dimensions that pertain to the calculation are shown in Figures 4 and 5 below.

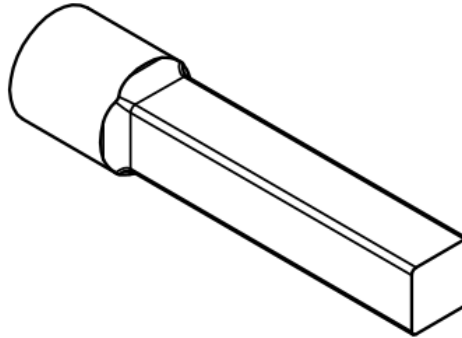


Figure 5: Tool, Orthogonal View

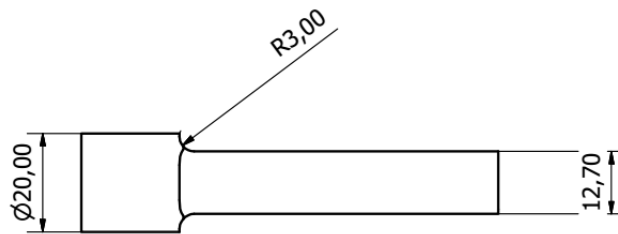


Figure 6: Tool, Dimensions for calculations

The critical area in the tool is at the end of the 12.70 mm squared cross-section shown in the figures. First, this is the thinnest part in the piece and secondly the critical area should be midpoint of this square shape. This is known from “Shigley’s Mechanical Engineering Design” which states in page 99 of the 9ed that: “The maximum shear stress in a rectangular profile, $b \times c$, is produced in the midpoint of the longer side b ”, in the tools case b and c are equal, as it is a square. From this same page the following equation (3-20) is used to calculate the maximum shear stress in a rectangular profile:

$$\tau_{max} = \frac{T}{bc^2} \left(3 + \frac{1.8}{b/c} \right)$$

This equation however simplifies to:

$$\tau_{max} = \frac{T}{b^3} \quad (4.8)$$

Because the tool is a squared cross-section.

Taking our experimental Torque of 85 N-m., and a length b of 12.7 mm, the maximum torque, τ_{max} , at the tool is found to be **199.18 MPa**.

The material chosen for the tool must resist this torque in the tool statically and at fatigue. In order to figure this out the factor of safety must be analyzed in both cases. These were calculated first using **AISI 1018 CD** steel as a design material as it is a common carbon steel alloy that is both inexpensive, readily available and easy to machine. The material properties for this steel were taken from “Shigley’s Mechanical Engineering Design” book and are shown in the table below.

| AISI 1018 CD Steel Properties (MPa) | |
|--------------------------------------|--|
| Ultimate Tensile Stress (S_{ut}) | 440 |
| Yield Strength (S_y) | 370 |
| Shear Ultimate Strength (S_{su}) | $S_{su} = 0.67S_{ut} = \mathbf{294}$ |
| Shear Yield Strength (S_{sy}) | $S_{sy} = 0.577S_{ut} = \mathbf{213.15}$ |

Table 6: AISI 1018 CD Mechanical Properties

With the properties from table 6 and the maximum shear stress calculated above the following calculations were made to figure out the static safety factor using the energy-distortion method.

First the von mises stress was calculated with the following equation:

$$\sigma' = (\sigma_{xy}^2 + 3\tau_{zx}^2)$$

In the present case $\sigma_{xy}^2 = 0$, as the only force entering is torsion, and therefore only shear stress must be accounted for. Plugging in **199.18 MPa** for τ_{zx} the von mises stress is found to be $\sigma' = \mathbf{344.49 MPa}$. Using this value and the yield strength (S_y) from Table 6 to calculate the safety factor n with the following formula:

$$n = \frac{S_y}{\sigma'}$$

one finds the safety factor to be $n = 1.07$, a value that barely passes safely when loaded statically.

Using the values from Table 6 and the maximum shear stress found, the following fatigue calculations were made, assuming a **minimum shear stress load of 0**, ($\tau_{min} = 0$), and a **maximum shear stress load of 199.18** ($\tau_{max} = 199.18$).

In order to calculate fatigue loading Marin's equation, written below must be used,

$$S_e = k_a k_b k_c k_d k_e k_f S_e'$$

Here, S_e , is the resistance to fatigue value in a critical part that needs to be found. All calculations relating to S_e are found in Table 7 below.

| S_e Calculations: Tool with AISI 1018 | | |
|--|--------------------------------------|----------------------------|
| k_a Surface Factor <i>Values for machined surfaces taken</i> | $k_a = a S S_u^b$ | $a = 4.51$ $b = -0.265$ |
| | $S S_u = 294 \text{ MPa}$ | $k_a = 1.0001$ |
| k_b Size Factor <i>Used equivalent diameter Equation for diameters between 2.79 and 51 mm</i> | $k_b = 1.24 d_e^{-0.107}$ | $d_e = 0.808 (h b)^{0.5}$ |
| | $h = b = 12.7 \text{ mm}$ | $k_b = 0.967$ |
| k_c Load Type Factor <i>Value for torsion only fatigue</i> | $k_c = 0.59$ | |
| k_d Temperature Factor <i>No temperature effects</i> | $k_d = 1$ | |
| k_e Reliability Factor <i>Value for 99% reliability</i> | $k_e = 0.814$ | |
| k_f Notch Sensibility Factor <i>K_{ts} value found from figure A15-8 using d_e as d q value found using fig. 6.21</i> | $k_f = 1 + q(K_{ts} - 1)$ | $K_{ts} = 1.2$ |
| | $q = 0.82$ | $k_f = 1.164$ |
| S_e' | $S_e' = 0.5 S S_u = 147 \text{ MPa}$ | |
| S_e | $S_e = 81.57 \text{ MPa}$ | |

Table 7: S_e Calculations: Tool with AISI 1018

If the source book is checked one can notice that the formulas change a little, this is because designs that are only exposed to **Torsion** fatigue must use S_{sy} and S_{su} instead of S_y and S_{ut} values. This is stated in page 331 of "Shigley's Mechanical Engineering Design" (Budynas & Nisbett, 2012).

Once the S_e has been found to be **81.57 MPa** the **Fatigue Safety Factor** can be found. In this case the ASME criterion will be used as it is one of the most used when referring to failure criteria. The ASME criteria fatigue safety factor is found using the following equation:

$$n_f = \sqrt{\frac{1}{(\sigma_a/S_e)^2 + (\sigma_m/S_{s_y})^2}}$$

Where $\sigma_a = \sigma_m = \mathbf{99.59 MPa}$ or $\tau_{max}/2$. Plugging in the values above, one can find that $n_f = \mathbf{0.715}$. Which means the tool using AISI 1018 steel will **fail in fatigue**. Since the tool fails in fatigue it is possible to calculate the number of cycles until failure. These are around **52,000 cycles**. This might seem like a lot but one must take into consideration the fact that the machine is designed to make machine shops operate in a 24 hr. cycle, which taking into consideration an average of 30 minutes per machined item, means that the machine will cycle 48 times a day, or 17,520 times a day. Meaning the tool must be changed in less than 3 years of use. Even less if one considers the friction that will affect the tool when entering and exiting the pinion hole.

If one wants to make a design robust design a different material must be considered. One with higher mechanical property values. And one that is resistant to the wear and tear of 24 hr. use. For this reason, **AISI 4340 steel** will be used in the following calculations for the tool. This steel is commonly used in applications which require resistance to torsion.

| AISI 4340 Steel Properties (MPa) (Callister & Rethwisch, 2014) | |
|--|-----------------------------------|
| Ultimate Tensile Stress (Sut) | 745 |
| Yield Strength (Sy) | 472 |
| Shear Ultimate Strength (Ssu) | $Ssu = 0.67Sut = \mathbf{499.15}$ |

| | |
|-----------------------------------|--|
| Shear Yield Strength (S_{sy}) | $S_{sy} = 0.577S_y = \mathbf{272.344}$ |
|-----------------------------------|--|

Table 8: AISI 4041 Steel Properties

Since the only thing that changes are the material properties, the equations and figures used to obtain values remain unchanged from the previous calculation with AISI 1018 Steel, as does the maximum shear strength, τ_{max} , found from the initial 85 Nm. Torque. With this in mind the static safety factor n is $n = \mathbf{1.37}$ using the energy-distortion equation from the previous calculation. This value gives an outstanding 37% of safety from a higher torsion and is an industry standard. This will be reflected in the following fatigue calculations.

As stated previously the equations used to calculate the safety factors won't change, so using Marin's formula just like in the calculations before one can define the following table and value for S_e in order to later apply the ASME criterion for the safety factor.

Table 9 below shows this calculation in detail.

| S_e Calculations: Tool with AISI 4340 | | | | | |
|--|--|-------------------------------|-------------------------|----------------------------|---------------|
| k_a Surface Factor <i>Values for machined surfaces taken</i> | <table border="1" style="width: 100%;"> <tr> <td style="text-align: center;">$k_a = aSsu^b$</td> <td style="text-align: center;">a = 4.51 b = -0.265</td> </tr> <tr> <td style="text-align: center;">$Ssu = 438.85 \text{ MPa}$</td> <td style="text-align: center;">$k_a = 0.899$</td> </tr> </table> | $k_a = aSsu^b$ | a = 4.51 b = -0.265 | $Ssu = 438.85 \text{ MPa}$ | $k_a = 0.899$ |
| $k_a = aSsu^b$ | a = 4.51 b = -0.265 | | | | |
| $Ssu = 438.85 \text{ MPa}$ | $k_a = 0.899$ | | | | |
| k_b Size Factor <i>Used equivalent diameter Equation for diameters between 2.79 and 51 mm</i> | <table border="1" style="width: 100%;"> <tr> <td style="text-align: center;">k_b $= 1.24d_e^{-0.107}$</td> <td style="text-align: center;">$d_e = 0.808(hb)^{0.5}$</td> </tr> <tr> <td style="text-align: center;">h=b=12.7mm</td> <td style="text-align: center;">$k_b = 0.967$</td> </tr> </table> | k_b $= 1.24d_e^{-0.107}$ | $d_e = 0.808(hb)^{0.5}$ | h=b=12.7mm | $k_b = 0.967$ |
| k_b $= 1.24d_e^{-0.107}$ | $d_e = 0.808(hb)^{0.5}$ | | | | |
| h=b=12.7mm | $k_b = 0.967$ | | | | |
| k_c Load Type Factor <i>Value for torsion only fatigue</i> | $k_c = 0.59$ | | | | |
| k_d Temperature Factor <i>No temperature effects</i> | $k_d = 1$ | | | | |
| k_e Reliability Factor <i>Value for 99% reliability</i> | $k_e = 0.814$ | | | | |
| k_f Notch Sensibility Factor <i>K_{ts} value found from figure A15-8 using de as d q value found using fig. 6.21</i> | <table border="1" style="width: 100%;"> <tr> <td style="text-align: center;">$k_f = 1 + q(K_{ts} - 1)$</td> <td style="text-align: center;">$K_{ts} = 1.2$</td> </tr> <tr> <td style="text-align: center;">q = 0.88</td> <td style="text-align: center;">$k_a = 1.176$</td> </tr> </table> | $k_f = 1 + q(K_{ts} - 1)$ | $K_{ts} = 1.2$ | q = 0.88 | $k_a = 1.176$ |
| $k_f = 1 + q(K_{ts} - 1)$ | $K_{ts} = 1.2$ | | | | |
| q = 0.88 | $k_a = 1.176$ | | | | |
| S_e' | $S_e' = 0.5 Ssu = 249.575 \text{ MPa}$ | | | | |
| S_e | $S_e = \mathbf{122.538 \text{ MPa}}$ | | | | |

Table 9: S_e Calculations: Tool with AISI 4340

Using the above values, the ASME fatigue safety factor n_f is found to be $n_f = 1.122$. This guarantees that the tool **will not fail under fatigue**. And therefore, no cycle calculations must be made. It is for this reason that **AISI 4340** is chosen as the material for manufacturing the tool.

HOUSING MATERIAL

With the tool material selection now finished the attention is turned to the housing. This piece which is detailed in the design section and has its own drawing in the annexes holds the actuators that will create the 85 N-m. torque. The housing made for the prototype holds the actuator with 4, 3mm fasteners. There is reason to believe therefore that the plate to which the actuator is fastened to must resist the shear stress produced by the actuator on these fasteners. The figure below pictures a simplified version of this part of the housing. With the geometry from this diagram the fatigue safety factor will be calculated using **AISI 1018 HR** steel.

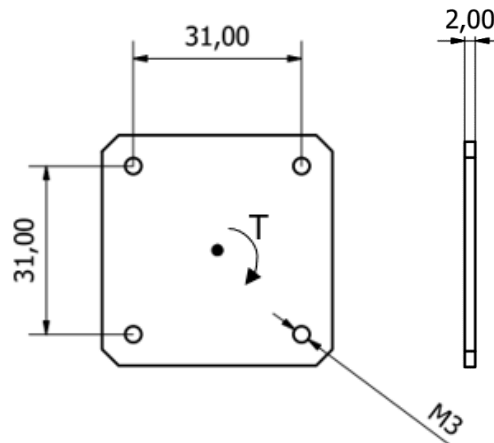


Figure 7: Housing: Motor Fastening

With the above diagram it is possible to figure out the force that is applied on each of the 3mm fasteners. It is already known that $T = 85$ N-m, with this in mind, one can use geometry to find that each of the fasteners is at a radial distance r of **21.92 mm** from the

center of the plate, as they are laid out in a square formation. This is seen in the equation below, where $\sqrt{2}$ is used because of the relations in a 45° right triangle.

$$r = \sqrt{2} \cdot \frac{31\text{mm}}{2} = 21.92\text{ mm}$$

After r has been found it is a question of applying equation (8-57) from Shigley's Mechanical Engineering Design to find the force loads due to moment F'' with the equation below.

$$F'' = \frac{T}{4r^2}$$

In the present case there are four fasteners equidistant from where the moment is applied. From this the force value is found to be $F'' = 969.4\text{ N}$. With this force value the stress made by the fastener on the plate can be found using the 2 mm thickness of the plate and the 3 mm diameter of the fastener. These two are multiplied to give an area of pressure of $A = 6\text{mm}^2$. Therefore, the axial stress on the plate is found simply by dividing the force by this value. This can be seen in the equation below

$$\sigma = \frac{F''}{A}$$

Where $\sigma = 161\text{MPa}$, with this value the calculations for the fatigue stress are found using the following properties of AISI 1018 HR steel. This steel is chosen as it is one of the most common plate steels used. It must be noted that the HR, or Hot Rolled values of this steel are chosen as they represent the lowest values for AISI 1018 steel and give the option of manufacturing the piece via the welding of steel plates to the housing. If the Hot Rolled variety of AISI hold up, a machined CD, or Cold Drawn piece will have no problem.

| AISI 1018 HR Steel Properties (MPa) | |
|-------------------------------------|-----|
| Ultimate Tensile Stress (Sut) | 400 |
| Yield Strength (Sy) | 220 |

Table 10: AISI 1018 HR Steel Properties

With these properties the Marin's equation method previously applied to the tool is used.

The following values shown in Table 11 are used in the S_e calculation.

| S_e Calculations: Housing with AISI 1018 HR | | | | | |
|---|---|----------------|------------------------|---------------|--------------|
| k_a Surface Factor Values for machined taken, as the fastening holes are drilled | <table border="1"> <tr> <td>$k_a = aSut^b$</td> <td>a = 4.51 b = -0.265</td> </tr> <tr> <td>Sut = 400 MPa</td> <td>$k_a = 0.92$</td> </tr> </table> | $k_a = aSut^b$ | a = 4.51 b = -0.265 | Sut = 400 MPa | $k_a = 0.92$ |
| $k_a = aSut^b$ | a = 4.51 b = -0.265 | | | | |
| Sut = 400 MPa | $k_a = 0.92$ | | | | |
| k_b Size Factor Value for axial only loads | $k_b = 1$ | | | | |
| k_c Load Type Factor Value for axial only fatigue | $k_c = 0.85$ | | | | |
| k_d Temperature Factor No temperature effects | $k_d = 1$ | | | | |
| k_e Reliability Factor Value for 99% reliability | $k_e = 0.814$ | | | | |
| k_f Various Effect Factor No notches or various effects are taken into consideration for this fatigue load | $k_f = 1$ | | | | |
| S_e' | $S_e' = 0.5 Sut = 200 MPa$ | | | | |
| S_e | $S_e = 127.31 MPa$ | | | | |

Table 11: S_e Calculations: Housing with AISI 1018 HR

With this value of S_e ASME's failure criteria from the previous calculations is used with

$$\sigma_a = \sigma_m = \frac{161MPa}{2} = 80.5 MPa \text{ to find that the fatigue safety factor is } n_f = 1.36$$

allowing for this kind of fatigue load to be carried by the housing if constructed with any variation of AISI 1018 steel. Making this material a completely viable choice.

Finally, a static study was performed using inventor stress analysis environment in order to assess the most critical point of the housing. As are two pictures of the simulation results being performed, shown in Figure 7 and 8.

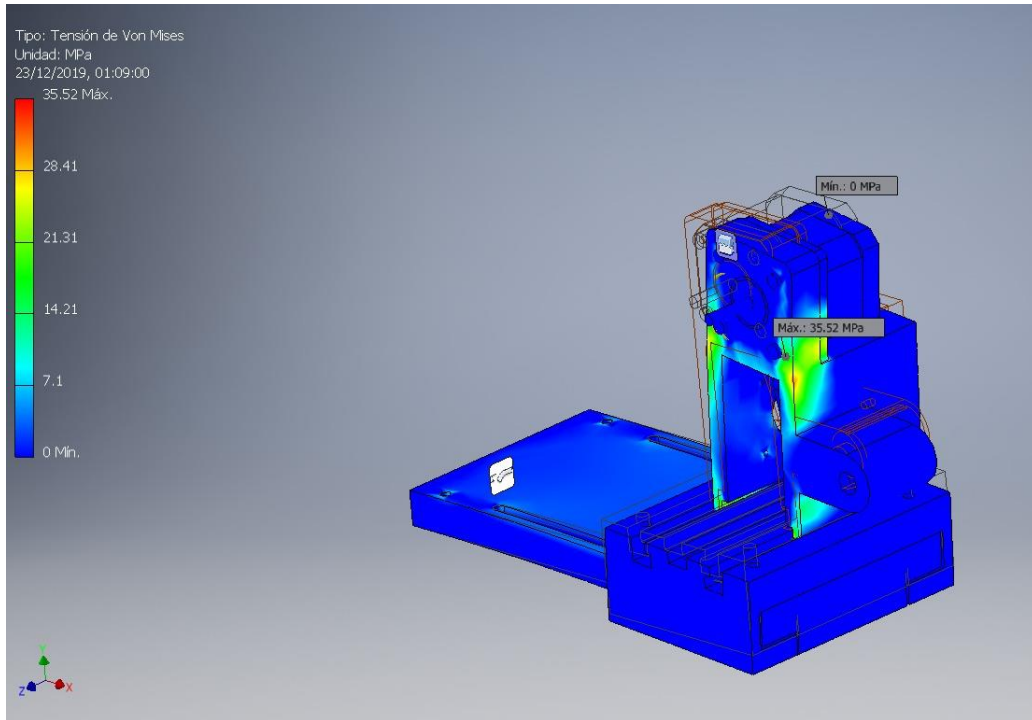


Figure 8: Housing: Static Stress Analysis. Von Mises Criterion.

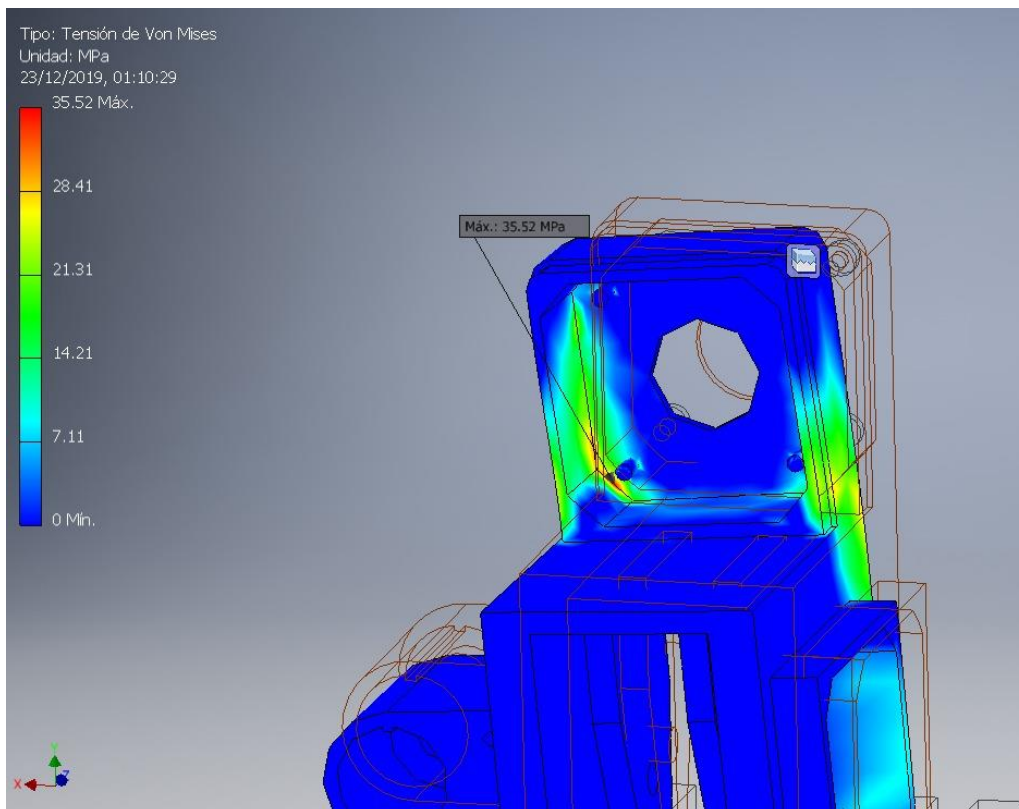


Figure 9: Housing: Static Stress Analysis Critical point. Von Mises Criterion.

Since the housing geometry is complicated a fatigue simulation was performed using COMSOL Multiphysics Software, maximum normal stress criterion was selected for the simulation, a comparative static analysis was performed in COMSOL as well, to make sure the load conditions are the same as used on inventor. Figure 9 shows critical points to be exactly the same as on inventor as well as the numerical value. Which proves the loading conditions parameters are correct. Fatigue analysis is shown in Figure 10.

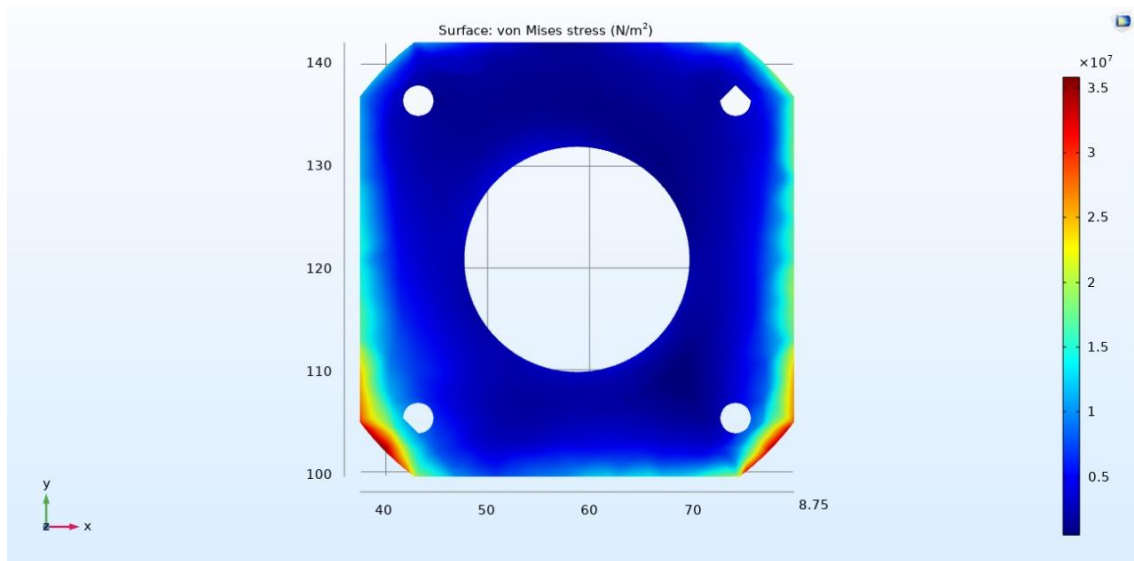


Figure 10: Housing: Static Stress Analysis Critical point. Von Mises Criterion).

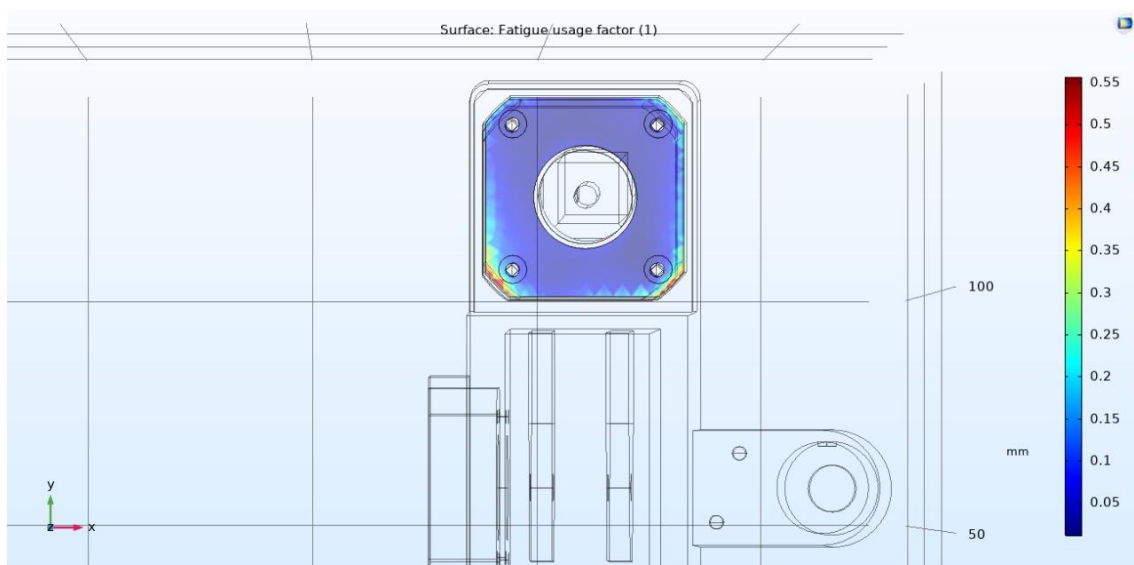


Figure 11: Housing: Fatigue Analysis Critical Point. Maximum Normal Stress.

As seen from simulation results under our normal load conditions a Fatigue usage factor of 0.55 was obtained. The housing geometry and the mounting procedure distributes the load around really effectively, therefore it has an infinite amount of cycles it can withstand.

COMPONENT SELECTION

1. Concept Prototype

In order to select the components of the concept prototype client consideration was taken, as well as previous knowledge working with similar projects. The client suggested utilizing NEMA stepper motors to move the various parts of the concept prototype. NEMA 17 motors were selected to be used in the concept prototype. This choice was made on previous experience, as the team, having already worked with these motors when 3D printing, knows that they are: hardy, inexpensive, easy to obtain and compact. In order to operate these motors with any kind of controller, be it PLC or micro, TB6600 controllers were selected from an in country provider as they work well with stepper motors of this and greater size and have a plethora of documentation attached to them online for further programming. These motors and drivers are to be used in every function of the prototype.

2. Future developments consideration

In order to achieve the 85 Nm torque needed to secure on to the lathe and maintain a compact profile pneumatic motors must be considered when developing the concept here proven. Motors such as the Globe Air Motors 9M, or motors from the Parker PIV-M series, could prove to be the solution to these problems. Both motors have a fastening surface of less than 10 cm and the design here presented can easily be modified to handle these kinds of actuators.

When thinking of moving the chuck itself, it is known from experimentation that the chuck needs less than 6 Nm to move, meaning that a compact pneumatic stepper motor, like those from Globe Air Motors series Rm 004 could be used. These motors produce up to 4 Nm of torque but can be paired with gear boxes. These motors weigh less than 2kg and provide a fastening surface of less than 9 cm.

PROTOTYPE DESIGN

The design is the following in CAD images. First 3 overview images of the design are shown, in order to make it easier on the reader to pinpoint different parts. Then the design of the support and holding structures is shown and explained, and finally the housing and the 3D printed parts are shown. The rack and pinion are not given much attention as its only function is to move and close the gap between the tool and the casing. The wheel design is straight forward and the rendering only lacks the spring that helps pressure the wheel against the chuck when turning it towards the casing which holds the sensor.

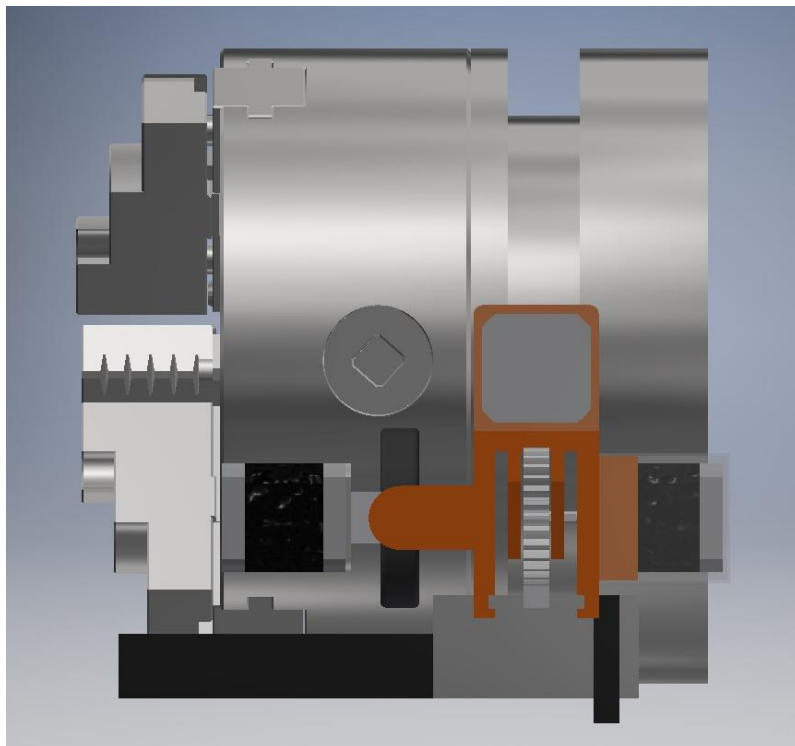


Figure 12: Chuck and Device, Side view

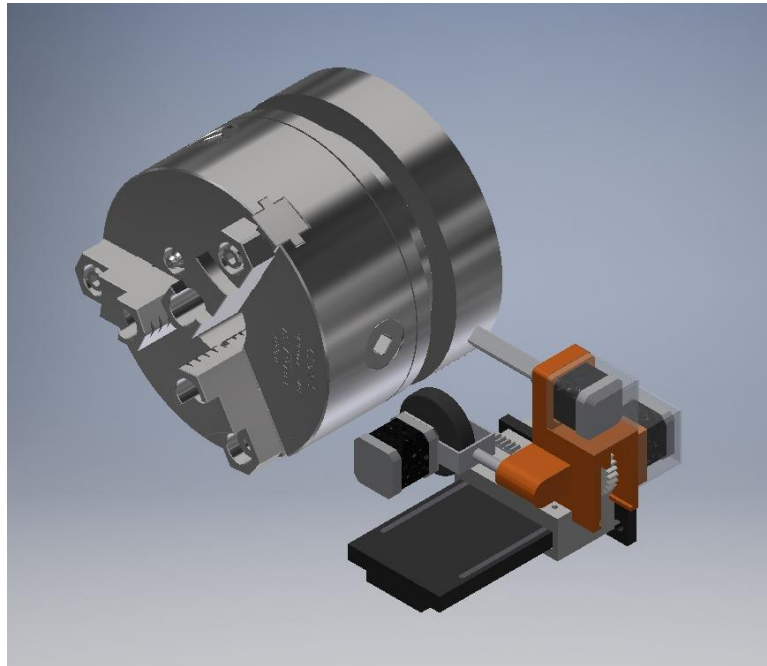


Figure 13: Chuck and Device, Orthogonal-front view

The supporting structures will be a combination of 3D printed pieces, shown in grey, and Nylon machined pieces, shown in black. The difference in materials and manufacturing was chosen as the black pieces support the structure and fasten it to the lathe, while the grey pieces are only placeholders and need just to slide, therefore not justifying high amounts of strain on them and having this manufacturing method give the most flexibility when it comes to fast prototyping. This is important as the fit of these parts must be precise and having cheap physical pieces whose mistakes can be identified and rectified quickly proved to be a blessing when assembling the concept.

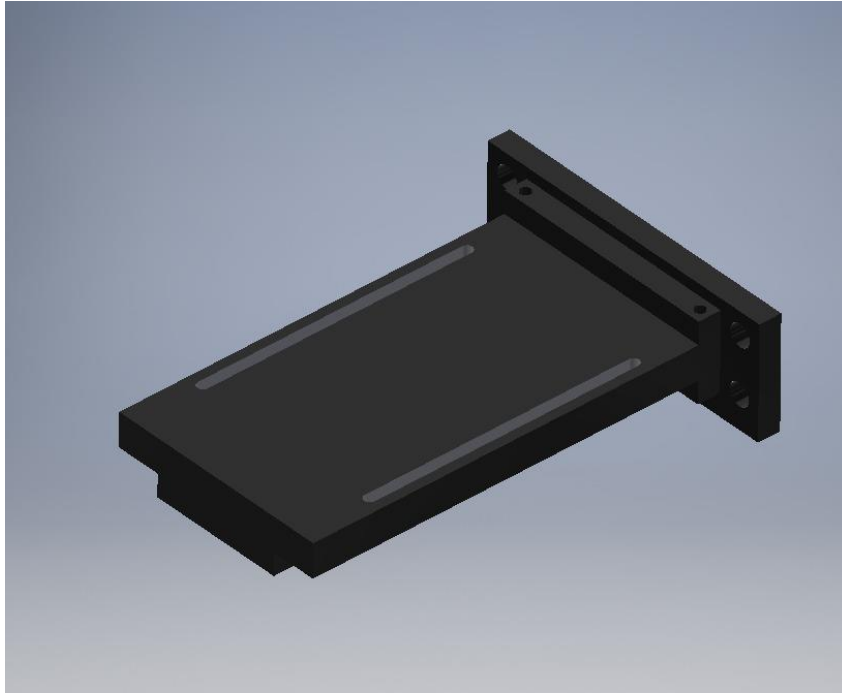


Figure 14: Main Rail

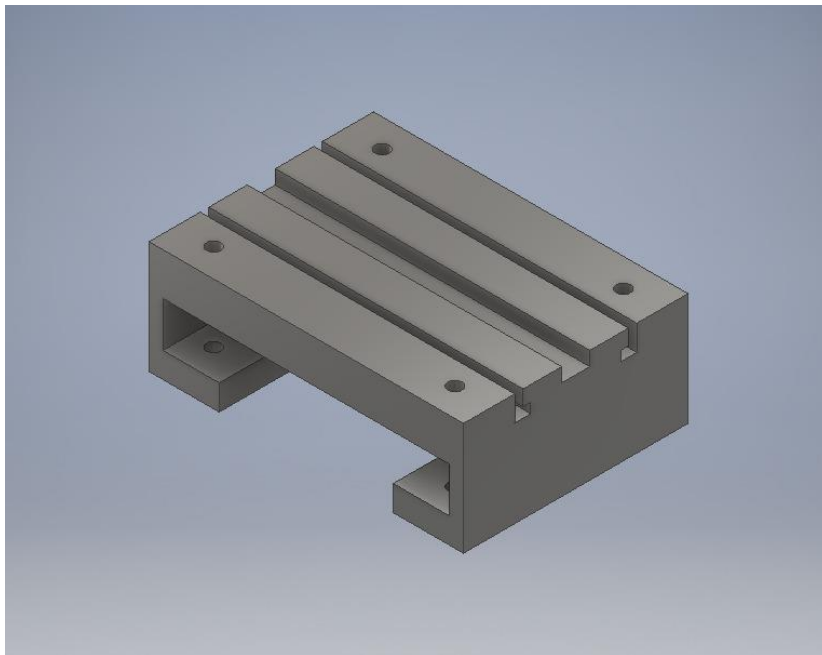


Figure 15: Rail for Rack

Because of the inherent mistakes one makes when drawing and assembling different parts in CAD modeling, the part pictured below, known here as the housing, was made using 3D printing for the same reasons the rail for the rack was. The need for this piece to improve as the design went on became obvious with the final concept prototype being many millimeters taller with respect to the initial prototype shown below. The drawings for this final prototype are shown in the Annexes section at the end of this report.

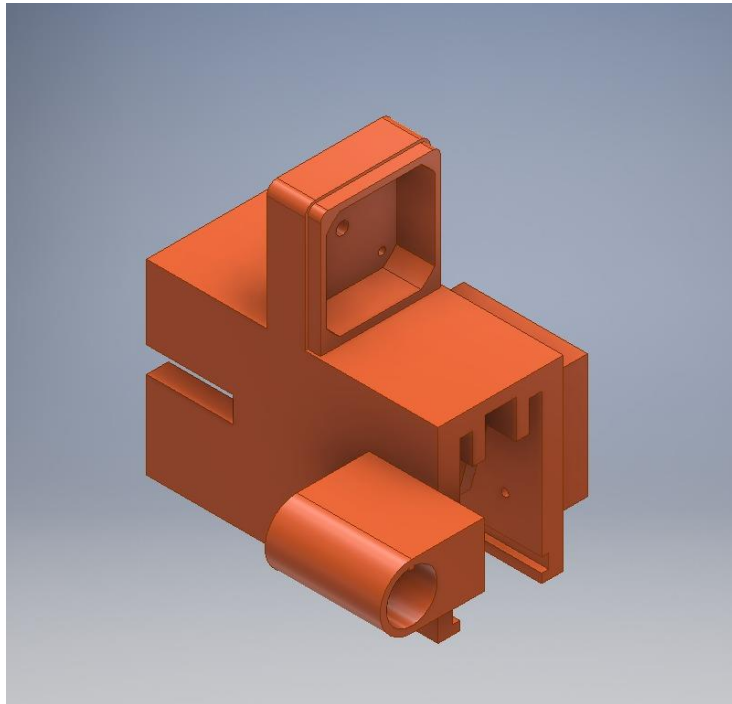


Figure 16: Main housing, Orthogonal view

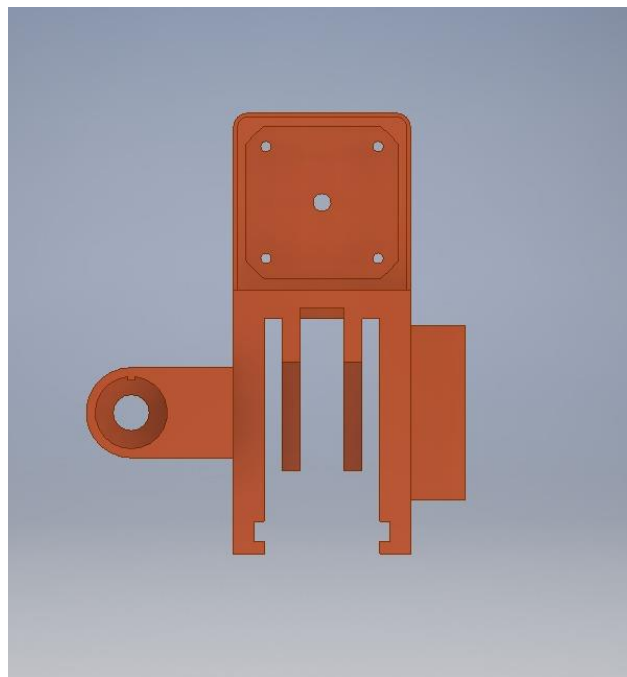


Figure 17: Housing top View

ENGINEERING EXPERIMENT

In order to find the forces that intervene with the design two different experiments were conducted. The first experiment consisted in the use of a large torque meter to find the forces required to appropriately close a lathe chuck and hold a piece. In place. In order to accomplish this task three different people, were made to fasten a 40 mm diameter steel rod with the chuck wrench tool on a CNC lathe. The results from this test are shown in the table below as are the average of the 5 fastenings. As are two pictures of the experiment being performed, shown in Figure 12.

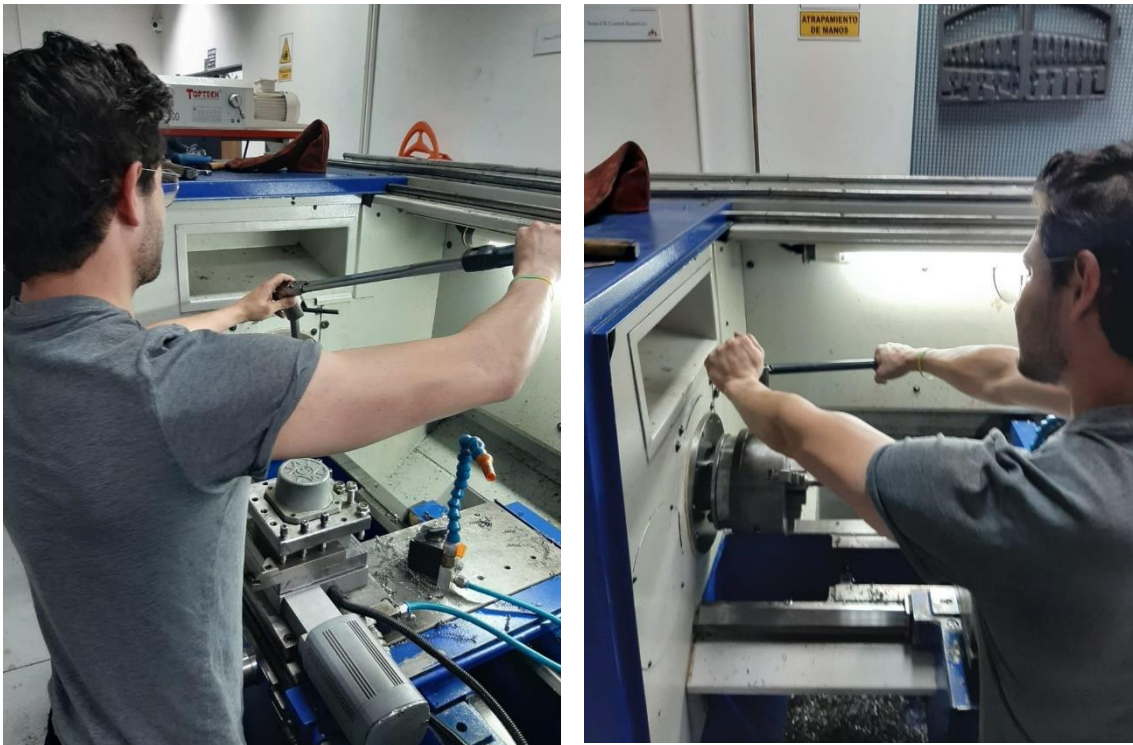


Figure 18: Left image, torque meter with attachment being placed on lathe wrench. Right image, torque applied

| Fastening Torque Tries in (Nm) | | | |
|--------------------------------|----------|----------|----------|
| Tries | Person 1 | Person 2 | Person 3 |
| 1 | 75 | 90 | 70 |
| 2 | 70 | 95 | 85 |
| 3 | 70 | 75 | 75 |
| 4 | 75 | 80 | 90 |
| 5 | 80 | 85 | 75 |
| Average | 74 | 85 | 79 |

Table 12: Fastening Torque Tries in (Nm)

From Table 12 the highest average value of 85 Nm was chosen to perform the calculations necessary to choose the materials of the design, and to check design parameters. It can be noted from the table that the values obtained from the experiments are in increments of 5 Nm. This is due to the use of a large torque meter whose characteristics are pictured below in figure 18.

| MOD. | REF. | CAP. |
|--|-------|-----------------------------------|
| <input type="checkbox"/> Lladina - 60 3/8" | 06709 | 8 - 60 N.m. 6 - 44 lbf.ft. |
| <input type="checkbox"/> Lladina - 100 1/2" | 06711 | 20 - 100 N.m. 15 - 80 lbf.ft. |
| <input type="checkbox"/> Lladina - 200 1/2" | 06712 | 40 - 200 N.m. 30 - 150 lbf.ft. |
| <input checked="" type="checkbox"/> Lladina - 300 1/2" | 06713 | 60 - 300 N.m. 45 - 250 lbf.ft. |

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58-20700 URRETXU (Spain)

Figure 19: Torque meter wrench model specs

The second experiment performed used a small torque meter, with a minimum measuring torque of 6Nm, and a maximum torque of 30 Nm to move the chuck itself. However, the chuck was able to be moved with the 6 Nm from the start of the experiment. This small torque value gives enough reason to assume that the torque needed to move the chuck is not going to warrant mayor design considerations. This value therefore can only be used as a reference when choosing an actuator for when the concept is to be applied.

DESIGN REPORT

The final concept prototype differs slightly from the one shown in the prototype design section of this report. As mentioned previously, the main housing of the device was manufactured using 3D printing as was the railing that holds the rack that is to move the device towards the lathe chuck. This was done in order to see possible conflicts in the geometry more clearly and correct them in a fast and cost-effective matter. All prints used the same infill density however, (50%), with a hexagonal infill pattern and 2mm walls.

However, problems with 3D printing materials, and geometrical conflicts made for 3 different iterations of the design. The road map below summarizes the reasons and steps taken in between iterations.

Road Map

- 1) CAD Design
 - a) Design of the Rack and pinion mechanism
 - i) Test of the rack and pinion in the software
 - b) Design of the Housing and the main support rail/beam
 - i) Design changes due to client suggestions*
- 2) Manufacturing of Mechanical parts
 - a) Search for rack and pinion in local market
 - i) Search unsuccessful, manufacturing required
 - (1) Rack and pinion machined
 - (2) Tool machined
 - (3) Wheel holder machined
 - b) Housing and Rail Construction**
 - i) PETG Selected
 - (1) First design rejected due to 3D printing problems
 - ii) PLA Selected
 - (1) Second design modified for functional problems***
 - (2) Final Design Printed.

*Initial design had 2 gears, client requested that a single gear and rack system serve as the moving element and that NEMA actuators be used

**One 3D printing's main advantages are the possibility to use the ease of fast prototyping to make design iterative. Even though this method of manufacturing was used because of the difficulty of the shapes involved in these parts, the iterative design

aspect of 3D printing became a big part of the design process, as it allowed for the quick change of features in the design.

***Rail canals where too small to properly fit the housing, a fitting issue was also found with the height of the housing, as it barely allowed for the gear to be placed in the machine.

Figure 14 shows a general evolution of the 3 iterations of 3D printed parts in order to further illustrate the changes that went into the design. The difference between the iterations should be clear to identify. The first iteration, which is located on the left of the image failed because of 3d printing mistakes. It must be noted that the rail rack for the first iteration of the design does not have the “C” shaped rail sides, this is because the print was stopped before these could be made, as the mistake was noted before the legs where constructed. PETG filament which was chosen as a material for the 3D printed parts of the prototype proved difficult to print. PETG must have a more controlled environment and higher temperature considerations when compared to PLA.

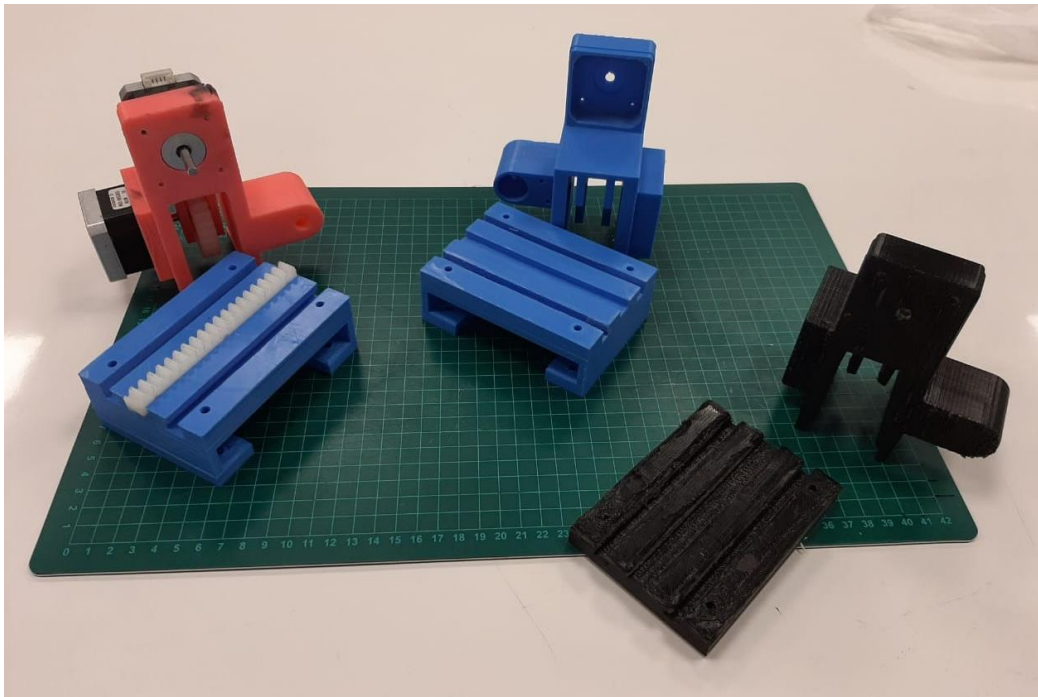


Figure 20: The three iterations of the housing and rail rack design. On the left, the initial design; on the right, the final design

PLA which is the workhorse of most 3D printing machines was used thereafter to produce both the second and final iterations of the design. As stated previously, the design was changed from the second to the final iteration due to a misfit error of the rail. There were also height issues when placing the gears, and the creation of a hole in the middle of the actuator hold parts was placed to utilize the full extent of the available axis of the NEMA motors that were to be placed. This can be seen in the comparison between the two iterations in Figure 15 below.

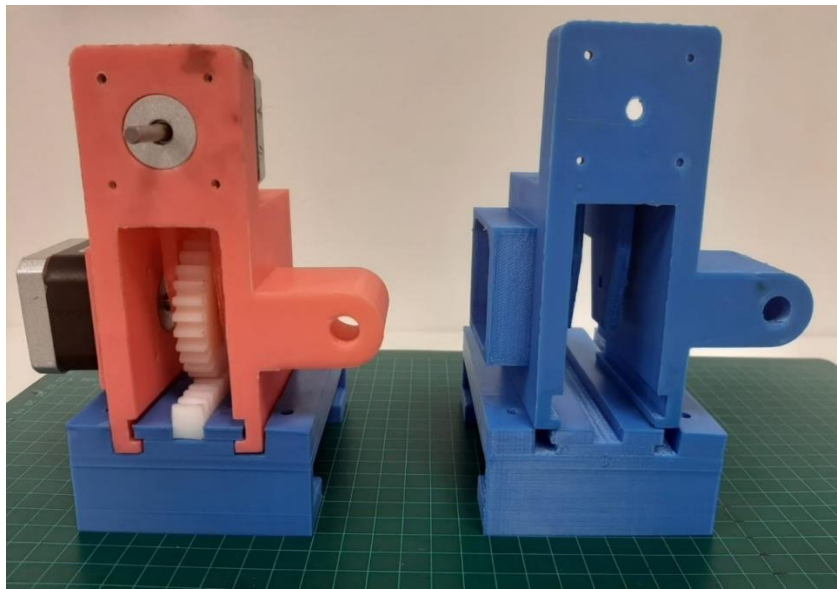


Figure 21: Right, final iteration. Left, second iteration

The final design can be appreciated in figure 16 below.

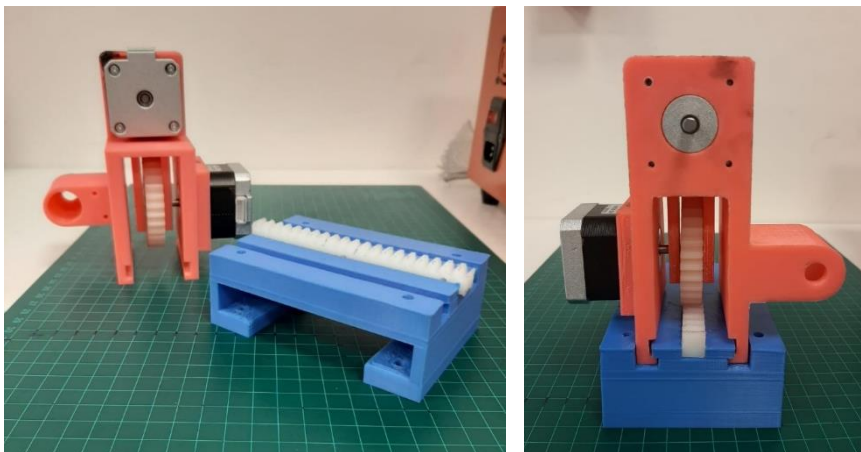


Figure 22: Final Iteration

The final concept prototype as assembled can be pictured in figure 17 Below.

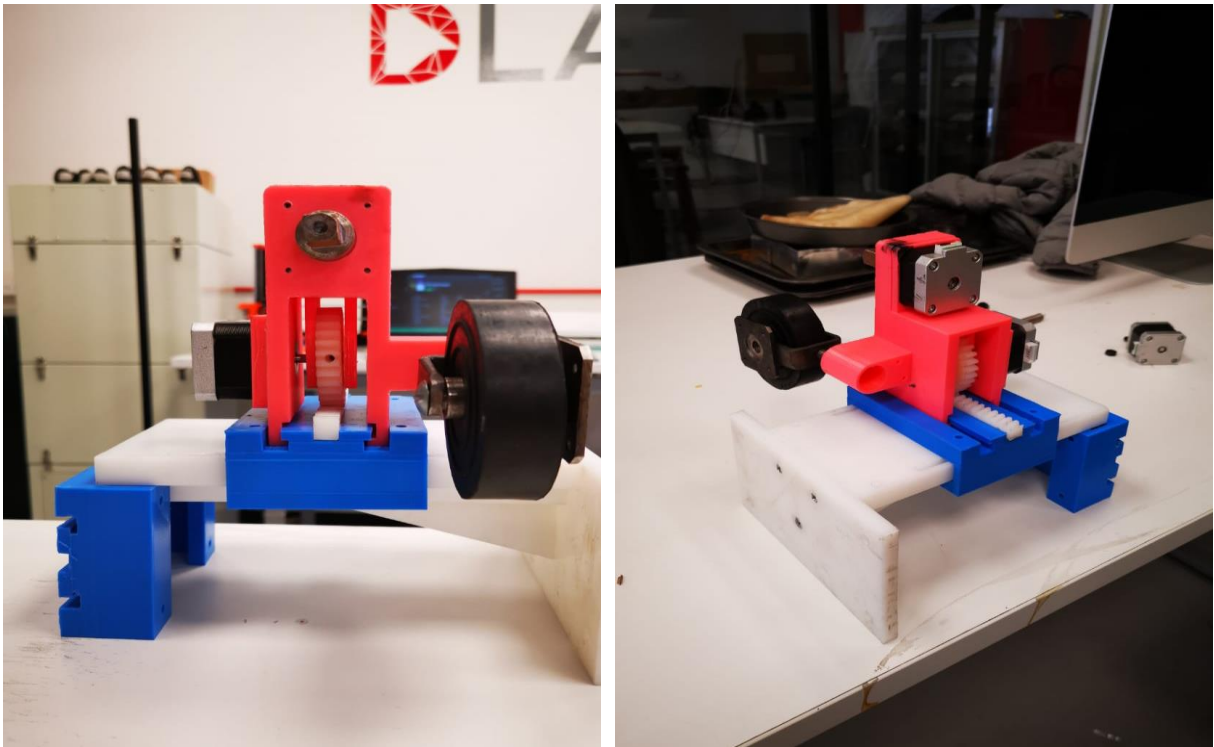


Figure 23: Final Prototype, assembled

Apart from the prototype design, a PLC controller code was developed as an early foray into the further development of the machine. The following code is used to run the device in a PLC controller and is described in the following table and figure:

| | |
|----------|---|
| Inputs: | I1: Machined finished signal coming from the chuck. I2: Hall Sensor Signal. |
| Outputs: | Q1: Main Gear stepper (Controls horizontal movement) Q2: Wheel Stepper (Controls Chuck Rotation) Q3: Tool Stepper (Controls tool rotation for chuck opening/closing) |
| Timers: | T001: Sets a waiting time after I1 goes on to let the chuck come to a stop. T003, T006, T008 Are security waiting times between operations, to avoid conflicts. T002, T004, T009, T005, T007 Are represented for the time the stepper will operate. |

Table 13: Code Variable definitions

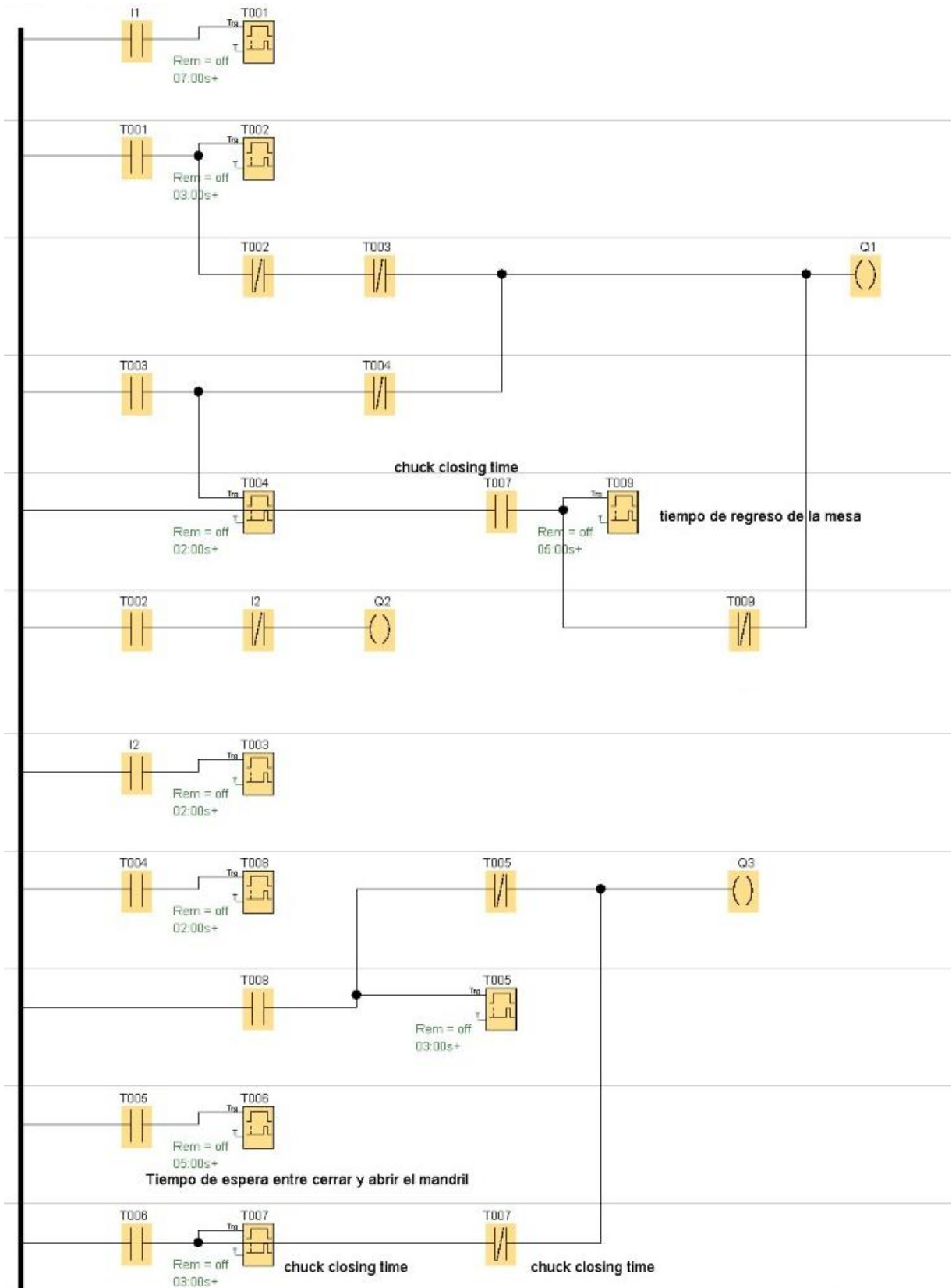


Figure 24: PLC code

DISCUSSION

The concept prototype produced can open and close a chuck lathe without problem using any controller. The tests done on the machine were meant to prove the concept of it moving and operating a chuck. This capacity was clearly seen when the movements of said machine were executed without flaws during testing. When the design is produced with the materials here stated then the machine will be able to resist the loads put upon it by the actuators. This was proven with the calculations in the materials section of the report. The code presented in this report is also capable of running the task that the device needs to function. One must bear in mind that this project aimed solely on producing a concept prototype for a future machine that operates the chuck of a CNC lathe and does so in conjunction with a bar feeding mechanism.

SAFETY THROUGH DESIGN

Safety features implemented include: The verification of spindle stoppage in the code, which receives this signal from the lathe and waits for an average of 15 seconds to begin operation. The rails in the design which forbid movement of the device to the sides and hold the main body of the machine in place even while the motor is applying torque to the chuck to close it. The machine will also automatically move back to prevent any collision with lathe tools once it has finished closing the chuck, the lathe must also program into its operation a code to move the tools backwards and away from the device when finishing a part, this will minimize the threat to the machine in a very effective way. The rail also counts with two hard stops, one in the front and one in the back, in order to successfully stop the machine and to calibrate the distance that the rack can travel in the pinion.

It must be noted that the machine in this state is not meant to be operated yet, as it is of no use until a bar feeder attachment is made to work after the machine completes the first action in its action list, this is why a space must be left in future design for an emergency stop button, which, apart from turning the motors off, moves back the device and securely puts the device away from any harm.

EXECUTIVE SUMMARY

In order to use the concept prototype to make a final product major investment, among other things, must be considered. First it must be re-stated that the chuck opener loses its purpose if it's not paired with a bar feeding mechanism. It has been stated previously that most of these are expensive, and that these are also not universal. However, unlike with the chuck opening mechanism presented here, for which there is no present design apart from the one in this report, a universal bar feeder design was presented at the 28th International Conference on Flexible Automation and Intelligent manufacturing (Silva, Campilho, Gouveia, Pinto, & Baptista, 2018). the device here presented must be manufactured using the materials suggested in the materials section, that being AISI 4340 steel for the tool and AISI 1018 or similar steel for the housing. The housing is clearly the most challenging of the pieces to be manufactured, as all other shapes are easily manufactured with machining, but it can be made using a 2 axis CNC mill for the best precision. T shaped mills must be used in the manufacturing of this piece for the milling of the canals.

These can be acquired through the client of this thesis, BKB, or bought online and imported. Other manufacturing methods, such as welding can be explored by whoever

takes the prototype here described to manufacturing, but they must take into consideration fatigue and design factors for this kind of manufacturing.

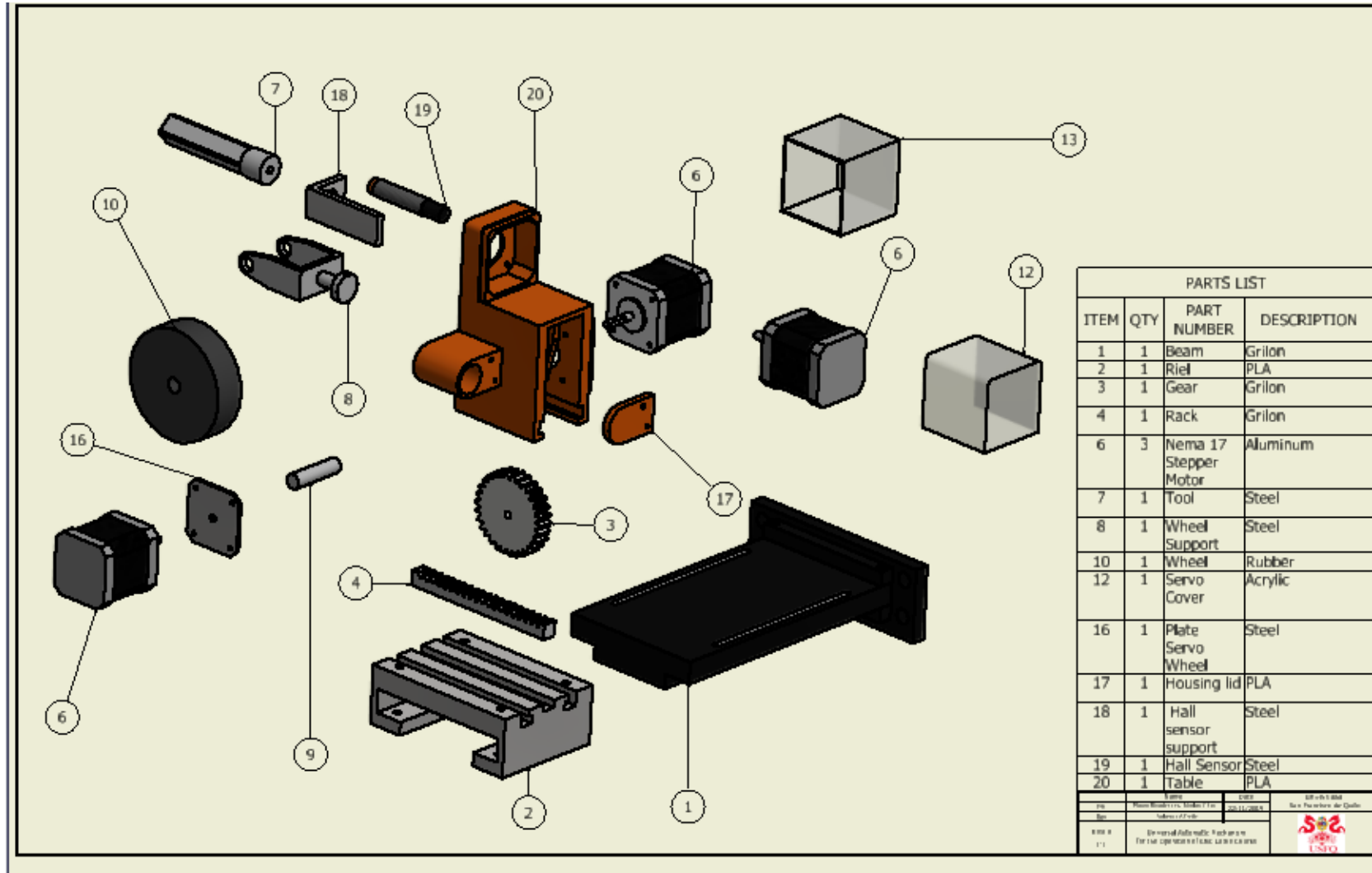
When selecting the correct actuators, whoever takes lead of further development must keep in mind that the torque necessary to securely hold pieces is around 85 Nm and must choose this to be as compact as possible, mainly because this will help with modifying the design here presented in the least bit possible, but also because space inside a CNC lathe is very cramped and the smaller the components the better. In the component selection section above several different pneumatic motors has been suggested to achieve the required torques.

In short, the concept prototype here presented completes the objective of being the first step towards the development of a universal CNC lathe operating system. The design, and the design concepts and lessons learned here can be applied to future development. The materials, components, and programming of such a future development has been given consideration in this report.

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ANEXO A: PLANO EXPLOSIVO



ANEXO B: PROVISIONAL ARDUINO CODE

```

#include <Keypad.h>

// Define stepper motor connections and steps
#define dirPinM1 2
#define stepPinM1 3
#define dirPinM2 4
#define stepPinM2 5
#define stepsMotor1 110
#define stepsMotor2 2000

const byte ROWS = 4; // Four rows
const byte COLS = 4; // Three columns
char keys[ROWS][COLS] = { // Define the Keymap
  {'1','4','7','*'},
  {'2','5','8','0'},
  {'3','6','9','#'},
  {'A','B','C','D'}
};

byte rowPins[ROWS] = { 31, 32, 33, 34 }; // Connect keypad ROW0, ROW1, ROW2 and ROW3 to
these Arduino pins.

byte colPins[COLS] = { 35, 36, 37, 38 }; // Connect keypad COL0, COL1 and COL2 to these Arduino
pins.

Keypad kpd = Keypad( makeKeymap(keys), rowPins, colPins, ROWS, COLS ); // Create the Keypad

int Motor1Foward = 0;

void setup()
{
  Serial.begin(9600);
  Serial.println("Starting");
  // Declare pins as output:
  pinMode(stepPinM1, OUTPUT);
  pinMode(dirPinM1, OUTPUT);
  pinMode(stepPinM2, OUTPUT);
  pinMode(dirPinM2, OUTPUT);
}

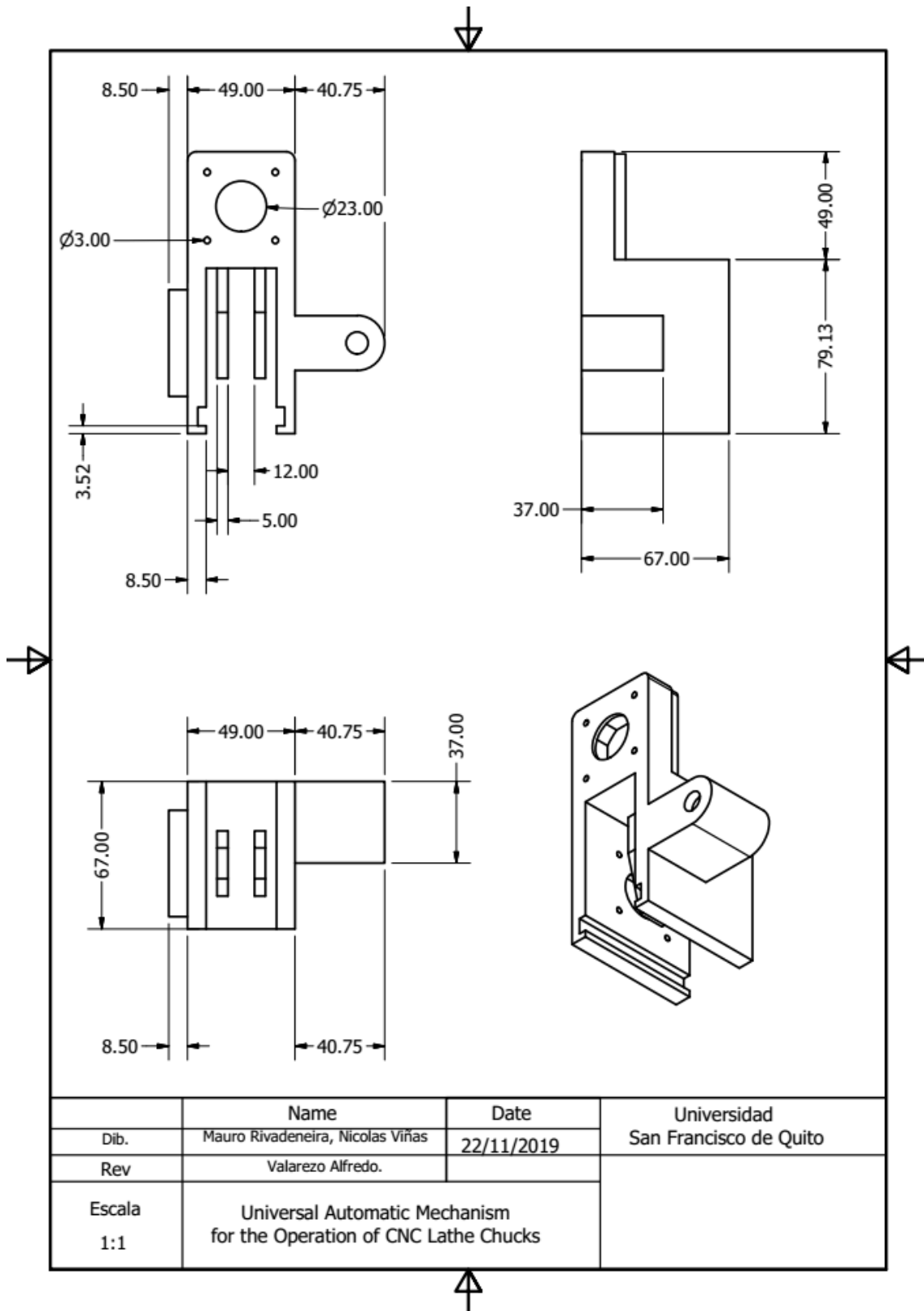
```

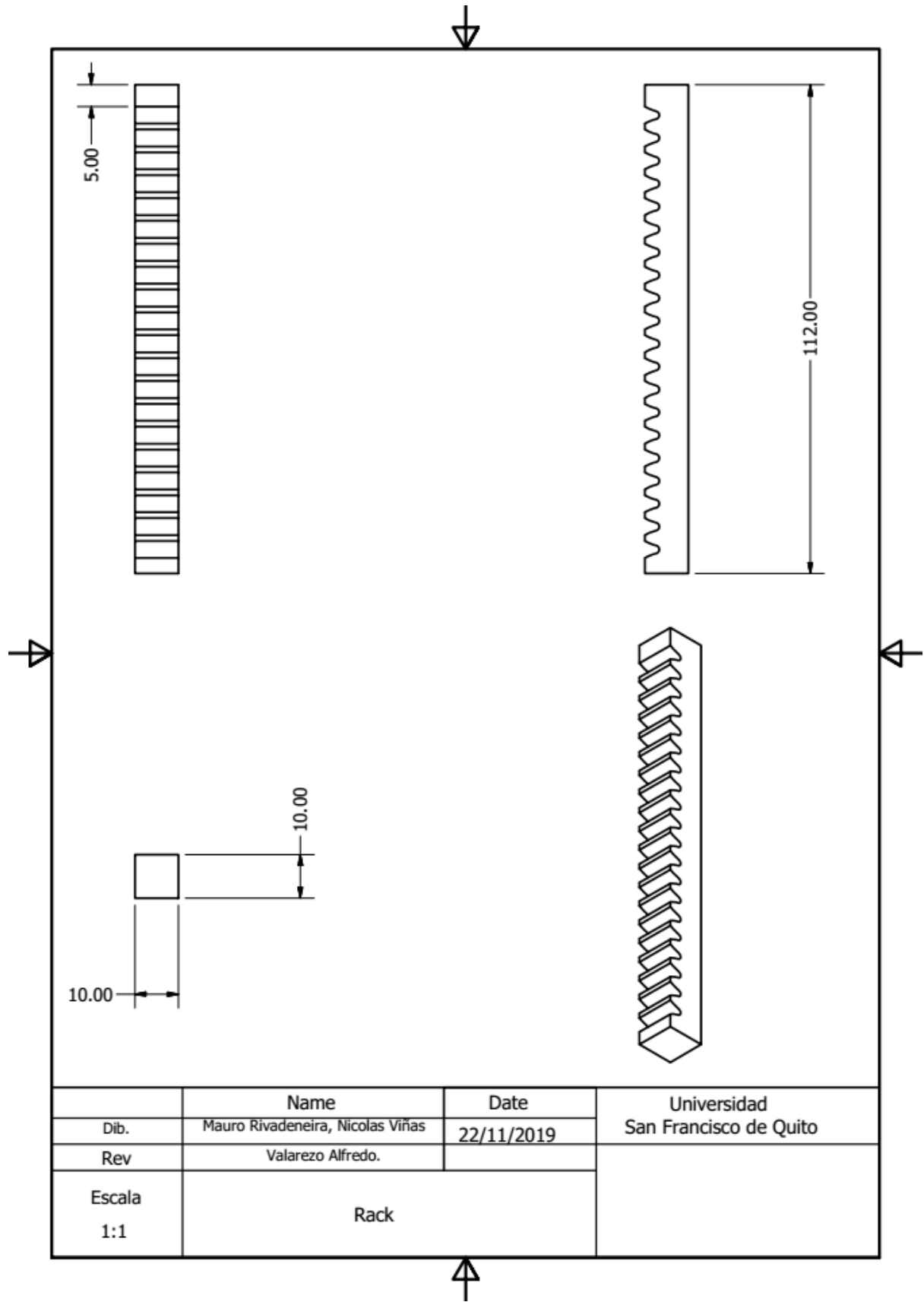


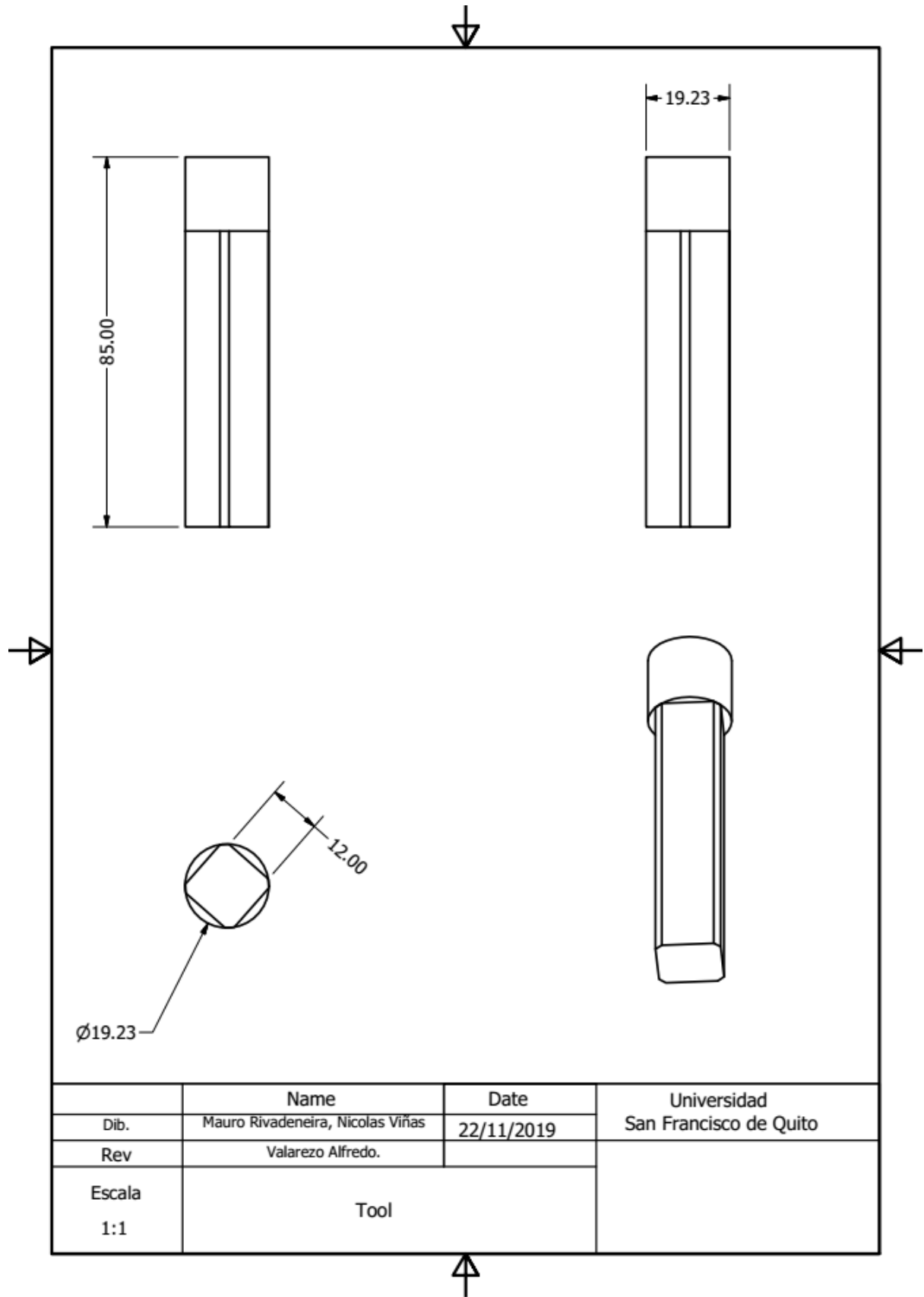
```
}  
void loop()  
{  
  char key = kpd.getKey();  
  if(key) // Check for a valid key.  
  {  
    switch (key)  
    {  
      case '1':  
        Serial.println("one");  
        // Set the spinning direction counterckwise:  
        digitalWrite(dirPinM1, LOW);  
        for (int i = 0; i < stepsMotor1; i++) {  
          // These four lines result in 1 step:  
          digitalWrite(stepPinM1, HIGH);  
          delayMicroseconds(3000);  
          digitalWrite(stepPinM1, LOW);  
          delayMicroseconds(3000);  
        }  
  
        break;  
  
      case '2':  
        Serial.println("two");  
  
        digitalWrite(dirPinM1, HIGH);  
        for (int i = 0; i < stepsMotor1; i++) {  
          // These four lines result in 1 step:  
          digitalWrite(stepPinM1, HIGH);  
          delayMicroseconds(3000);  
          digitalWrite(stepPinM1, LOW);  
          delayMicroseconds(3000);  
        }  
      }  
    }  
  }  
}
```

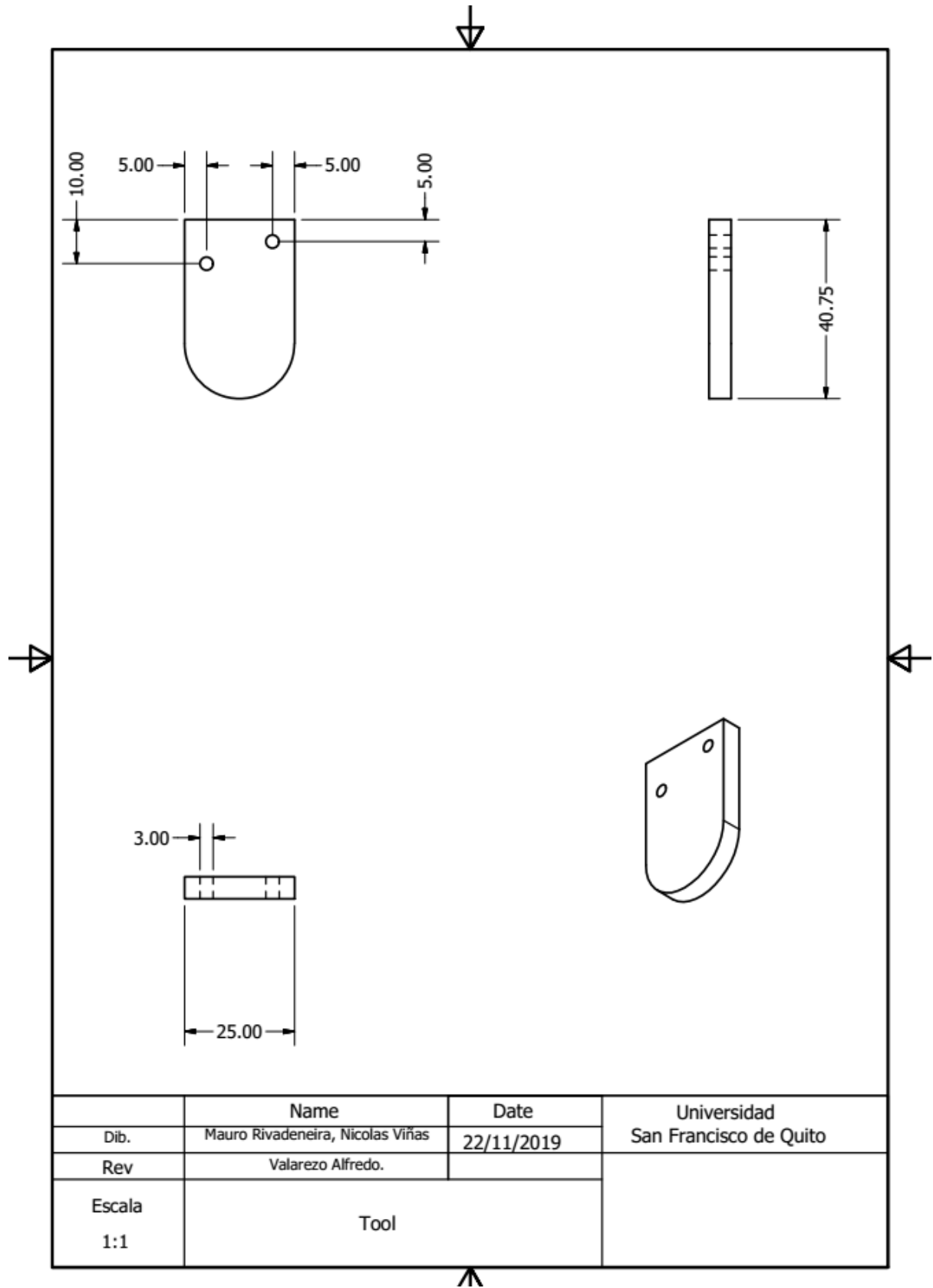
```
}  
break;  
  
case '3':  
  Serial.println("three");  
  digitalWrite(dirPinM2, HIGH);  
  for (int i = 0; i < stepsMotor2; i++) {  
    // These four lines result in 1 step:  
    digitalWrite(stepPinM2, HIGH);  
    delayMicroseconds(2000);  
    digitalWrite(stepPinM2, LOW);  
    delayMicroseconds(2000);  
  }  
  break;  
  
case '4':  
  Serial.println("four");  
  
  digitalWrite(dirPinM2, LOW);  
  for (int i = 0; i < stepsMotor2; i++) {  
    // These four lines result in 1 step:  
    digitalWrite(stepPinM2, HIGH);  
    delayMicroseconds(2000);  
    digitalWrite(stepPinM2, LOW);  
    delayMicroseconds(2000);  
  }  
  break;  
  
  default:  
    Serial.println(key);  
  }  
}  
}
```

ANEXO C: INDIVIDUAL PIECE DRAWINGS

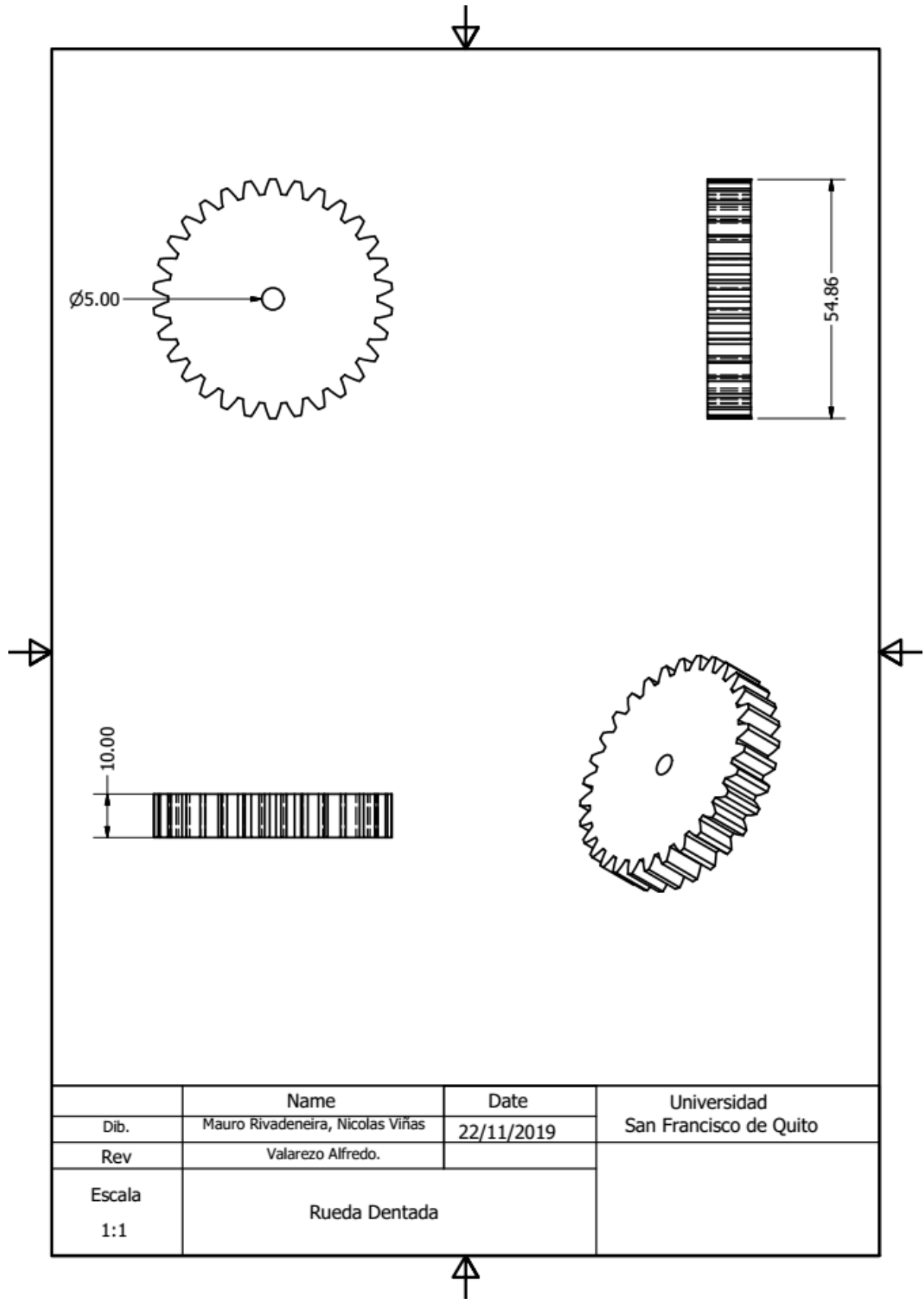


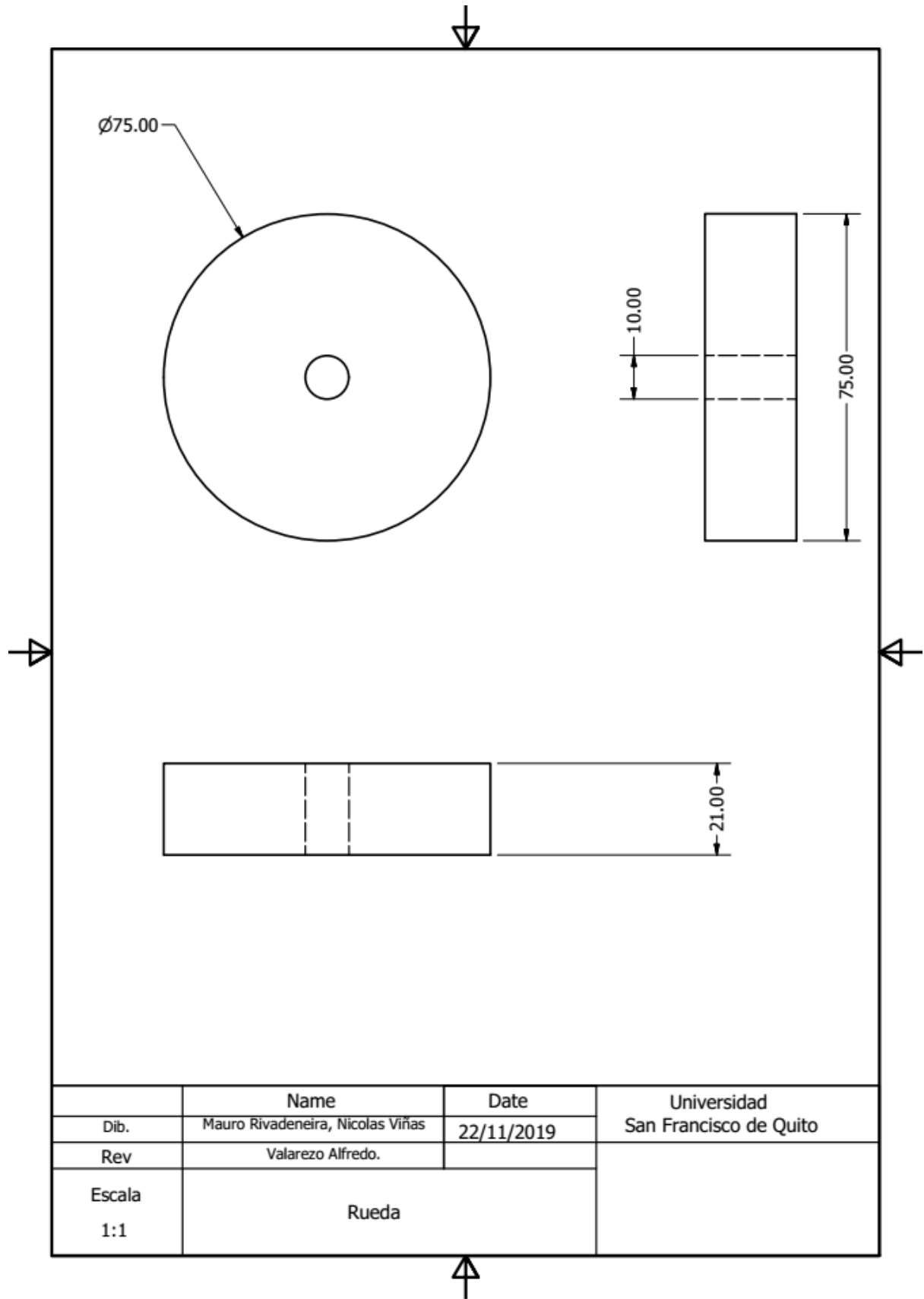




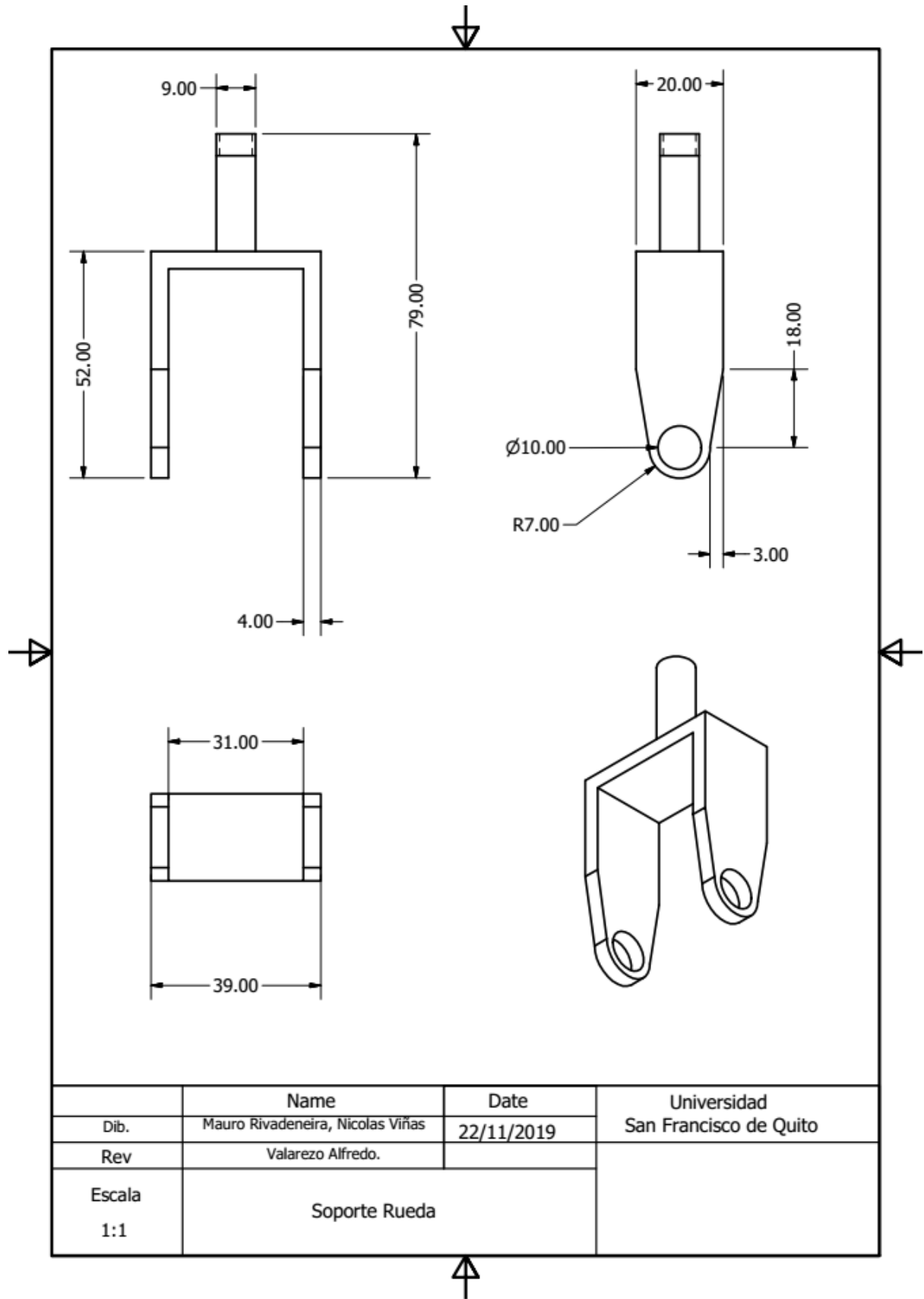


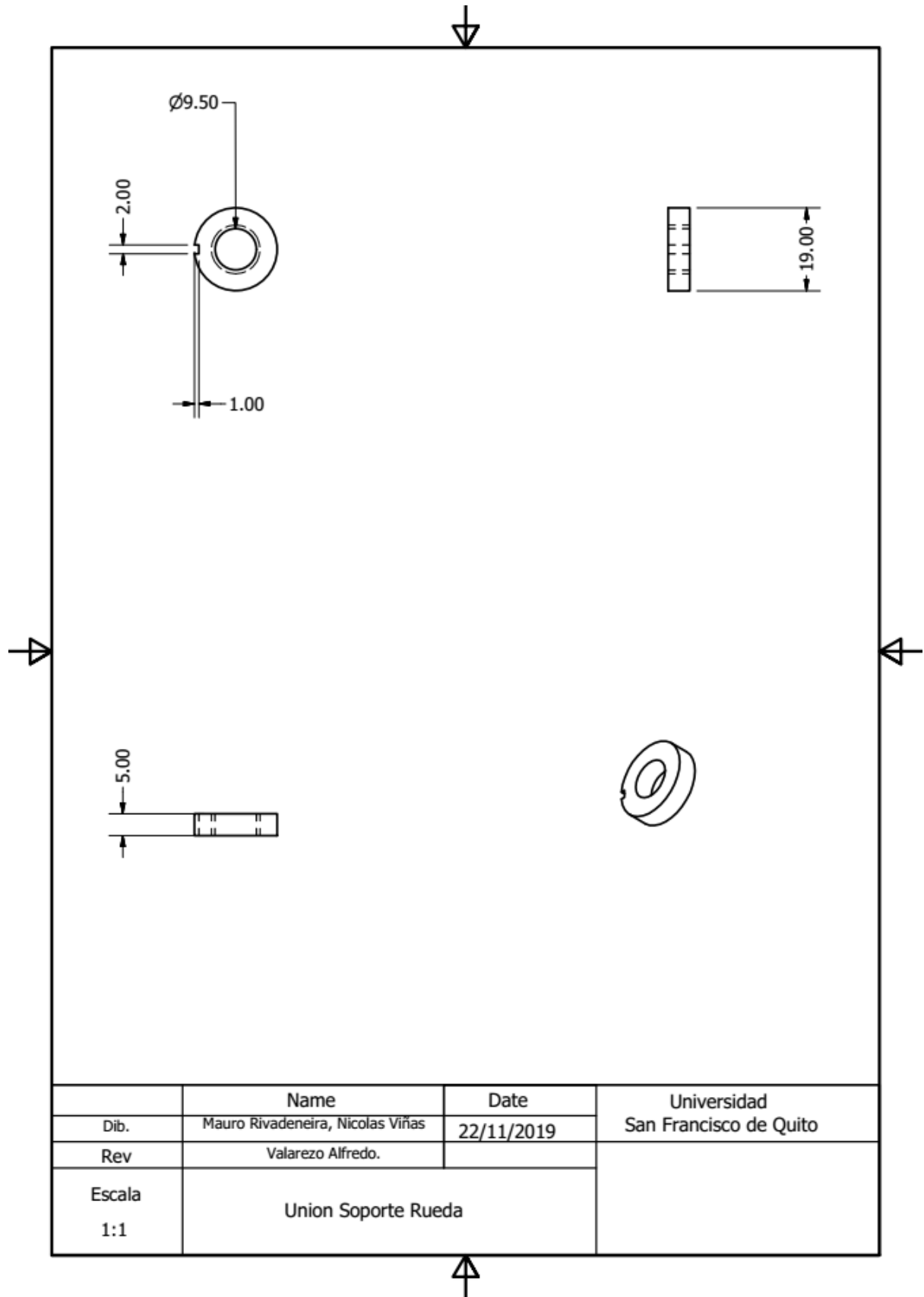
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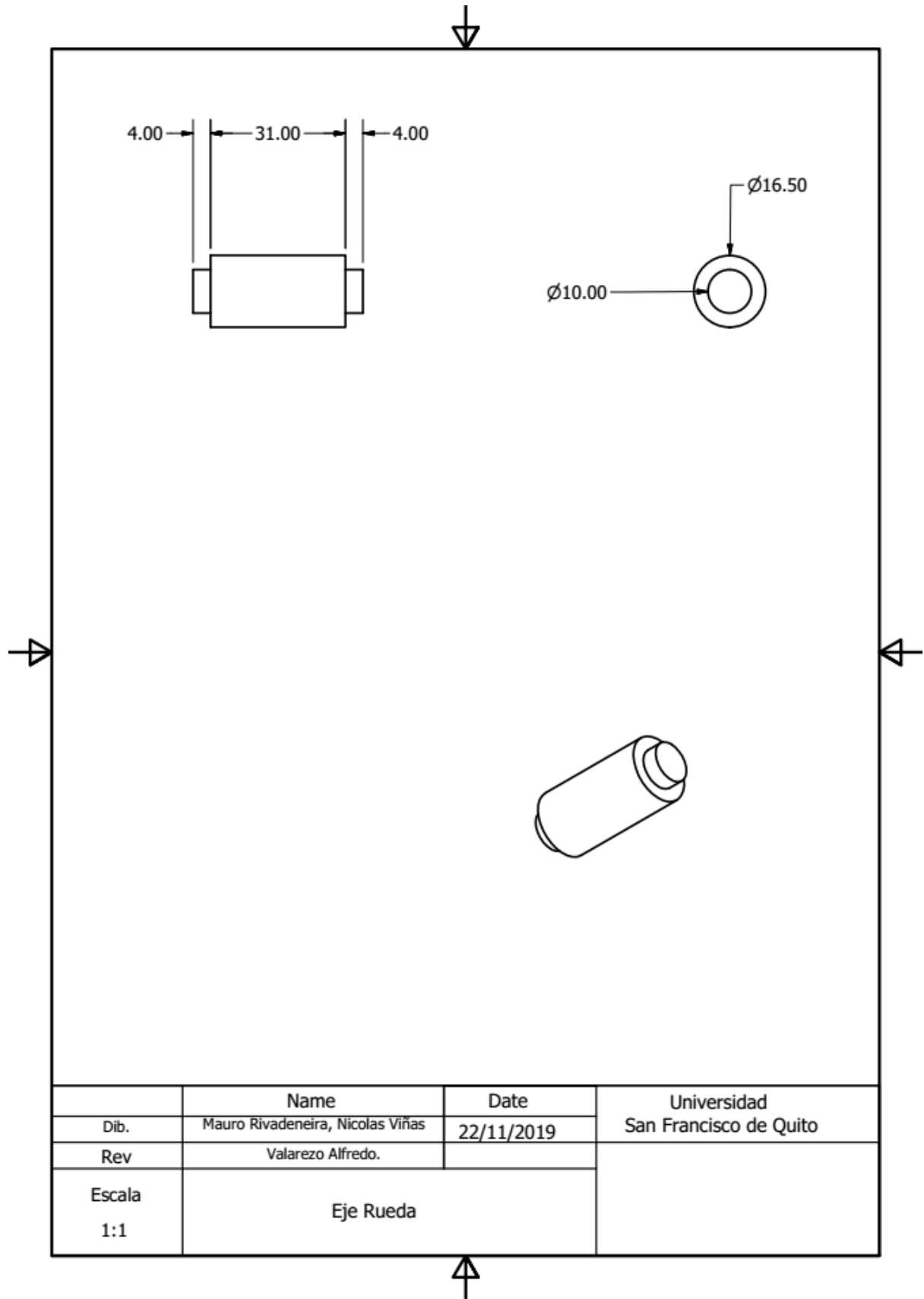


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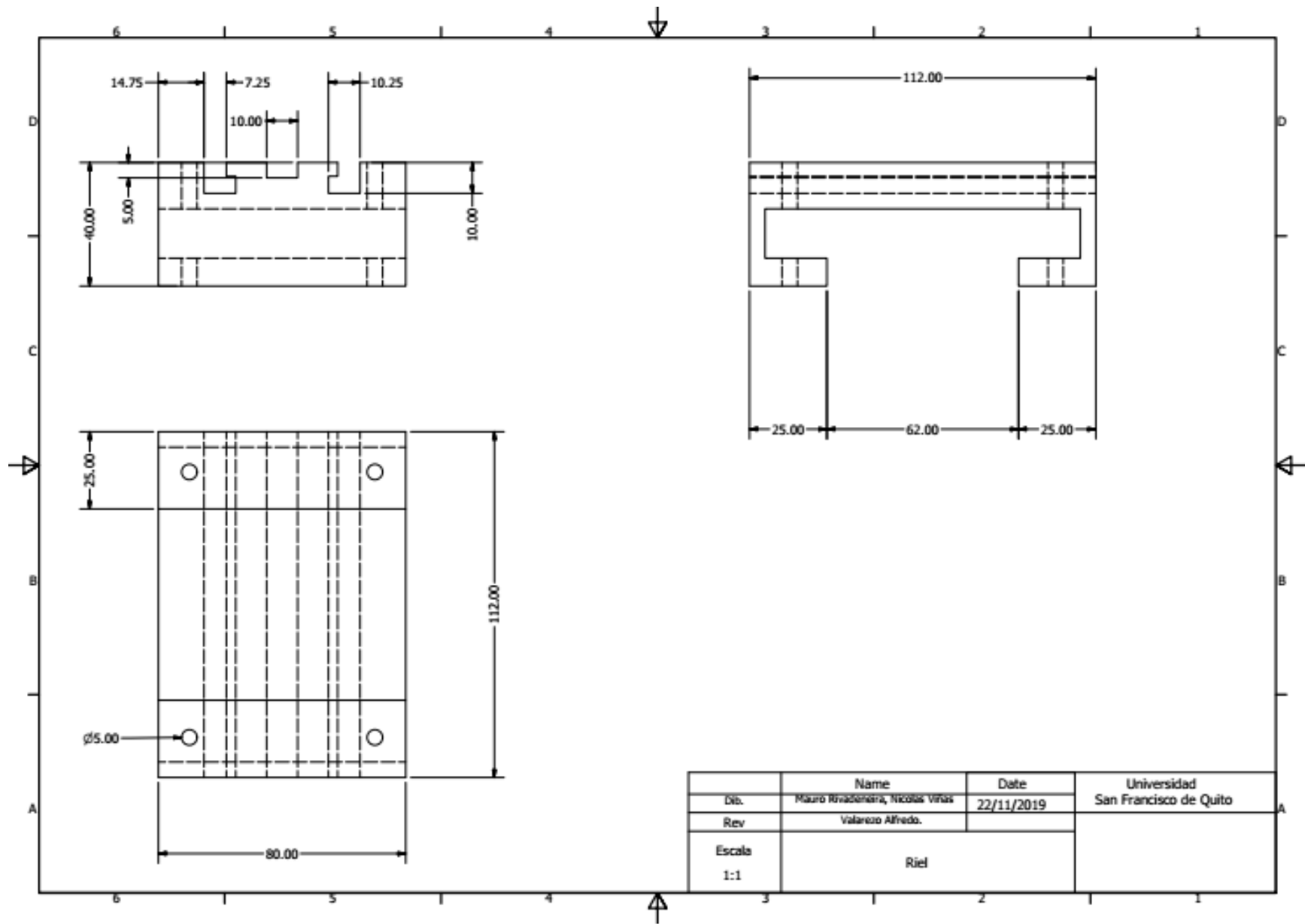


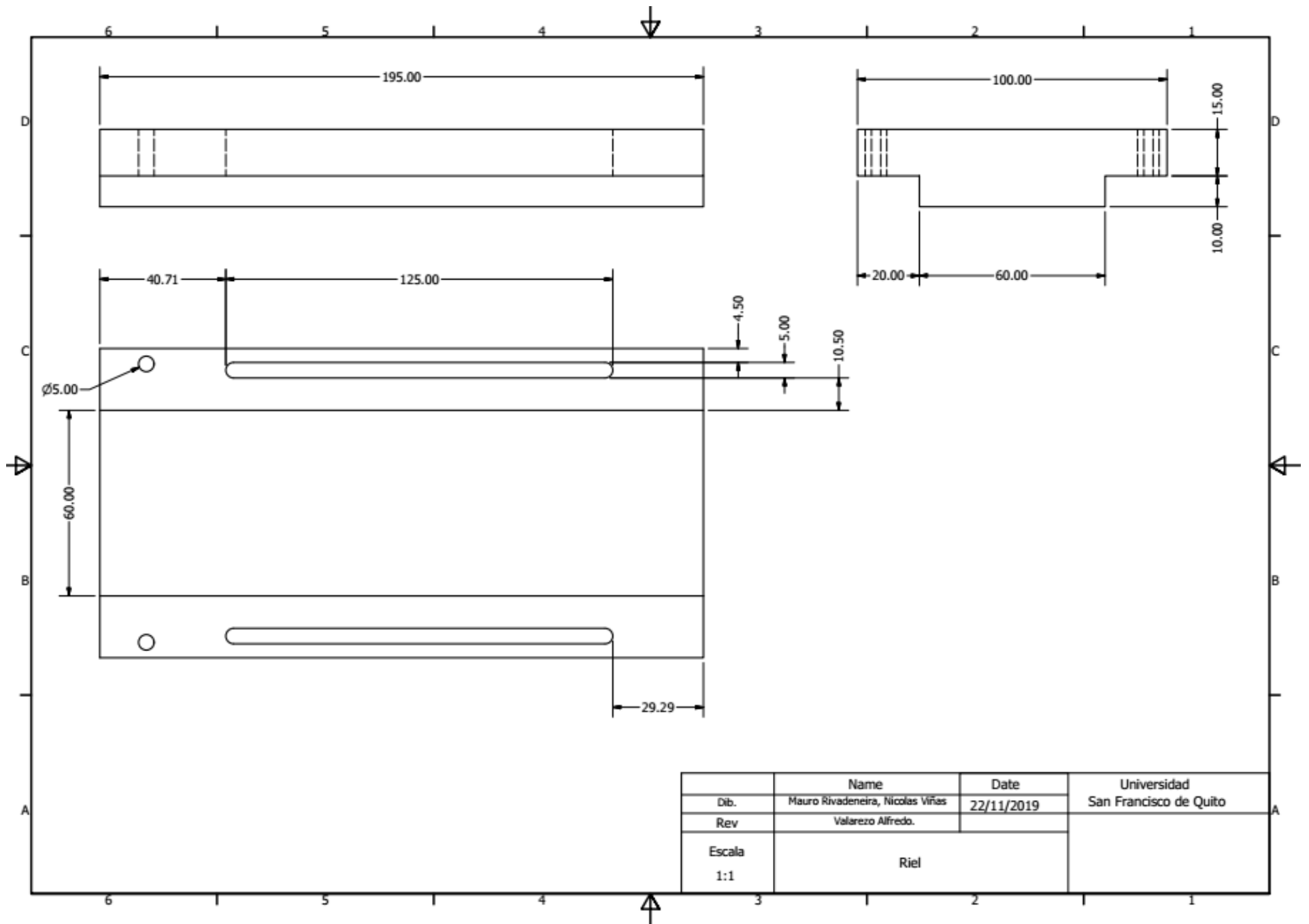


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| Rev | Valarezo Alfredo. | | |
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