Keybot

Mr P. Marx

29703662

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Supervisor: Dr H. Marais

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Abstract

The Keybot project is a mechatronics demonstration platform capable of receiving items like keychains and transporting them to an engraving station to performing subtractive manufacturing processes on the items (engraving).

The main objective of this demonstration platform, besides performing the above task, is to act as a main attraction at open days for prospective students considering a career in mechatronics. It should be able to leave an impression on not only the items, but on the young and bright engineering minds of the future.

In this miniature dissertation, the domain context for the Keybot project was analysed and explained from the NWU's perspective. The complex engineering problem was defined and constrained according to the client's primary definition of the problem.

The requirements, project scope and limitations were defined for the project, and the conclusion arose that the proposed solution is plausible.

The process flow of the Keybot was analysed and the phases were determined. Possible problems were identified, and a literature study was performed on each topic to minimise the effects that the problem might bring forward.

We then further investigate the possibility of implementing a SCARA mechanism with an automatic tool changer as a design concept and implement, test and evaluate the system.

Keywords: Actuators, G-code, HMI, Industrial-type Robots, Keybot, Mechatronics, Pathfinding, SCARA bot, Subtractive Manufacturing, UI, UX.

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1 Problem Formulation

This chapter entails the contextualization of the Keybot project wherein the domain context is analysed and explained from the client's (NWU's) perspective. The complex engineering problem is defined and constrained according to the client's primary definition thereof.

This chapter also briefly describes how the Keybot will act as a mechatronic demonstration platform capable of demonstrating concepts such as material handling, Computer Numerical Control (CNC) subtractive manufacturing processes (i.e. mechanical- or laser engraving), digital signal processing (DSP) and control theory. The details regarding this statement will become apparent in the next chapter.

Finally, the chapter ends with a list of system requirements of the Keybot, the project scope and limitations of the project.

1.1 Background

In modern society, competition is at an all-time high. It becomes inevitable to perform at one's peak potential to be successful in the career world. Therefore, the decisions we make, play a vital role in a successful career. One of the most career defying decisions we will ever make is the course and university we choose for further studies. With all this pressure and competitiveness in today's world, this becomes a daunting task, and one needs to make an informed decision.

That being said, one of the most commonly confused fields of study is mechatronics. According to [1] and [2], Mechatronics started in the 1960s as the union of mechanical and electronic components to present new and innovative solutions to the complex problems of the time. The term "Mechatronics" originated from an engineering company in Chiyoda-Ku, Tokyo Metropolis in Japan called Yaskawa Electric Company [1] - [4]. The person responsible for the term is Tetsuro Mori and the president of the company, Ko Kikuchi, coined the term in 1971, but soon released the rights to the public in 1982 [1] - [4].

In the 1970s, mechatronics consisted mainly of mechanical components with the aid from electronics [1]. Advances were made and automated, mechatronic products were developed, such as mechatronic doors, vending machines, self-focusing cameras and advanced vehicle controls. In the 1980s, Information Technology (IT) and microprocessors made its way into the mix, which leads to more advanced mechatronics, boosting the performance of products such as CNC machines, automotive vehicles and machines using databases [1]. In the 1990s, telecommunication started to contribute to the field, and advances were made in products such as teleoperation systems and mechatronic networks. Furthermore, micro mechatronics started to be developed for higher precision applications [1]. In the previous three decades, advanced software in IT, DSP, Computer-Aided Design (CAD) and complex decision-making algorithms was the main focus of the field and it continues to grow and change as a complex, and concurrent, multidisciplinary field [1].

It is clear that mechatronics has developed dramatically over the decades and therefore, finding a definition of the term is a task in its own right. However, over two decades ago (1996), a definition was formulated, which was recently accepted by the technical committee of the International Federation for the Theory of Machines and Mechanism situated in the Prague, Czech Republic [3].

According to [1] – [3], the formal definition of mechatronics is as follows: "the synergetic integration of physical systems with information technology and complex-decision making in the design, manufacture and operation of industrial products and processes.''

Many people will still confuse mechatronics with electromechanics; this is understandable since they both share some constituents. According to [5], electromechanics is the union of mechanical systems with electrical systems, while mechatronics is the additional union of computer systems and control/information systems. Figure 1, from [5] and [6], depicts this relationship, and it can be seen from this Venn diagram that they are indeed similar, but not the same.

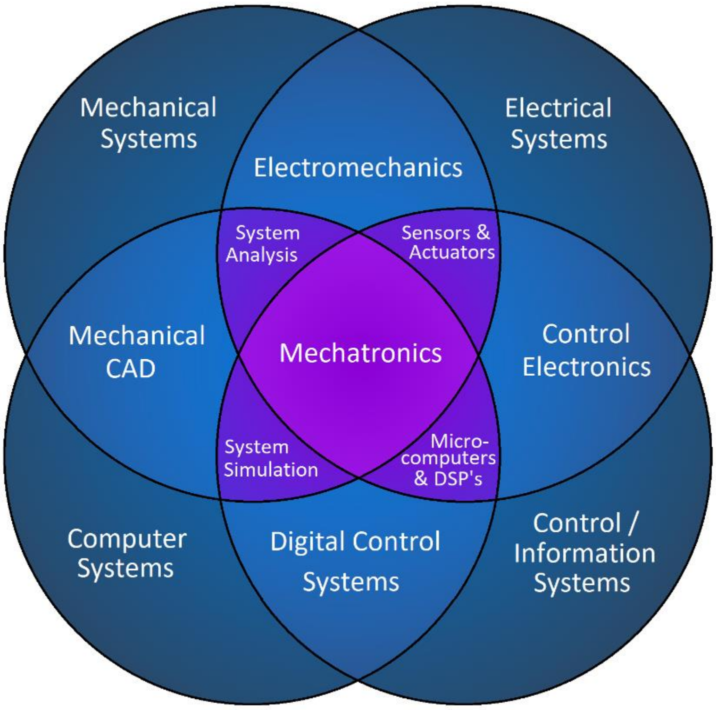


Figure 1: Venn Diagram of the Constituents of Mechatronics

According to [5], the diagram of the key elements of mechatronics can be better represented as in Figure 2. From this figure, it is clear that the information systems act upon the physical system, which is comprised of the mechanical, electrical and computer systems, while the electromechanical subsystem still only exists of the mechanical and electrical systems [5].

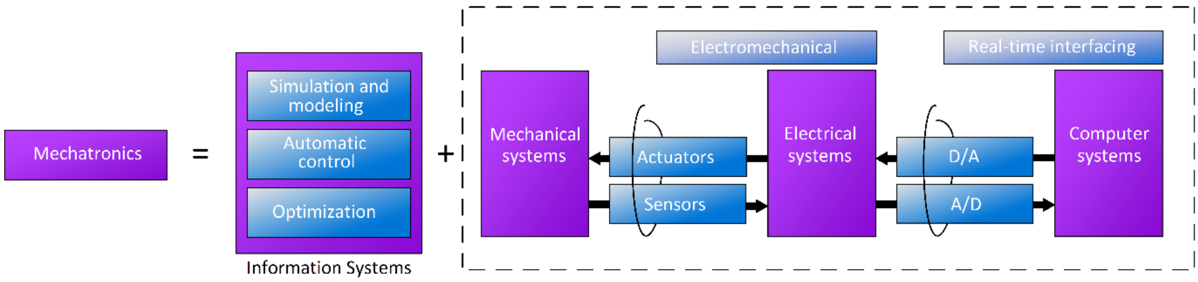


Figure 2: Diagram of the Key Elements of Mechatronics

1.2 Motivation

The North-West University in Potchefstroom is at the beginning stage of implementing mechatronics as a field of study. Therefore, two questions arise, firstly, whether prospective students fully understand what mechatronics is and, secondly, whether the NWU is a worthwhile option for prospective students interested in this field. Therefore, the NWU needs to demonstrate the concept of mechatronics successfully so that the prospective students can make an informed decision, and it needs to demonstrate its capability to excel the competence of its mechatronic students to prove that they are a viable option.

1.3 Problem Statement

Mechatronics is a commonly confused field of study, which means that prospective students might make an ill-informed decision regarding what line of study they want to pursue, being it mechatronics, because of a misconception of what it is, or other fields when they would have fitted perfectly into the mechatronics field. Therefore, a need arises for clarification of this common misunderstanding of mechatronics. The problem that this project will attempt to solve is that the NWU desires some mechatronics demonstration platform capable of clearly demonstrating the elements of mechatronics to improve their overall comprehension of what the field entails and simultaneously demonstrate the NWU's capability to excel their students in the mechatronics field. The NWU has open days and other live events at different geographical locations where a salesperson or representative can operate this platform to demonstrate the concept for prospective students and their parents.

1.4 Objectives

The objectives of this project can be divided into primary and secondary objectives. Primary objectives are not negotiable, while the secondary objectives can be attended to as extra objectives, which need not be completed.

1.4.1 Primary Objective

The desired demonstration platform, called Keybot, must exhibit the concept and elements of mechatronics at live events. The Keybot shall accept some small item (e.g. a keychain) and perform mechatronic based manufacturing processes on it. These processes include the handling of materials and subtractive manufacturing. The subtractive manufacturing processes must be personalised to the users' needs by allowing them to provide text through an interface mechanism, which the Keybot should etch/engrave into the item. This will further demonstrate the dynamic aspect of mechatronics. The Keybot will perform this demonstration in a while-you-wait fashion, and it will dispense the personalised item as a keepsake to the user. Since the demonstrations will take place at different geological locations, the Keybot should provide for easy transportation.

1.4.2 Secondary Objective

The Keybot could make use of a subtractive manufacturing process capable of being performed on a wide variety of materials. The Keybot could provide for the possible change in item shape, size and weight. The Keybot could also provide for the input of images to be etched/engraved into the item instead of/together with the provided text to be etched/engraved. Other secondary objectives could entail the provision of the overall percentage of completion, i.e. maybe LED strips that change colour/ turns on as the process carries on or even just a displayed progress bar, or the queueing of designs while the Keybot is busy with the processing of an item.

1.5 Deliverables

The Keybot system will consist of three primary mechanisms, which will have to work in harmony to perform successful demonstrations.

1.5.1 Interface Mechanism

This mechanism will display the Graphics User Interface (GUI) and receive commands from the user, such as providing the text to be etched/engraved or changing the settings of the Keybot system.

An LCD screen with mechanical buttons for navigation and selection should suffice or a mobile device capable of Wi-Fi/Bluetooth communication. Alternatively, a touchscreen (capacitive or resistive) is a valuable option and will be able to display the GUI and receive commands at the same time. Figure 3 depicts an example of such a touchscreen.

Figure 3: Touchscreen for User Interface

1.5.2 Controlling Mechanism

This mechanism will be able to receive commands from the Interface Mechanism and will generate and execute the necessary G-code to control the Manufacturing Mechanism, therefore acting as the active interface between the other two mechanisms. The Keybot should be a standalone machine in this regard, and all the motion planning/pathfinding should take place on one Programmable Logic Controller (PLC)/ Microcontroller Unit (MCU).

1.5.3 Manufacturing Mechanism

This mechanism will be able to pick up and dispense the small item, transport and place it on the manufacturing area and perform the manufacturing processes on the item. The main structure can be a 3D printed robotic arm supplied with a vacuum pickup tool, enabling the robotic arm to perform the necessary displacement motions to and from the pickup area, manufacturing area and the dispensing area. Examples of such robotic arms exist in industrial factories and include the SCARA robot seen in Figure 4. This robot has a wide range of motion and has three to four axes with the rotation of the pickup tool being optional. The other three axes exist of two rotary axes in the XY-plane and a linear one along the Z-axis, which can be seen in Figure 4.

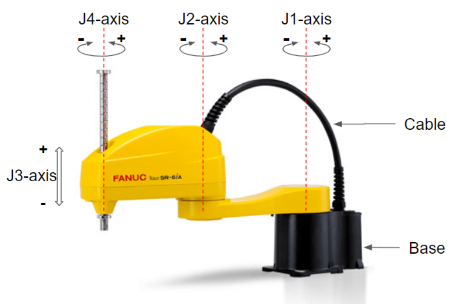


Figure 4: Fanuc SR Series SCARA Robot

Furthermore, a manufacturing tool will be attached to this robotic arm, capable of either mechanically engraving, chemically etching or laser engraving the small item. The motions of the arm while engraving is executed through G-code, which could become complicated. Otherwise, the arm could remain stationary while the platform, supporting the item, moves in the Cartesian plane with G-Code. The latter will be redundant but will allow straightforward motion planning.

Table 1 compares the actuators available for robotic arms, and according to [7], servos are the best option for closed-loop systems in specific contexts. However, the precision of the stepper motors is more desirable in this project.

Table 1: Comparing the Different Types of Actuators

Actuator Type	Strengths	Weaknesses
Air Motor	Low Cost Easily Maintained Simple to Operate	Audible Compressor Noise Inefficient System Difficult to Regulate Speed
Hydraulic Motor	High Loads Possible Simple to Operate	Slow System Inefficient System High Maintenance Requirements
Clutch/Brake	Low Cost Effective for Light Loads Easy to Perform Speed Matching	Uncontrolled Acceleration Components Prone to Wear Non-repeatable System
Stepper Motor	Simple Control Constant Load Accurate Position	Cannot Vary Load Can Lose Steps Resonance Problems
Servomotor	High Performance Small Motor Size Can Operate at High Speeds	Higher Cost System Performance Limited by Controls Speed Limited by Electronics

1.6 Technical Requirements

Power Supply

A DC power supply shall power the rest of the Keybot System when it is connected to a South African standard, the outlet power supply of 220 – 230 V AC at 50 Hz. The rest of the Keybot system will consist of a few actuators, microcontrollers and other electronics that need to be powered by this supply, by distributing it amongst these devices at their required power ratings. This DC power supplied to the system shall have a maximum current rating of at least 20 A DC and a maximum power rating of at least 240 W.

Handling Materials

When the Controlling Mechanism is finished with generating the g-code, the Manufacturing Mechanism starts to be controlled through automation, and therefore, the physical demonstration of the concept of handling materials, i.e. the displacement of the item, commences. Material handling entails the displacement of the item with a pickup tool from the pickup area, to the manufacturing area and then again from the manufacturing area to the dispensing area. The Manufacturing Mechanism should be able to handle materials with a flat to 5° concave surface, the volume between 30 mm and 70 mm radius, height between 3 mm and 50 mm and weight not exceeding 200g.

G-Code

When the Controlling Mechanism of the Keybot has received the desired design and location of the item for engraving, this mechanism shall implement an elegant algorithm to generate more efficient g-code than the brute force, pixel algorithm. This generation of the g-code should not take longer than one minute before the execution thereof, which will control the manufacturing mechanism to handle the small item and perform the engraving process. The total time during unnecessary movements determines the quality of the g-code, and it should be limited as far as possible.

Engraving Materials

When the Controlling Mechanism is finished by executing the g-code for displacement to the engraving area, the Manufacturing Mechanism starts to be controlled through automation. Therefore, the physical demonstration of the concept of personalised subtractive manufacturing of materials, i.e. the engraving of the item according to the desired design, commences. The engraving of the material entails the control of the speed, number of loops, power level and engraving tool size required to produce a finely finished engraving. The Manufacturing Mechanism should be able to engrave/etch various materials, including MDF, balsa, paper, wood, fabric, plastic, acrylic, leather, plywood, foam paper and anodized aluminium and steel. The speed of the engraver should not be too slow, as to exceed 30 minutes to fully engrave a 10 cm^2 area or equivalently 18 seconds per 1 cm^2.

1.7 Scope Definition

The scope of this project is solely the Keybot System, i.e., the Manufacturing Mechanism capable of performing manufacturing and material handling tasks, the Interface Mechanism capable of display and receiving commands and the Controlling Mechanism capable of interpreting commands, generating G-Code and executing it. The system will provide a loading interface for manually reloading the items to be manufactured on, but the system is not responsible for the supply thereof. The project will contain a DC power supply unit, which converts the AC power to DC power. However, the system is not responsible for the supply of external power. An attached platform will aid with fastening the mechanisms, but the surface underneath should be flat, and the system is not responsible for levelling itself or the supply of the surface. The system will have safety precautions such as barriers, tampered glass in case of the laser and possible sensors for civilians, but the system will not provide any other form of extra safety precautions such as glasses for the crowd's, prospective students' or animals' eyes. Although the system will be as enclosed as possible, exposure to weather elements such as rain or extreme heat will not be accommodated for by the system. The Keybot shall provide a design for easy transportation, but not the transportation channel itself. The system is not responsible for providing a marketer, movers or a custodian for the system. For clarification, see the scope diagram in Figure 5, which describes which elements fall within the scope and those that are excluded.

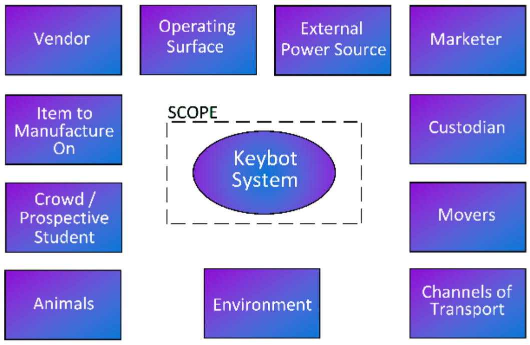


Figure 5: Scope Diagram of the Keybot System

1.7.1 Limitations

There exist some limitations on the system as listed below.

Cost

The project enjoys industrial funds, and therefore, there is no specific budget. However, it should be manageable to produce the system around R7500 and upward.

Temperature

The temperature limits are yet to be formally determined. However, temperatures between -10°C and 50°C are the reasonable standard for electronic devices during operation.

1.8 Anticipated Benefits of Solution

This solution provides a cost-effective way of demonstrating the concept of mechatronics for prospective students and their parents. It will demonstrate this concept in a way that could spark interest and possibly persuade prospective students and their parents that the NWU is competent enough to be considered as a top university for mechatronics.

1.9 Conclusion

The Keybot project is a demonstration platform for the automation of repetitive work done by mechanical and electronic components, also known as mechatronics. This system will accept some small item such as a keyring and through personalised subtractive manufacturing, demonstrate the concept of mechatronics. The Keybot will dispense the manufactured items as keepsakes for the users at many different live events situated at different geographical locations. Some limitations are yet to be determined; however, the proposed solution to the problem seems plausible.

2 Literature Study

Before starting with the detailed design, a conceptual design needs to be considered. This will improve the quality of the detailed design and save time and money since a wide variety of options is considered before any in-depth research is performed or time is spent on an impractical solution. This will also minimise any chance for unforeseeable issues later.

In this chapter, an investigation is performed to identify all the potentially problematic phases of the Keybot System to understand the problem better. Possible solutions to these problems will also be investigated, weighing the advantages against the disadvantages, identifying the best solution. In some cases, the impression left by the solution will be considered more valuable since the client specified that this is an important characteristic to consider.

2.1 Identifying the Phases

As mentioned in Chapter 1, the Keybot exists of three macroblocks: the Interface-, Controlling- and the Manufacturing Mechanism. The synergy of these three mechanisms will utilise some key elements of mechatronics, clarifying the concept of mechatronics to the prospective students and their parents. For this synergy to take place, the whole process should be thoroughly investigated to identify potential downfalls so that they can be mitigated through research or experiments.

This process starts with the user that needs to communicate their desired design to the Keybot through the Interface Mechanism. This design is transmitted to the Controlling Mechanism, which will analyse the design to generate an elegant toolpath for better efficiency. After the toolpath is identified, this path is converted into a Computer Numerical Control (CNC) language code. This code is then interpreted by the respective CNC language code interpreter program, which will act as the interface between the Controlling Mechanism and the Manufacturing Mechanism. At this point, the Keybot must be loaded with the desired item(s) intended for undergoing the subtractive manufacturing process at the loading station. One of these items will then be transported from the loading station to the manufacturing station. Here, the Manufacturing Mechanism, which will consist of various actuators, will execute the commands from the Controlling Mechanism to perform the subtractive manufacturing process on the item. After the design is completely processed onto the item, the Keybot will finally dispense the item to the dispensing station for collection by the user.

The main phases of the Keybot System can thus be summarised as follows:

1. Design communication with a human-machine interface
2. Design processing for elegant toolpath planning
3. Conversion to a CNC language code
4. Transportation with motion platforms
5. Material handling
6. Material engraving
7. Product dispensing

2.2 Human-Machine Interfaces (HMI)

According to [8], a Human-Machine Interface, or HMI, is "a channel across which the user's plan of action is transmitted to the machine for execution". This means that an HMI can be any software, hardware or combination of the two that acts as an interface between an operator and a machine. HMI's have two main components to keep in mind when being designed: The User Interface (UI) and the User Experience (UX). The UI is about the actual interface, i.e. the technology and programs necessary to interact with the machine. The UX on the other hand is about the user's experience, i.e. how user-friendly the interface is. According to [9], it has a large impact on the design of the UI itself.

With the Keybot System, the UX needs to be taken into consideration to ensure that it can be used by a wide variety of users regardless of their education background. This includes a user-friendly Graphical User Interface (GUI) as well as a user-friendly physical interface.

2.2.1 UX and the GUI

According to [9], there are some guidelines that can help to improve the UX of the GUI. These guidelines are for easy navigation of the UI and a more organised display.

Easy Navigation of the UI

1. There should exist a standard task sequence in the design for similar actions.
2. Links should have an accurate description regarding their destination.
3. Use headings that are an accurate description of the content.
4. Use the appropriate elements for specific tasks, such as radio buttons versus checkboxes.
5. Text should have a good visibility at all time.

Organised Display

1. Use consistency, i.e. a consistent colour theme, formats and terminology.
2. The format or task at hand should be easily understandable.
3. Make use of different locations to emphasize important information.
4. The UI should not rely on the user for any commitment of information to their memory.
5. Proper input types should be of a convenient type.

2.2.2 UX and the Physical Interface

There are many types of physical interfaces that could be considered for a UI, however, choosing the most suitable one for the best UX is the problem. The physical interfaces could be divided into two types: mechanical and digital interfaces.

Mechanical

Mechanical interfaces include components that need to move to communicate with the system, including pushbuttons, joysticks, levers and knobs. These input components are usually pared with some type of digital display for notifications from the system. Since moving components tend to wear due to friction, the UX will decrease over time. Therefore, this option will no further be considered as a valuable option for the physical interface.

Digital

Digital interfaces, unlike mechanical interfaces, do not *move*[1] to communicate with the machine, meaning that minimum wear occurs, increasing the UX compared to mechanical interfaces.

[1] With the exception of resistive touchscreens.

Digital interfaces are mainly touchscreen. There are different types of touchscreen technologies each with their advantages and disadvantages. These types are as listed in Table 2 [10] – [11], which lists the different types of touchscreens with a brief description of how it works with all the advantages and disadvantages of each type.

Table 2: Comparing the Digital Physical Interfaces

Touchscreen Type	Advantages	Disadvantages
Resistive Touch - An external force causes the internal metallic layers to touch, resulting in a change of resistance and detectable voltage drop.	Responds to any object. Cheapest. Low power rating. Resistant to dust and moisture.	Low image clarity. Surface is vulnerable to scratches.
Surface Capacitive Touching the transparent electrode layer with a charged entity, causes the capacitance to change, which is measurable.	Durable Surface. Better image clarity. Resistant to dust and moisture.	Responds only to finger or stylus. Vulnerable to EMI and RFI.
Projected Capacitive Like surface capacitance but is multitouch and senses some gloves.	More durable surface. Even better image clarity. Resistant to dust and moisture. Multi-touch. Can use certain thin gloves.	Vulnerable to EMI and RFI.
SAW Touch Piezoelectric transducers and receivers create an ultrasonic wave grid which causes a measurable interruption when a digit is present.	Even better surface durability. Great image clarity.	Does not respond to hard items. Vulnerable to false triggering if wet. Could become unresponsive if a contaminate is present on the screen.
Infrared Touch Infrared receivers measure the interruption of an invisible infrared grid when a digit is present.	Best image clarity. Best durability.	Vulnerable to false triggering if wet or in ambient light. Expensive.

Upon inspecting Table 2, resistive touch is the best choice when it comes to price, power usage and accessibility. However, it lacks the image clarity, durability and sensitivity of the projective capacitive touchscreen, which means that, with the latter, the UX will be better in the long run.

2.3 Toolpath Planning

The subtractive manufacturing process must not take too long, as people do not like to have their time wasted. Therefore, it is very important to improve the speed of this stage.

After the Keybot has transmitted the design to the Controlling Mechanism, the design must be analysed by an elegant toolpath finding algorithm. This will limit any airtime (the time that the engraving tool does not perform any actual engraving), which will speed up the process and save power. According to [12], theoretically, the total time needed to execute the toolpath is obtained by adding the total lengths of the path segments taking into consideration the feed rate and the time it takes to accelerate and decelerate the tool, which dramatically affects the total time. There are many toolpath algorithms, but according to [12], the success of each depends on the least number of path segments, which implies that longer path segments are desirable.

As per illustration, consider Figure 6. Option (a) uses the circular algorithm [13], which creates too many path segments, which will slow down the process because of the extra time used for acceleration and deceleration of the tool. Option (b), the one-way directional-parallel X algorithm [14], has less path segments depending on which directional-parallel method is used, as we will see lateron. Option (c) uses the same algorithm as (b), with the exception that the orientation of the path has changed, leading to longer path segments and less wasted time. Therefore, the angle of the path also determines the efficiency thereof. Finally, (d) uses the contour-parallel algorithm, which has the least amount of path segments and therefore, less time is exercised using this algorithm.

Figure 6: Demonstrating the Effects of Different Toopath Approaches. (a) Circular, (b) One-way Directional-Parallel X, (c) One-way Directional-Parallel Y and (d) Contour-Parallel

In [12], the authors conducted an experiment using four different toolpath algorithms. These were:

- The directional-parallel one-way toolpath algorithm (see Figure 7 (a)).
- The directional-parallel pure-zig-zag toolpath algorithm (see Figure 7 (b)).
- The directional-parallel smooth-zig-zag toolpath algorithm (see Figure 7 (c)).
- The contour-parallel toolpath algorithm with the Voronoi diagram (discussed in [15]) approach (see Figure 6 (d)).

The authors came to a rather odd result, which was that the smooth-zig-zag algorithm was the fastest because it does not have multiple path segments such as the one-way algorithm and it does not have sharp corners like the pure-zig-zag algorithm, which still causes acceleration and deceleration.

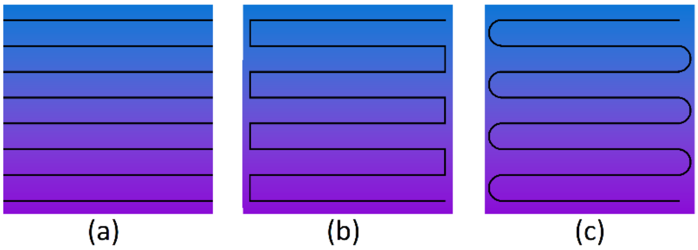


Figure 7: Demonstration of the Different Directional-Parallel Approaches. (a) One-way, (b) Pure-zig-zag and (c) Smooth-zig-zag

This finding should raise a flag since we just established from Figure 6 that the contour-parallel algorithm was faster. This is because the authors only experimented on one shape every time, where in reality, these shapes change, and the optimal algorithm also changes. The authors used a closed dense pocket figure with no island in the middle (similar to the shape type of Figure 8 (a) and (b)) that caused that the directional-parallel smooth-zig-zag algorithm version of Figure 8 (a) have fewer path segments than the contour-parallel algorithm of Figure 8 (b) [12]. When introducing islands into the same shape, the directional-parallel smooth-zig-zag algorithm version of Figure 8 (c) will have a longer path to follow than the contour-parallel algorithm of Figure 8 (d).

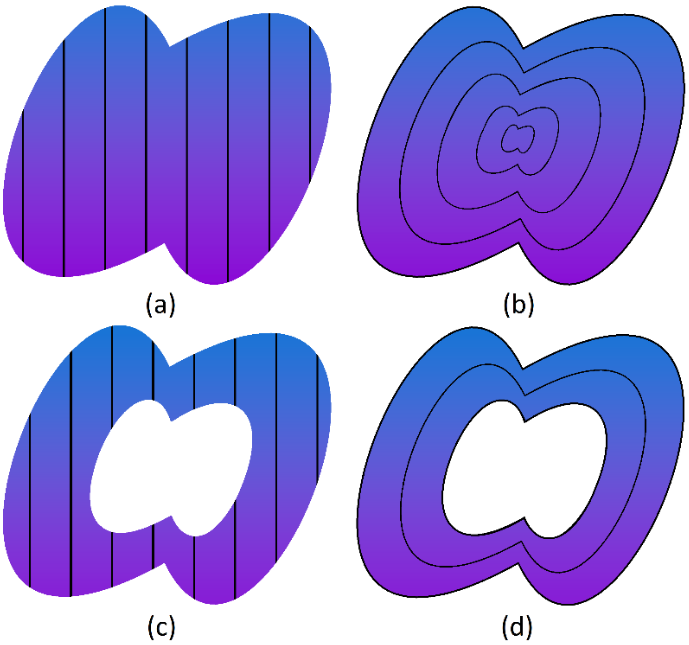


Figure 8: Effects of Islands and Density of the Pockets on the Directional-Parallel Algorithm versus on the Contour-Parallel Algorithm. (a) Directional with no Island, (b) Contour with no Island, (c) Directional with Island and (d) Contour with Island

Since this experiment performed by the authors of [12], had results where the contour-parallel and directional-parallel algorithms' time was relatively close to one another, it becomes clear that the contour-parallel algorithm is the better of the two. However, although the texture left behind by the engraver for a rough engraving with the contour-parallel algorithm will look good for the text-based input and the times are relatively similar, it does not look uniform enough for images and preference will still have to be determined for the image input type.

2.4 CNC Language Codes

After the tool paths have been determined, the Controlling Mechanism needs to convert the path into executable lines of code. One way of doing this is to write an algorithm that generates g-code. This is a software language of its own, and the details will not be covered in this literature study, as the exact protocol is unimportant and replaceable in this design. The same generated g-code will then be stored as a text file, which will later be reinterpreted by another algorithm as instructions to control the Manufacturing Mechanism. Therefore, the only purpose of the g-code will be to store the instructions in a format that can easily be retrieved later and executed without all the processing power that was necessary to do the toolpath planning. With this g-code document, the design can be reused without the repetition of the toolpath planning algorithm.

2.5 Motion Platforms and Material Handling

When the Keybot System is finished with the conversion of the design into g-code, the item needs to be retrieved from the loading stage for processing. First, the position and orientation of the item needs to be known by the Keybot System for it to place the item in the right orientation at the engraving stage. There are a few motion platforms and sensors capable of solving this issue, however, to simplify the already complex system at these trivial problems, a tray with cavities specifically made for the shape of the item with a predefined positioning algorithm need to be considered. These items will then be loaded into their respective cavity pockets at the loading stage with the help of a human, say the marketer, ensuring that the Keybot knows where the items are and their orientation with the aid of the predefined positioning algorithm. Now that the Keybot knows where the items are and what their orientation is, the material handling of the item can commence to the engraving stage. Since the problem statement provided by the client asked specifically for some type of industrial-type robot to perform this task, only the possible attachments for picking up the item will be considered, i.e. no conveyor or funnel systems will be considered. These attachments are called pickup tools or grippers. There are several types of pickup tools and, Table 3 describes each type, according to [16].

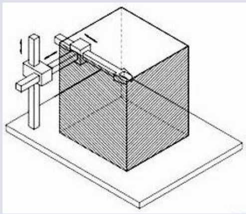
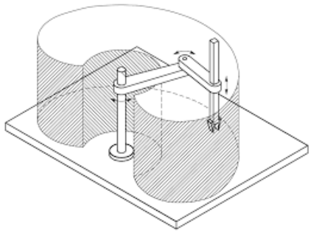
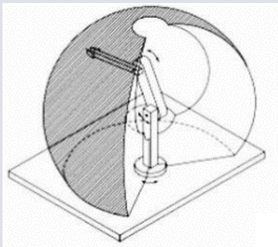
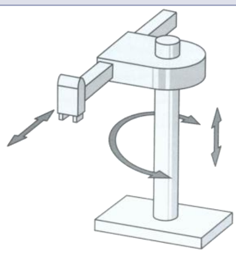
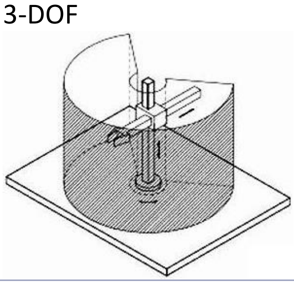
Table 3: Comparing the Pickup Tools

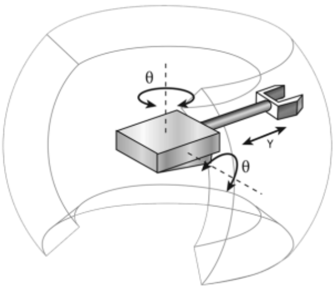
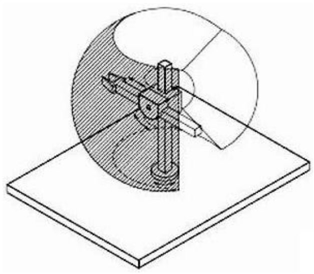
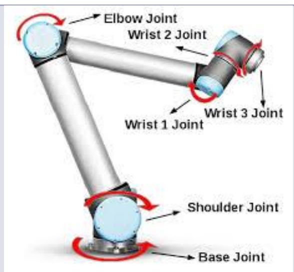
Name	Description	Advantages	Disadvantages
Hydraulic Grippers	Uses hydraulic principals (oil) to flex and relax a claw.	Can handle very heavy objects.	Claw limits item shapes for pickup. Might damage the item with large force. Claw needs to be designed.
Pneumatic Grippers	Uses pneumatic principals (air) to flex and relax a claw.	Strength is variable with pump choice.	Claw limits item shapes for pickup. Claw needs to be designed.
Rack and Pinion	Linear actuator moves the rack, which drives the pinions to flex and relax a claw.	Strength is variable with actuator choice.	Claw limits item shapes for pickup. Claw needs to be designed.
Two Pincher Gripper	A cord is pulled by an actuator to flex and relax a claw.	Strength is variable with actuator choice.	Claw limits item shapes for pickup. Claw needs to be designed.
Vacuum Pickup Tool	A vacuum pump sucks air through a porous material or suction cup.	Strength is variable with actuator choice.	Can only lift light objects. Can damage the item if suction is too high.

When studying Table 3, it becomes clear that the vacuum pickup tool is the best fit for the pickup tool. It has variable strength, can only lift relatively light items and is the only pickup tool with more degrees of freedom when it comes to the shape of the item.

Now that the item can be gripped and released by a pickup tool, an informed decision regarding the type of the industrial robot performing the motion or material handling, they can be made. Again, there is a wide variety of robot types, and Table 4 is used to compare the different types according to [16] and [17]. Images came from [17] - [19].

Table 4: Comparing the Industrial Robot Types

Name	Illustration	Range	Description
Cartesian Robots (Gantry)		3-DOF 	The Cartesian robots are the simplest robots and are used in CNC tables. They are very accurate robots and the range of motion fits into a rectangular prism.
SCARA Robots (Selective Compliance Assembly/ Articulated Robot Arm)		3-DOF Or 4-DOF 	Commonly faster than Cartesian robots and better space utilisation than Cylindrical robots. They lose accuracy further from the base. The range of motion is a C-shape.
Articulated Robots (Jointed Arm)		6-DOF 	Most popular in industry. Has the widest space utilisation, consisting of a trunk, shoulder, upper arm, forearm, wrist and effector capable of roll, yaw and pitch. Complicated control and lose accuracy further from the base.
Cylindrical Robots		3-DOF 	Very compact robots for simple assembly. Loses accuracy further from the base and utilise less operation space than the SCARA robot.

Delta Robots (Parallel Robot/ Pick and Place)		3-DOF 	Commonly has 6 pistons to position a plane within a semicircle. Failure of one piston does not affect the performance of the robot too much.
Polar Robots (Spherical Robots)		3-DOF 	Polar Robots can only access space of a constant radius from a common point. One of the first robots ever to be developed.
Collaborative Robots		6-DOF Same as articulated robots.	Same as articulated robots with the acception that they can safely interact with humans. Commonly used for assistance.

Studying Table 4, we see that the Cartesian and SCARA robots are the best options. The articulated robot and collaborative robot are unnecessarily complex and utilise space that will never be used. The cylindrical robot has a smaller range than the SCARA robot. The Delta robot needs to be installed from a hanging position and cannot reach surfaces far away from its centre position. The polar robot will not be able to perform the necessary material handling operations. Although the SCARA robot seems more complex than the Cartesian robot, it still only has two inputs for a given location in the XY-plane, the same as for the Cartesian robot. Because the client specifically requested that the Keybot system must leave an impression on the spectators and almost all common 3D printers are Cartesian robots, the SCARA robot is the better fit. The accuracy of the SCARA robot is not a problem since it can be improved with a few gearboxes.

2.6 Material Engraving

Now that the industrial-type robot is identified with its pickup tool mechanism, the item can be transported to the manufacturing station with the help of the Controlling Mechanism. Now, the question arises as to what type of subtractive manufacturing process the Keybot will use to personalise the item with the desired design. Since the item should not get wet, and we only have a SCARA robot is a moving mechanism, we are limited to a few options. Chemically etching (dry), mechanical rotary engraving and laser engraving are the most common and easy subtractive manufacturing processes to be performed on small items with industrial-type robots.

In Table 5, these three possible solutions to the manufacturing problem is summarised for comparison.

Table 5: Comparing the Different Subtractive Manufacturing Processes

Name	Description	Advantages	Disadvantages
Chemically Etching (dry)	Chemicals are applied to the surface of an item and the same route as laser engraving is followed from hereon.	Works on metals. Works on glass.	Expensive chemicals need to be purchased. Has all the disadvantages that Laser Engraving has. Does not work on all materials.
Mechanical Rotary Engraving	A mechanical tool bit is fastened to a motor which rotates at high velocities. The bit is lowered onto the item until contact is established with the item. The friction between the bit and the item's surface causes the surface to chip away, leaving an impression into the surface.	Easy to operate. Not so dangerous. Works on metals.	Cannot be used on any materials. Clamping needs to take place and since the Keybot should be automated, another problem is created. Moving parts cause friction, wearing the system over time. Detail depends on finer bits.
Laser Engraving	A laser module is mounted on the front of the SCARA robot and generates a concentrated beam of light onto the item. The energy of the laser is absorbed by the item and it heats up, changing the molecular structure of the item.	Easy to operate. No moving parts or friction for wear. Can be directly used on almost any material, accept metals. Can apply chemicals to metal surfaces to enable the engraving off metals. Fine detail engraving.	High power usage. Module is relatively expensive. Dangerous reflected lasers can harm eyes if no tampered glass is used.

Inspecting Table 5, mechanical rotary engraving is less dangerous and easy to operate. However, except for being dangerous in the absence of tampered glass and a bit expensive, laser engraving is the best option for the variety of materials, no wearing, most detailed outcome and easy to operate. Laser engraving will also leave a better impression on the prospective students and their parents. However, this technique presents just as much issues in the form of possible health related risks and price. It is therefore decided that laser engraving should eventually be integrated into the project at a later stage, however, for now, rotary machine engraving will feature in the first version of the Keybot system.

2.7 Conclusion

The process flow of the Keybot was analysed and the phases were determined. Possible problems were identified, and a literature study was performed on each topic to minimise the effects that the problem might bring forward. Furthermore, some solutions were found for the problems and indicated throughout this chapter. These solutions are not final, since the client has the final say as to which solutions to exercise. For the HMI, it was concluded that the projective capacitive touchscreen was a valuable solution, for the toolpath finding algorithm the contour-parallel algorithm is preferred for text and the directional-parallel smooth-zig-zag algorithm for images. It was stated that g-code will be used and that the designs will be available after manufacturing for future design options. A SCARA robot will be the design for the Manufacturing Mechanism and a vacuum pickup tool will be used to aid the robot with displacement processes. It is also stated that Laser Engraving is the more valuable option when it comes to the subtractive manufacturing process.

3 Design

In this chapter, the design of the Keybot system is conducted. It is important to consider as much detail possible during this phase since it will correlate with the effective success of the phases to follow.

3.1 Introduction

This system is a hardware- and software-based problem and will therefore be designed from both perspectives. To do this, several design tools are considered to aid in the identification of the necessary functions, libraries, storage, components, technology and performance required for a well-integrated system.

3.2 Hardware-Based Design

The hardware-based design of the Keybot is used to identify the type of components, number of components, the interfaces between each connected pair of components and the protocol used to efficiently communicate between the components.

3.2.1 Operational Flows

An operational flow diagram is used to identify the expected external processes that the system undergoes during normal operation. This helps to scope the expected usage of the system in a way that will aid in the interfacing of the system's internal functions with the practical environment and its functions.

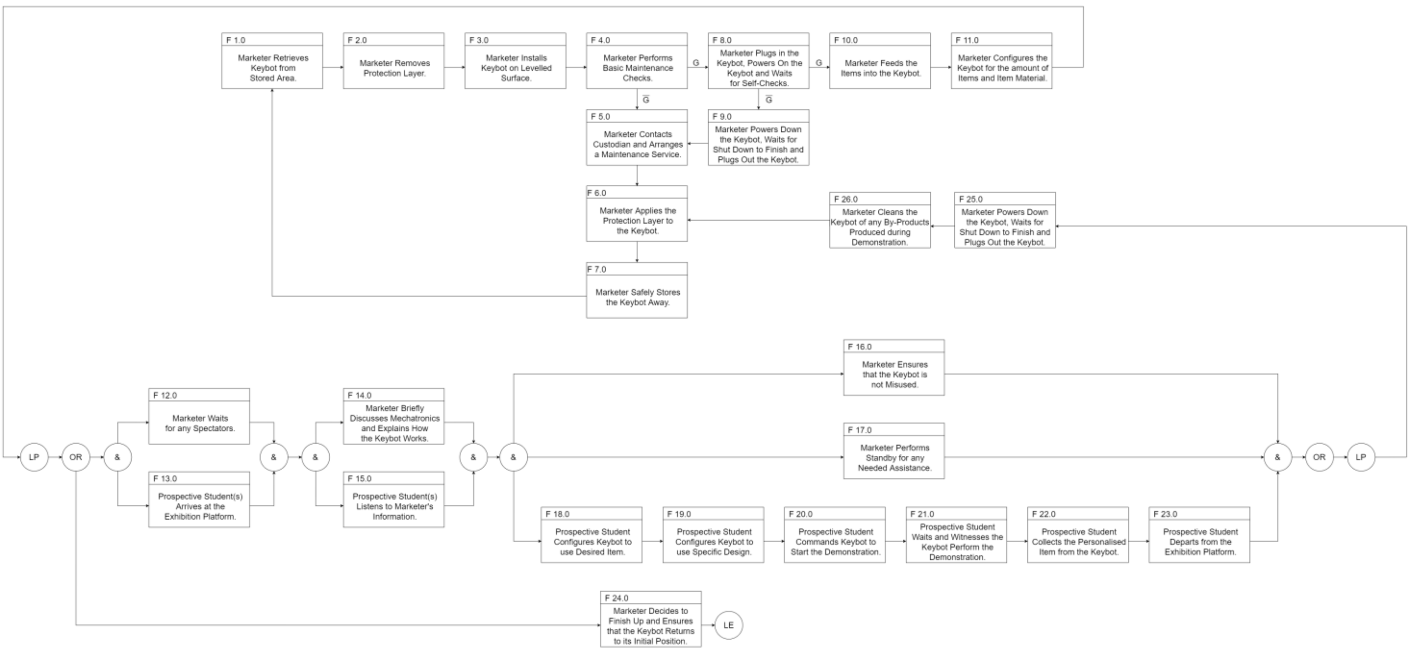


Figure 9: Operational Flow Diagram of the Keybot System

From this diagram, it is apparent that the system should be protected from the environment (heat, dust, liquids and misuse). It is also clear that an HMI is needed between the user and the Keybot system. It should also be noted that the user waits a while for the Keybot to perform the necessary procedures. Thus, the system should not be too slow as to irritate the user, as this will devalue the whole demonstration experience and, therefore, undermine the primary objective of the project.

3.2.2 Functional Flow Block Diagrams (FFBD)

The Functional Flow Block Diagrams aids in the necessary interaction between the system and the stakeholders to ensure that the system is functional. It also helps identify all the necessary functions, interaction and logical flow of the software of the system for easier implementation thereof later. Lastly, these identified functionalities that the system requires should be executable by the system, and therefore, aids in the identification of components necessary to integrate a working system.

3.2.2.1 Level 0

Level 0 identifies the overview of the logical flow of functionality. It is used to understand more about the flow of the system and greatly simplifies and clarifies the rest of the design of the system's functionality if done properly.

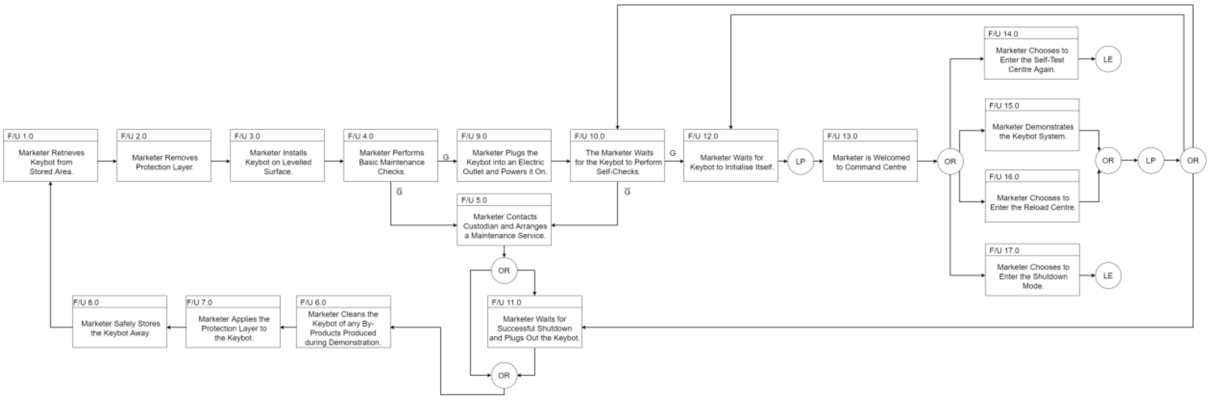


Figure 10: Level 0 of the Functional Flow Block Diagrams

Figure 10 illustrates the high-level depiction of the functionality of the whole system. From this figure, it is clear that the system will have to be able to perform self-tests, communicate the details of the custodian, perform a shutdown routine, initialise itself, and provide options for the user to navigate between the Reload Centre, Design Centre, Self-Test Centre and the Shutdown Routine.

3.2.2.2 Level 1

Level 1 allows the designer to explore level 0 in a deeper context. This helps identify more functional units that need to be addressed and how the system will have to interact with the user and its internal components. Level 1 (Figure 11) shows that the self-test mode will be able to check if the system encountered a previous power failure, if the internal data interfaces and external calibration interfaces are working, if the system is indeed mobile and notifies the user of failure points.

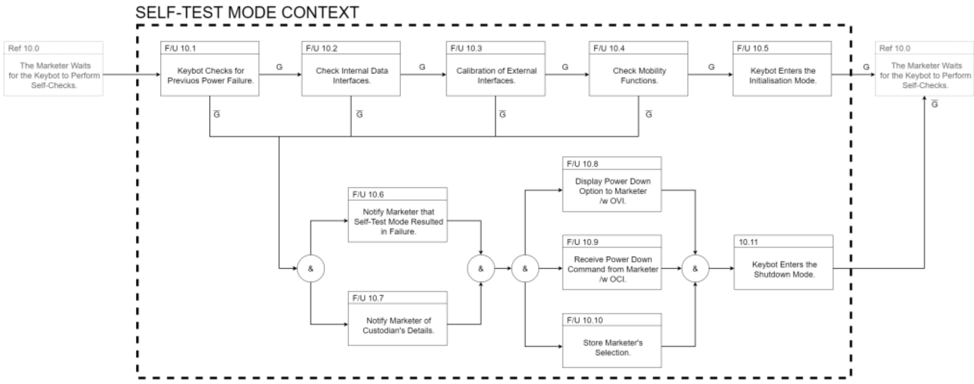


Figure 11: FFBD of the Self-Test Mode's Context

The Shutdown Mode Context (Figure 12) shows that the Keybot should be able to initialise the tools of the Keybot system, reset the position of the manufacturing mechanism and create a shutdown log to be used when the self-test procedure is executed. In the occasion that the self-test resulted in a failure, the Keybot will skip the initialisation and reset functions to not potentially harm the system.

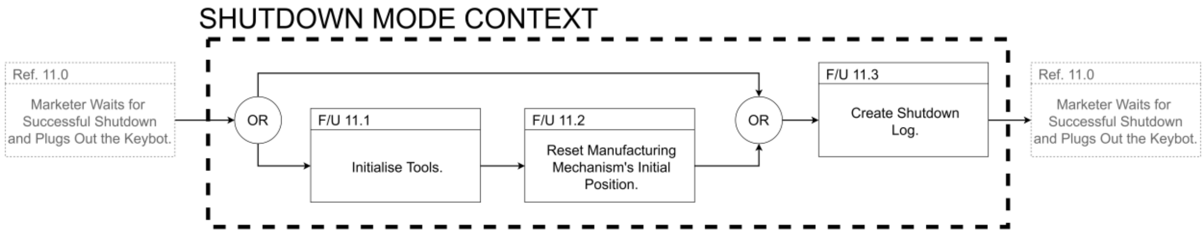


Figure 12: FFBD of the Shutdown Mode Context

The Initialisation Mode Context (Figure 13) illustrates that the Keybot system should be able to reinitialise the position of the manufacturing mechanism, sense whether the pickup tool or the engraving tool is installed and, thereafter, enter the command centre.

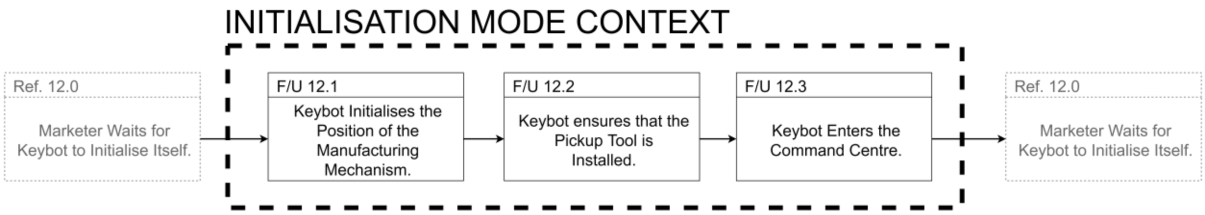


Figure 13: FFBD of the Initialisation Mode Context

The Idle Mode Context (Figure 14), shows that the Keybot system should be able to wait for further instructions at the neutral assembly point i.e. the Command Centre.

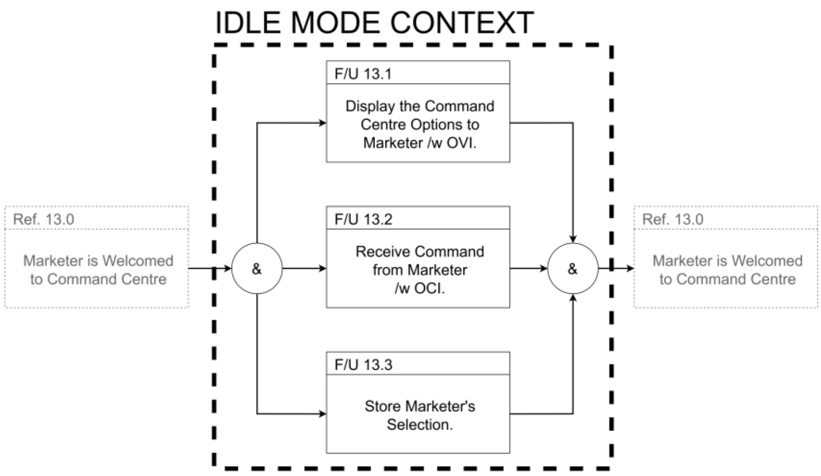


Figure 14: FFBD of the Idle Mode Context

The Demonstration Context (Figure 15) shows that the Keybot will allow for the formalities to occur between the marketer and the prospective students, provide the students with a means to command the Keybot to create an item, demonstrates the functionality of the Keybot to the student in a while-you-wait fashion, provide a means for the student to retrieve the engraved item from the dispensing station and for the whole process to repeat an indefinite amount of times.

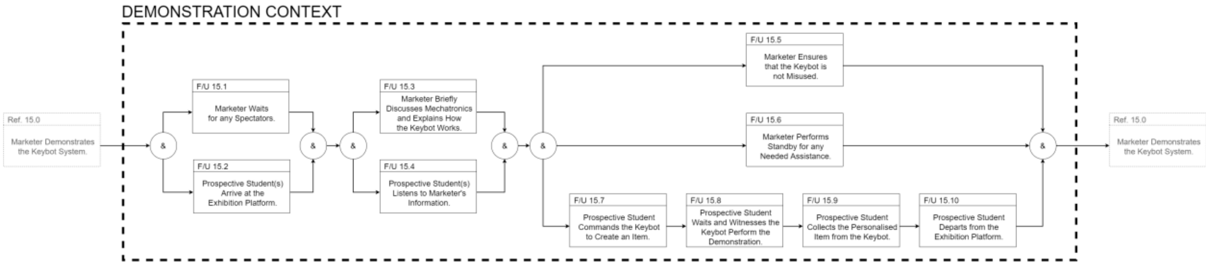


Figure 15: FFBD of the Demonstration Context

The Reload Mode Context (Figure 16) shows that the Keybot should be able to display options to the user, provide a means to receive orders and respond appropriately to these commands. These commands include the communication of the physical positions of the reloaded items, to create a new palette for a new type of item, delete the existing palettes in the system (database is required) and to return to the command centre.

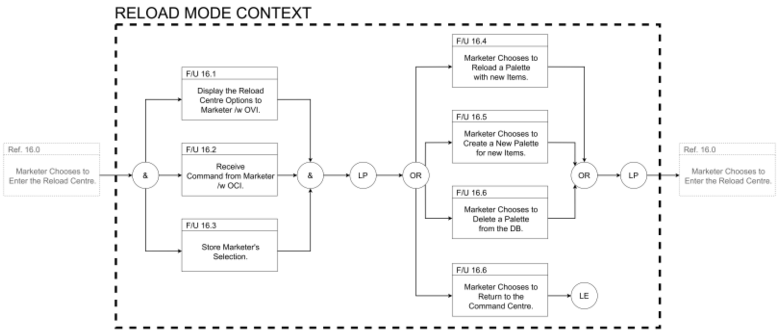


Figure 16: FFBD of the Reload Mode Context

3.2.2.3 Level 2

Level 2 analyses the contexts from level 1 in a deeper level, and therefore, identifies necessary components, interactions and functionality even further.

The Design Mode Context (Figure 17) shows that the Keybot should be able to receive commands to edit the design, to specify the item to be engraved and to start the engraving process.

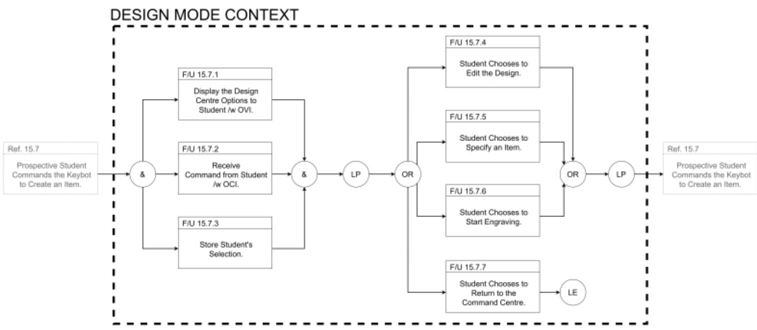


Figure 17: FFBD of the Design Mode Context

The Demonstration Context (Figure 18) shows that the Keybot must be able to manoeuvre the manufacturing mechanism between the loading-, manufacturing- and dispensing stations, interchange between the pickup tool and engraving tool, and lower, lift, activate and deactivate these tools. Furthermore, the Keybot should have a sense of the manufacturing mechanism's height relative to the items to be engraved. Also, the Keybot must be able to perform engraving commands of an indefinite amount and re-enter the initialisation mode.

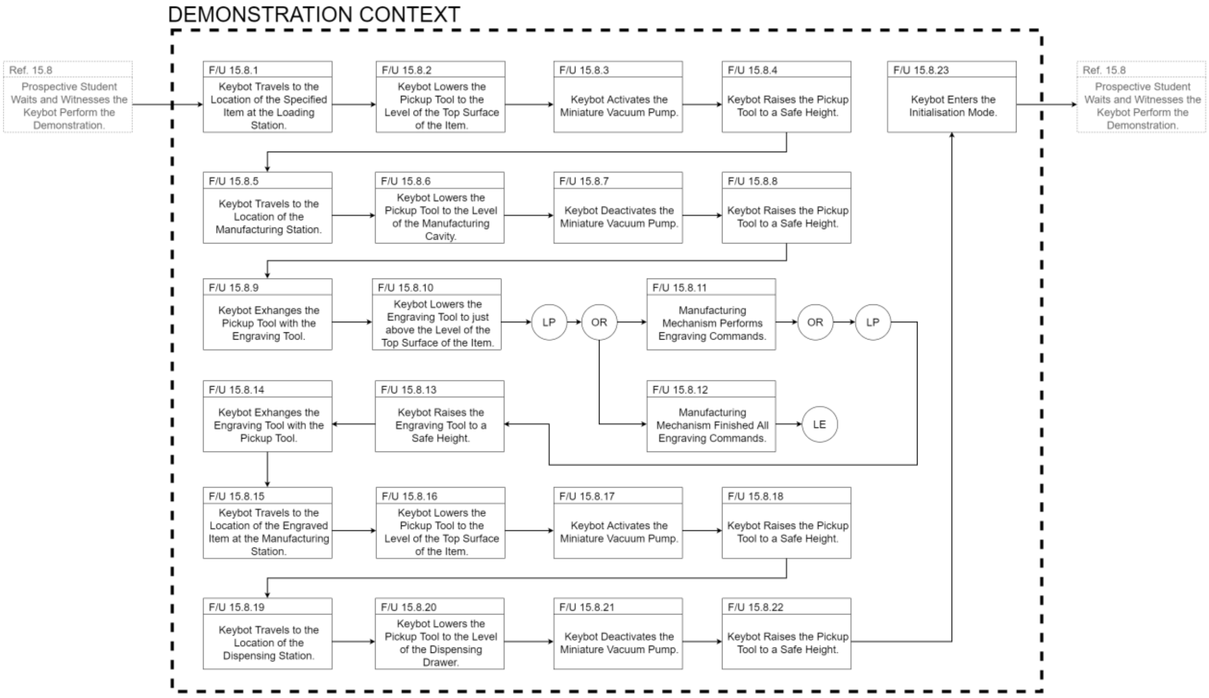


Figure 18: FFBD of the Physical Demonstration Context

The Item Reload Context (Figure 19) illustrates that the Keybot system must be able to display the appropriate reload options, provide a means to receive them and respond appropriately to these commands. These commands include to specify a different palette to be installed, occupied slots, download the palette layout plan's description, accept or abandon the changes made during the reload session and to return to the main reload centre.

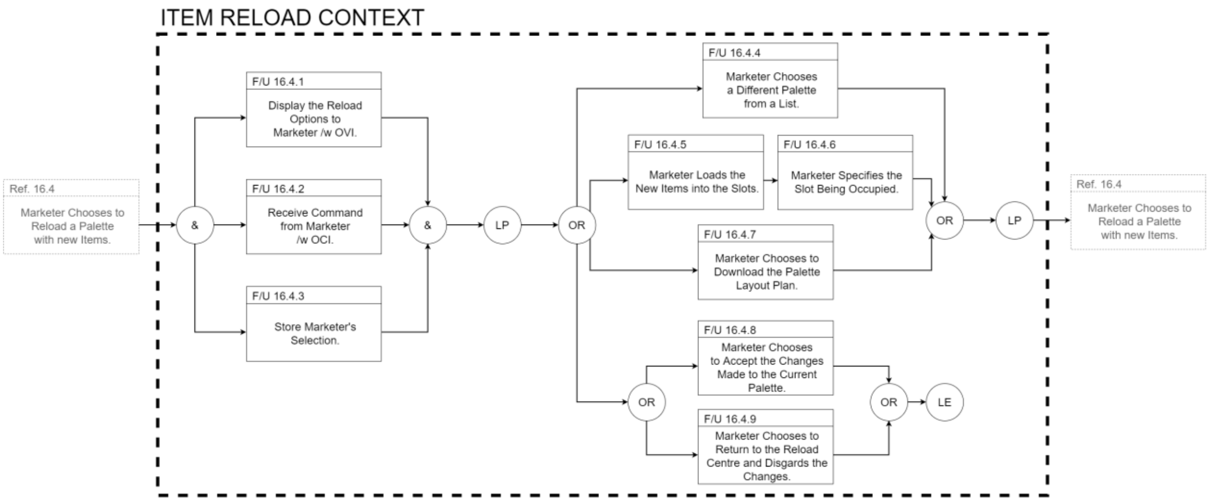


Figure 19: FFBD of the Item Reload Context

The Create New Palette Context (Figure 20) shows that in order for the user to create an new palette, a name for the palette, material, circumscribed radius from the item's centre of mass and the amount of items hostable on this palette. Also, further details regarding the circular engraving area's offset angle, offset length and engraving radius must be provided. Also, a means to download this palette layout plan for future physical construction thereof, must be provided.

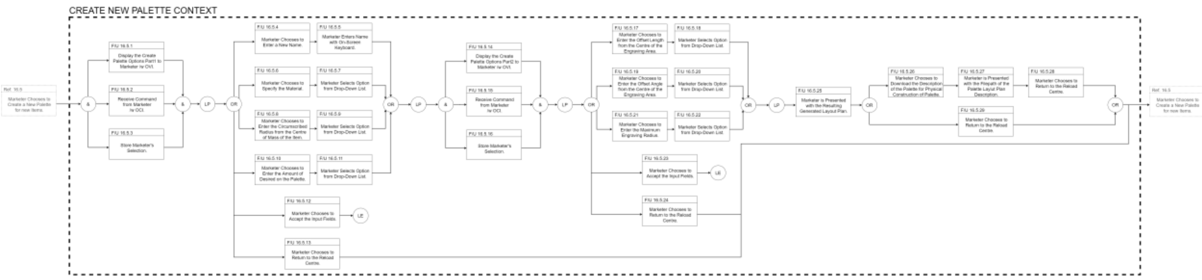


Figure 20: FFBD of the Create New Palette Context

The Delete Palette Context (Figure 21) shows that the Keybot must be able to display a list of all the existing palette designs to the user. It should also be able to provide a means to select and deselect these designs, as well to accept the changes or discard them.

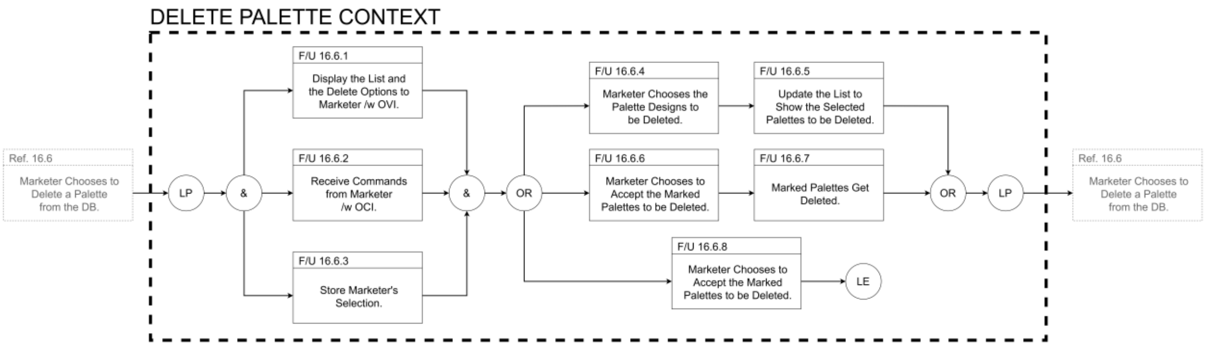


Figure 21: FFBD of the Delete Palette Context

3.2.2.4 Level 3

Since this FFBD can become quite large and the system becomes completely independent of the user after this level, level 3 will be the last level to feature in the FFBD.

The Physical Design Context (Figure 22) shows that the Keybot must provide the user with at least an on-screen keyboard for changing the design and to submit the new design.

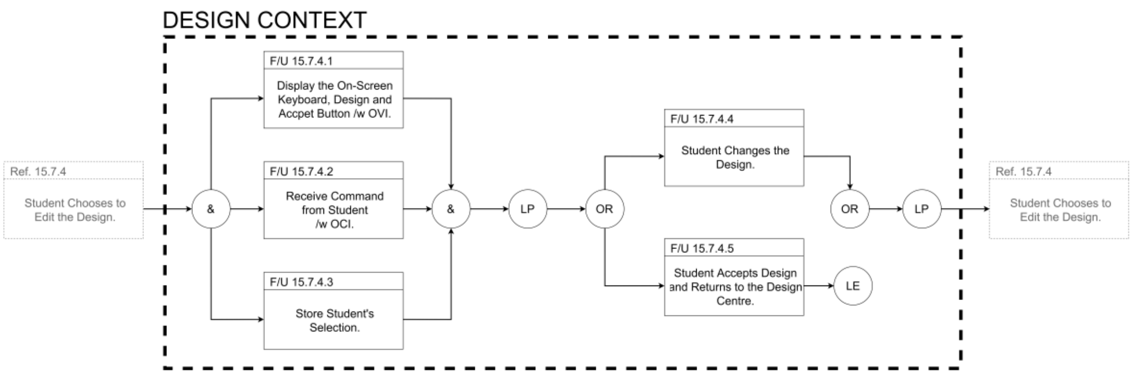


Figure 22: FFBD of the Physical Design Context

The Choose Item Context (Figure 23) shows that the Keybot must be able to provide the user with a means to specify which item loaded into the palette has to be used for the engraving demonstration.

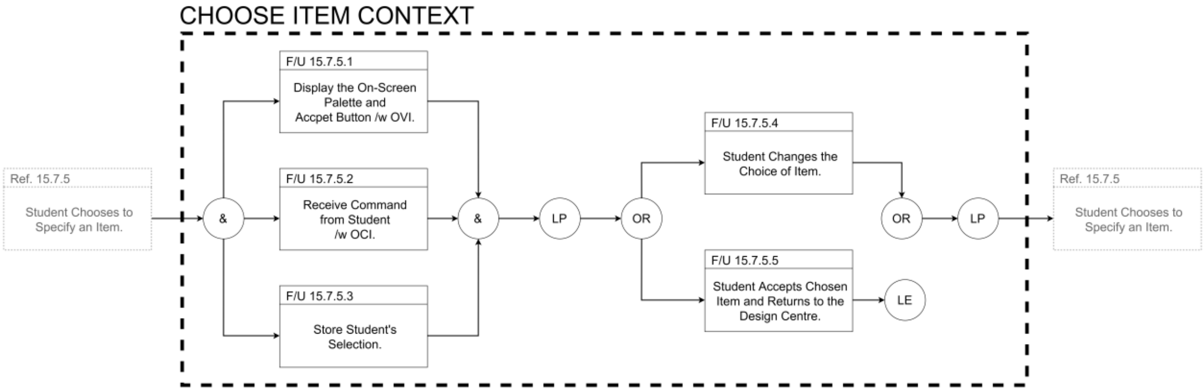


Figure 23: FFBD of the Choose Item Context

The Toolpath Planning Context (Figure 24) shows that the Keybot must be able to convert designs into a BMP file, perform signal theory on the pixels to find the shortest path, divide this path into machine executable movements and convert the movement's path segments into G-Code. Furthermore, an interface between the toolpath planning functional MCU to communicate with the G-Code interpreting unit must be accounted for, and the interpreter should be able to send the resulting signals to the drivers of the actuators.

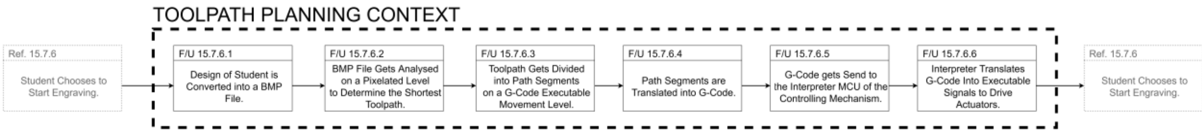


Figure 24: FFBD of the Toolpath Planning Context

Finally, the Engraving Commands Execution Context (Figure 25) shows that the Keybot must be able to consist of interfaceable drivers capable of generating microstepping sequences, which must be able to control the manufacturing mechanism. This control features include the lifting and lowering of the engraving tool with respect to the item and to switch the engraving tool on and off at the appropriate instances.

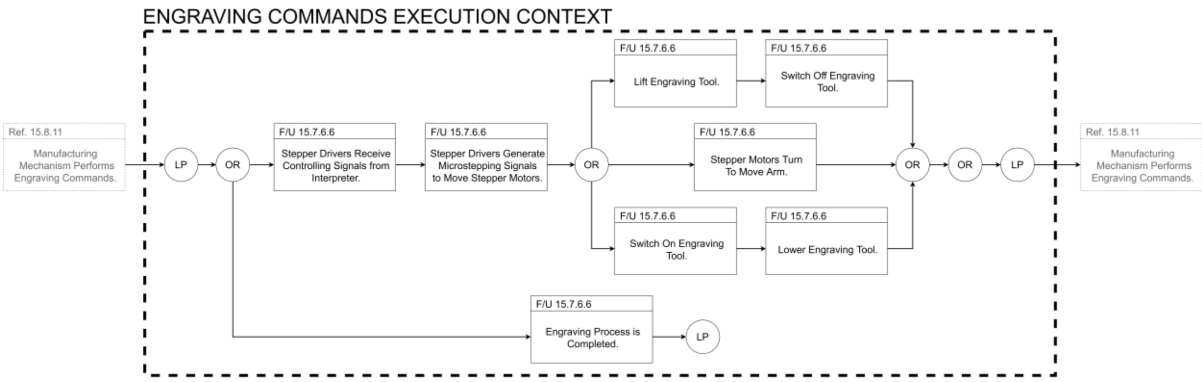


Figure 25: FFBD of the Engraving Commands Execution Context

3.2.3 Trade-offs

Since it is not always possible to achieve the desired performance of each aspect of a system, trade-offs need to be considered to achieve the best practical results. This is where decisions must be made to achieve a successfully integrated system at reasonable expenses.

3.2.3.1 Touchscreen Choice

The Keybot system requires an HMI to fulfil the duplex communication need between the Keybot system and the user. The HMI must be able to provide a lot of different options to the user and be able to receive the commands to execute these chosen options. The HMI should therefore be dynamic. This will improve the UX (user experience) of the system and provide a sense of familiarity to any user that interacts with touchscreens in their everyday life.

There are a few aspects to consider when choosing the correct touchscreen for the application. These include the data interfaces of the screen and touch overlay with the MPU (Micro Processing Unit), size of the screen, sensitivity of the touch overlay, durability of the cover, pixel density, multitouch capabilities and, of course, the price.

Research was done of all the touchscreen products available at the following South African online stores.

- Alexnld
- BotShop
- Cesdeals
- Digi-Key
- DIY Electronics
- Geeekpi
- Hashrate
- ImportItAll
- Manicaa
- Micro Robotics
- Pc Link Computers
- Pifactory
- PiHut
- PiShop
- RS-online
- Shiptu
- Ubuy SA
- WantItAll
- Waveshare

From these stores, over 90 products were considered, and the best option had to be identified.

It was already decided previously (see section 2.2 Human-Machine Interfaces) that a projected capacitive touchscreen will be the best option, since it is more sensitive to touch commands, has a durable overlay, better pixel clarity and can perform multitouch operations. Applying this criterion to the list of products, resulted in at least 24 options to remain. The products that were not specified as being capacitive touchscreens, were not considered.

Figure 26 illustrates a collection of all the possible sizes of the touchscreens available at these stores.

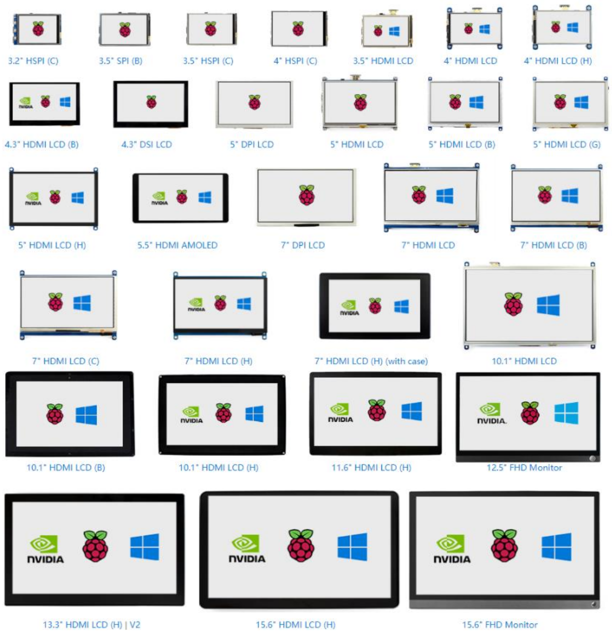


Figure 26: Collection of Possible Capacitive Touchscreens on the South African Market

Now, the interface type, size of the screen, pixel density and price will be considered in this trade-off to determine the best option of a projected capacitive touchscreen for the Keybot system.

The remaining products had a touch interface option of either an I2C, SPI or serial interface. The display component had HDMI, GPIO and DSI type of interfaces. Since all these interfaces are supported by a generic MPU, such as the Raspberry Pi, this does not limit the options. The preferred interface of the MPU to be spared will be the GPIO pins and either one of the SPI or I2C interfaces. Therefore, the HDMI port should be the preferred interface for the display and either of the three options for the touch overlay is acceptable. This reduced the touchscreen options to 19 products. Next, a price limit was introduced of R 1,000.00, which resulted in the options being reduced to 10 touchscreens.

Finally, the size and pixel density of the available displays were analysed to choose the option that will result in the best UX (see Table 6).

Table 6: Analysis of the Best View UX

Diagonal Touchscreen Size (inch)	Physical Dimensions (mm)	Pixel Grid Dimensions	Pixel Density (PPI)	Retina Distance (mm)	Orthogonal View Spread (Degrees)
4.0	87,9x51,0	480x320	144.2	610.0	9.5
4.0	87,9x51,0	800x480	233.2	380.0	15.0
4.3	94,5x54,8	800x480	217.0	410.0	14.9
5.0	109,9x63,7	800x480	186.6	460.0	15.4
5.5	120,8x70,1	1920x1080	400.5	230.0	31.3
7.0	153,8x89,2	800x480	133.3	660.0	15.1
7.0	153,8x89,2	1024x600	169.5	510.0	19.2
10.1	221,9x128,7	1024x600	117.5	740.0	19.1
10.1	221,9x128,7	1280x800	149.4	580.0	23.9

According to the online Retina calculator [20], the Retina of a pixelated presentation is the distance from which a human eye cannot distinguish between the pixels anymore. This will be used to calculate the orthogonal view spread of the corresponding touchscreen to indicate which options will enhance the UX the most. The shortest Retina length with a higher orthogonal view spread means that the person will not be less able to discriminate pixels from one another and that the person does not have to stand as close to the screen to perceive a good view of the screen. If this can be combined with a relatively large screen, more people will be able to view the screen at the same time, which improves the demonstration UX.

The orthogonal view spread is the angle denoted by Θ in Figure 27. It is important to note that the distance used to calculate this angle is the Retina distance and the equation for this angle is given by (1).

$$\Theta = 2 \times \tan^{-1}\left(\frac{DiagonalScreenSize}{2 \times RetinaDistance}\right) \quad (1)$$

It is clear from Table 6 that the 5.5-inch touchscreen with a pixel grid of 1920x1080 is the best option, followed by 10.1-inch touchscreen with 1280x800 display and in the third place, the 7-inch touchscreen with a 1024x600 display.

However, the 5.5-inch display is a very rare product and therefore, very expensive at R 2,215.11. The second option is also quite expensive (at R1999.95) and it does not have an HDMI interface. The third option is by far the best option when taking its price of R 660.78 into consideration. This product can be bought at PiShop.

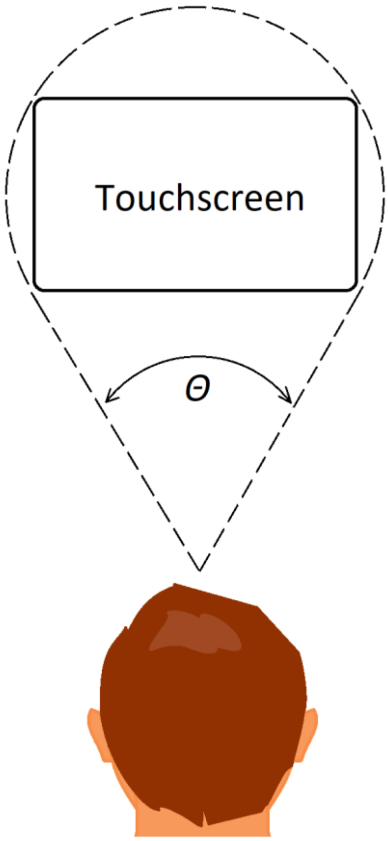


Figure 27: Illustration of the Orthogonal View Spread

3.2.3.2 Enclosures

Electrical enclosures must be chosen correctly for the best possible lifespan, safety and ease of transport for a system such as the Keybot. The inappropriate characteristics of the incorrect enclosure could lead to hazards, damage to internal components and even ergonomic issues. To design the appropriate electrical enclosure, one can consult the list of NEMA (National Electrical Manufacturers Association) specifications for electrical enclosures in Table 7 and Table 8. [21]

Table 7: NEMA Standard Enclosure Requirements

NEMA	Indoor	Outdoor	Protect Personnel Against Hazardous Parts	IP Solid Foreign Objects	IP Water Ingress	Protection External Formation of Ice	Additional Corrosion Protection	Knock-outs
1[2]	•		•	2	0	Damaged		
2[2]	•		•	2	2	Damaged		
3	•	•	•	5	5	Undamaged		
3R[2]	•	•	•	2	4	Undamaged		
3S	•	•	•	5	5	Simultaneously Operable		
3X[2]	•	•	•	5	5	Undamaged	•	
3RX	•	•	•	2	4	Undamaged	•	
3SX	•	•	•	5	5	Simultaneously Operable	•	
4	•	•	•	6	6	Undamaged		
4X	•	•	•	6	6	Undamaged	•	
5	•	•	•	5	3	Damaged		
6	•	•	•	6	7	Undamaged		
6P	•	•	•	6	8	Undamaged	•	
12	•		•	5	4	Damaged		
12K	•		•	5	4	Damaged		•
13[3]	•		•	5	4	Damaged		

Table 8: IP Standard Enclosure Requirements

IP Code	Foreign Body Intrusion Protection	Moisture Protection
0	None	None
1	Objects greater than 50 mm	Vertical dripping water
2	Objects greater than 12.5 mm	Vertical dripping water @ 15° incline
3	Objects greater than 2.5 mm	Vertical spraying water @ 60° incline
4	Objects greater than 1 mm	Splashing water from any direction
5	Dust protected (some dust allowed)	6.3 mm water jets from any direction
6	Dust tight	12.5 mm powerful water jets from any direction
7	N/A	Immersion up to 1 m
8	N/A	Immersion beyond 1 m

[2] May be ventilated enclosures.
[3] Protected against spraying, splashing and seepage of oil and non-corrosive coolants.

Since the system will be situated at different geographical locations and in crowded environments, one could assume that dust and inadvertent liquid spillage could be the most logically, radical type of concerns. Because the system will most probably still be operable if a small amount of dust enters the system, the system need not be dust tight, but dust protected. Also, splashes could occur from any direction and the system should therefore be splash protected. This means that the system must at least have an IP rating of IP54, however, since a higher IP rating means that the system will become more expensive and time consuming to make, this information limits the system to a NEMA 12, 12K or 13 type enclosure. Since the system will have knockouts (for wiring) and not need to be protected from oils and non-corrosive coolants, a NEMA 12K enclosure seems like the best solution.

3.2.3.3 Structure Material

The material used for the structure is an important consideration from durability, strength, passive system cooling, electromagnetic interference (EMI) protection, weight and more. Table 9 Shows some general properties of the most general material groups: ceramics, metals and polymers. Wood is not considered since it absorbs moisture easily. A high moisture content means that short-circuiting is more likely, which will cause the flammable material to combust and cause fire hazards.

Table 9: Qualitative Characterisation of Structure Materials

Properties	Ceramics	Metals	Polymers
Chemical Stability	High	Low	Low
Density	Low	High	Very Low
Elasticity	Low	Low	High
Electrical Conductivity	Low	High	Low
EMI Protection	Low	High	Low
Hardness	High	Low-High	Low-Medium
Heat Conductivity	Low	High	Low
Malleability	Low	High	Low
Melting Point	High	Low-High	Low
Strength	High	High	Low
Wear Resistance	High	Low	Low

From the table, it should be clear that a metal structure is the best option for the Keybot. Some main advantages of metal are EMI protection, electrical conductivity (for grounding purposes), heat conductivity (for cooling purposes), malleability (for easy construction), generally high melting point and strength. Disadvantages are low chemical stability and low wear resistance, which the metals can be treated for. Now, we look at some popular metal types for construction in Table 10. [22]

Table 10: Comparison of Aluminium and Stainless Steel

Property	Aluminium	Stainless Steel
Corrosion Resistance	Less	More
Cost	Less	More
Melting Point	Lower	Higher
Specific Heat Capacity ($\mathrm{J/kg \cdot K}$)	897	466
Strength	Lower	Higher
Strength to Weight Ratio	Higher	Lower
Thermal and Electrical Conductivity	More	Less
Welding	Harder	Easier
Workability	Easier	Harder

From Table 10, it should be clear that Aluminium is the best option for the Keybot. Some main advantages are lower cost, more electrical conductivity (better grounding, EMI protection and passive cooling), higher specific heat capacity (more heat energy is necessary to raise its temperature), much better strength to weight ratio (ergonomic for movers), more thermally conductive (better passive cooling) and it is easier to work with. The main downsides are more susceptible to corrosion (can be treated with powder coating), lower strength (can choose stronger aluminium grade) and a more difficult weldability (still possible and some grades are relatively easy to weld).

Now that we have chosen aluminium, the different grades are compared in Table 11. [23][24]

Table 11: Quantitative Comparison of Different Aluminium Grades

Material[4]	Base Metal Price (% Relative)	Modulus of Elasticity (GPa)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Corrosion Resistant	Impact Resistance	Machining	Weldability	Workability
Al 1100	9	69	28 – 150	86 – 170	5	1	4	5	5
Al 2011	11	71	140 – 310	310 – 420	1	5	5	1	4
Al 2024	11	71	100 – 490	200 – 540	1	5	2	1	4
Al 3003	9.5	70	40 – 210	110 – 240	4	3	4	5	5
Al 5052	9.5	68	75 – 280	190 – 320	5	4	2	4	4
Al 6061	9.5	69	76 – 370	130 – 410	5	4	4	4	4
Al 6063	9.5	68	49 – 270	110 – 300	4	3	2	4	4
Al 7075	10	70	120 – 510	240 – 590	3	5	2	1	1

Since 1100 has a too low impact resistance, 2011 and 2024 have a too low corrosion resistance and weldability and 7075 a too low weldability and workability, they will not be considered further.

Considering the rest of the table, 5052 and 6061 has better corrosion resistance, yield and ultimate strengths and impact resistance, they should be considered better options than 3003 and 6063. 5052 is harder to machine, since the alloy chips during machining due to its bendability (5052-H32 is a more machinable solution for the 5052 series, is the most easily weldable Aluminium and is very common). 6061 is a bit more brittle when being bent and extra care should be taken to form the bends (use bigger inside radii, multiple bends, or thicker sheets). It should be noted that 6061 is more conductive than 5052 and they both have the same specific heat capacity. Also, if annealed, the strength of 5052 surpasses 6061. Therefore, both 5052 and 6061 present their own advantages and challenges (with 5052-H32 being more preferred), therefore, the one with the better price should be the final option.

[4] 1 – Poor 2 – Fair 3 – Average 4 – Good 5 – Excellent

3.2.3.4 Maximising Stepper Motor Torque of Unlevelled System

If the torque generated by the motors (T_m) is not enough to overcome the torque (T_F) generated by the gravitational force (F) by a factor enough to overcome other effects such as frictional force and motor- or system inertia, the system will not be able to perform as expected. Outcomes could be a system incapable of moving, excelling faster in one direction (could skip steps) or a system excelling slower and therefore, mis steps (this is also known as slipping).

To prevent the manufacturing mechanism from carrying an unnecessary load, due to a gravitational component, the system needs to be properly levelled. This will minimise the torque needed to move the manipulator's arms, enabling it to carry heavier loads and to exert more force on items when engraving without damaging the system or tainting its performance by losing steps.

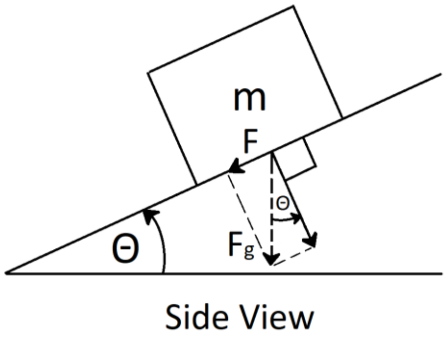


Figure 28: Illustration of Unnecessary Load of an Unlevelled System

$$F_g = ma \tag{2}$$

$$F = F_g \sin(\Theta) \tag{3}$$

$$T_{Fmax} = F_m(a + b) \tag{4}$$

To calculate the torque generated by the unlevelled load, equation (2) and (3) can be used to determine the tilted force and should then be used together with (4) to calculate the load torque, where a and b are the respectable lengths of the first and second arms of the SCARA robot.

It should be clear that to minimise this inertia, the angle should be as small as possible. Adjustable feet can be used to level the system by rotating the foot while the threaded shaft is held in place by, for instance, nuts, which will lift or lower the respective corner of the system, resulting in better stepper motor performance.

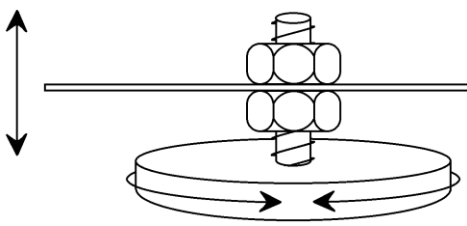


Figure 29: Demonstrating the Essential Physics of Adjustable Feet

3.2.3.5 Stepper Motor Choice

Some research was done on all the stepper motors available at the following South African stores.

- 3D Printing Store
- BotShop
- Communica
- Da Vinci Lab
- Digi-Key Electronics
- DIY Electronics
- DIY-Geek
- Hobbytronics
- Mantech
- Micro Robotics
- Mouser Electronics
- Neotronics SA
- Netram Technologies
- PiShop
- RS Components
- RSE Electronics
- Ubuy SA
- UniHobbies
- WantItAll

The first characteristic noted, was that the stepper motors are either closed or open loop systems. It was, however, very clear that a closed loop stepper motor cost more than double the amount of an open loop one. The same was observed for stepper motors with a gearbox attached. This seemed unnecessary, seeing as that a stepper motor could still be very accurate if all the necessary resonance, load torque and speed of the motors are carefully considered. Next, the NEMA rating (size) of the motor was considered. The most common sizes are NEMA 6, 8, 11, 14, 16, 17, 23, 24, 34, 42 and 52.

To determine the size of the motor in millimetres from the NEMA rating, multiply the NEMA rating by approximately 0.4. The physical constraint kept in mind to choose the proper motor size, was the weight of the motor, which should be installed in the second arm of the SCARA robot. The plan was to install two or three of these motors in the second arm and therefore, the weight should be kept at a minimum to not load the arm unnecessarily, as well as the current that will be drawn by the larger motors will cause the system to heat up unnecessarily. Therefore, a NEMA rating above 24 (60 x 60 mm ranging at 0.5 to 1.5 kg) was not considered. This resulted in a total of 41 stepper motors found with NEMA sizes discriminated in Table 12.

Table 12: List of the Amount of NEMA Stepper Motor Sizes Found

Size	NEMA 8	NEMA 11	NEMA 14	NEMA 16	NEMA 17	NEMA 23
Amount	1	1	1	1	25	12

The motors had step angles of either 0.9 or 1.8 ° and prices ranging from R 139.90 to R 1030.00 per motor. All the motors were bipolar stepper motors and had current ratings per phase from 0.4 to 4 A.

Next, the cost per holding torque was calculated and motors with a cost per holding torque of more than R 700.00 /Nm was excluded. Also, a further cut of motors with holding torque below 0.4 Nm was applied. The result remaining can be seen in Table 13.

Table 13: NEMA Stepper Motor Sizes Remaining After Cost per Torque and Holding Torque Cuts

Size	NEMA 17 (1.8°/step)	NEMA 17 (0.9°/step)	NEMA 23
Amount	5	3	4

Next, the percentage deviation of the remaining motor's holding Torque, Current and R/Nm were calculated for further decision making of which motor to choose. Thereafter, the percentages were normalised, and the result can be seen in Table 14. Keep in mind that the closer the values are to zero, the better the option (torque was already inverted).

Table 14: Normalised Percentage Deviation of Torque, Current and R/Nm with Respect to Size

Size	Product Link	Torque Deviation Percentage	Current Deviation Percentage	R/Nm Deviation Percentage
NEMA 17 (1.8°/step)	DIY ELECTRONICS	0.00	0.00	16.39
	PiShop	37.50	74.14	0.00
	DIY ELECTRONICS	37.50	56.90	58.98
	DIY ELECTRONICS	48.38	100.00	88.21
	Da Vinci Lab	100.00	31.03	100.00
NEMA 17 (0.9°/step)	MicroRobotics	0.00	2.78	0.00
	Hobbytronics	19.13	100.00	46.49
	DIY ELECTRONICS	100.00	0.00	100.00
NEMA 23	DIY ELECTRONICS	0.00	100.00	0.00
	DIY ELECTRONICS	65.30	80.00	43.40
	DIY ELECTRONICS	100.00	0.00	91.12
	Hobbytronics	98.29	0.00	100.00

This resulted in Table 15 with the following rankings with respect to the motor size and step angle.

Table 15: Score and Ranking Results of Stepper Motors

Size	Product Link	Normalised Score out of 10	Ranking of Stepper Motor
NEMA 17 (1.8°/step)	DIY ELECTRONICS	10.0	1
	PiShop	5.7	2
	DIY ELECTRONICS	3.8	3
	Da Vinci Lab	0.3	4
	DIY ELECTRONICS	0.0	5
NEMA 17 (0.9°/step)	MicroRobotics	10.0	1
	Hobbytronics	1.7	2
	DIY ELECTRONICS	0.0	3
NEMA 23	DIY ELECTRONICS	10.0	1
	DIY ELECTRONICS	1.0	2
	DIY ELECTRONICS	0.7	3
	Hobbytronics	0.0	4

It should be noted that this is a highly normalised result and that any of these motors are actually very good solutions to the Keybot system. However, only one option can be chosen and taking weight and cost into consideration the following options are proposed (see Table 16).

Table 16: Stepper Motor Product Details of Chosen Options

Rank	Product Link	Cost	Size	Holding Torque (Nm)	Step Angle (°)	Current per Phase (A)
1	DIY ELECTRONICS	R 170.00	17	0.48	1.8	0.85
2	PiShop	R 139.90	17	0.45	1.8	1.7
3	DIY ELECTRONICS	R 210.00	17	0.45	1.8	1.5
4	Da Vinci Lab	R 230.00	17	0.40	1.8	1.2
5	DIY ELECTRONICS	R 240.00	17	0.44	1.8	2.0

These stepper motors should be kept in mind further down the line, as it is not clear what size gearbox and stepper drivers should be used, yet.

3.2.3.6 Choosing the Planetary Gearbox Ratios

Since the Keybot system requires relatively good accuracy and torque, a few techniques need to be considered to provide these characteristics. A gearbox is one of the ways to simultaneously improve both characteristics.

A planetary gearbox is a special kind of gearbox that assures that the input and output shafts are concentrically aligned, while occupying a relatively small amount of space. As can be seen in the figure, the gearbox exists of three types of gears. These gears are called the planet gears, sun gear and annular (or ring) gear (see Figure 30). The sun gear is normally connected to one of the shafts and the combination of the planet gears is normally connected to the other shaft with a carrier. The annular gear can be fixed while the sun gear rotates or vice versa. These gearboxes are widely used in transmission systems and can also be stacked to achieve greater gear ratios.

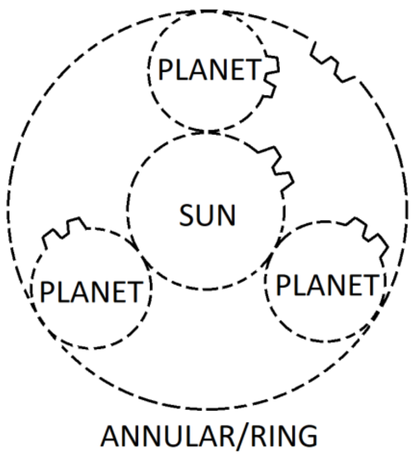


Figure 30: Basic Illustration of a Single Planetary Gearbox

To design a planetary gearbox, equation (5) is used to calculate the ratio (i), number of teeth (z), or gear sizes (d – pitch circle diameter or r – pitch circle radius).

$$i = 1 + \frac{d_{Ring}}{d_{Sun}} = 1 + \frac{r_{Ring}}{r_{Sun}} = 1 + \frac{z_{Ring}}{z_{Sun}} \tag{5}$$

The module (m) is an important factor, which must be the same for all the gears that meshes with one other. The module is calculated using equation (6).

$$m = \frac{d}{z} \tag{6}$$

To ensure that the profiles of the gears do not interfere with each other, equation (7) can be used, where Ø is the pressure angle, which normally equals to 20° to minimise vibrations and noise.

$$z_1 \geq \frac{2h_a \frac{1}{z_2} m}{\sqrt{1 + \frac{1}{z_2}\left(\frac{1}{z_2} + 2\right)\sin^2 \emptyset} - 1} \tag{7}$$

Designing gear profiles is a science in and of its own but can be greatly simplified with the help of profile calculators and involved curves. These calculators can be found on websites such as www.otvinta.com. Here, you only need to provide some basic requirements for your gears, such as the number of teeth, module, pressure angle and phase shift. The result is two equations that describes the involved curve of the gear teeth profile and are provided in the following form (se equations (8) and (9)). Here, d_b is the base diameter of the gear.

$$x(u) = d_b(\cos u + u \sin u) \tag{8}$$

$$y(u) = d_b(\sin u - u \cos u) \tag{9}$$

The online calculator also provides the tooth thickness at the base in degrees, as well as the centre distance in the case of an internal and external gear setup. One can also provide a factor that is called the phase shift, which is used to correct the curve in a way as to increase or decrease the tooth thickness for optimal gear meshing and to avoid interference of the teeth.

All these generated equations and parameters can then be used in a CAD package of one's choice (such as NX12) to construct the gears to be exported as STL files for additive manufacturing later.

Since the 3D printed gears are subjected to wear, minimum friction is desired. There are a few ways to achieve this, such as to simply choose a more wear resistive material, add lubrication, smart mechanical support structures etc. Another thing to keep in mind is the deformation of the material when exposed to high temperatures, as will be the case when the system is transported on warm journeys to other demonstration events.

All these problematic factors have led to two important design choices.

- Use Polyamide (Nylon) filament when 3D printing the gears.
- Use a Herringbone teeth pattern.

Nylon filament is relatively more wear resistant, flexible and has a higher melting temperature than other filaments. The Herringbone pattern will hold the planet gears in place with minimal contact to external mechanisms, decreasing the amount of friction that the gears are exposed to (see Figure 31).

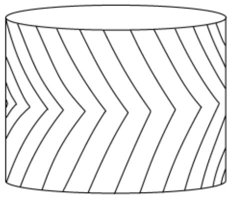


Figure 31: Gear Profile of a Herringbone Pattern

Now, the five options for the stepper motor will be used to calculate the gear ratio of the gearbox required to move a 3 kg load with the fully stretched out arm length of 470 mm at an uneven angle of 5 °. To do this, first we need to calculate the maximum speed achievable by the stepper motor due to it being an inductive load.

$$MinimumTime/Step_{ms} = \frac{2H_{mH}I_{rated}}{V_{rated}} \tag{10}$$

$$Speed_{max} = \frac{1000}{MinimumTime/Step_{ms} \times Steps/Rev} \tag{11}$$

$Speed_{max}$ is measured in revolutions per second and can be slower due to mechanical inertia and other mechanical characteristics. However, the stepper motor is going to be connected to a stepper driver, which will apply a higher voltage to the phases of the stepper motor than its rated voltage. Doing this with a duty cycle of 100 % will cause more current than the rated current per phase to pass through the coils and cause permanent damage to the motor. However, using a driver capable of current chopping, will limit the current passing through the coils by means of PWM, which will protect the motor from overcurrent. This allows the motor's electrical time constant to decrease while the torque of the motor is preserved. Therefore, the stepper motor will be capable of higher speeds at relatively the same torque, with no damage done to the stepper motor.

Therefore, the $Speed_{max}$ is just an indication of the ballpark of the actual maximum speed of the motor and can be made much higher than these calculated values (see Table 17), if necessary.

Table 17: Calculated $Speed_{max}$ of each Stepper Motor Option

Motor Option	1	2	3	4	5
Holding Torque (Nm)	0.48	0.45	0.45	0.44	0.4
Rated Voltage (V)	3.6	4.08	2.9	2.2	2
Rated Current (A)	0.84	1.7	1.5	2	1.2
Inductance (mH)	8	3.7	4.4	2.6	4.5
Steps/Rev	200	200	200	200	200
Min Time (ms)	3.73	3.08	4.55	4.73	5.40
Max Speed (Rev/s)	1.34	1.62	1.10	1.06	0.93

Next, equations (2) to (4) is used to calculate the load torque caused by an unlevelled system. This tilted load torque value of 1.21 Nm (see Table 18) must be compensated for by the holding torque of the stepper motor and gearbox ratios, for the system to not lose steps and become inaccurate. Note that the tilted load torque is being over engineer for to overcome additional inertias.

Table 18: Results from Calculating the Tilted Load Toque that must be Compensated for

Characteristic Description	Value
Load Mass (kg)	3.00
Mass to Weight (N/kg)	9.81
Weight (N)	29.42
Arm Length (m)	0.47
Torque (Nm)	13.83
Max Angle (°)	5.00
Tilted Load Torque (Nm)	1.21

The theoretical equation for determining the required gear ratio is given by equation (12).

$$GearRatio \geq \frac{TiltedLoadTorque}{MotorIncrementalTorque} \tag{12}$$

The $MotorIncrementalTorque$ is the practical torque exercisable by the stepper motor while stepping from one position to the next. This characteristic drastically decreases with an increase in microstepping order. However, microstepping is an essential technique that must be used to reduce the resonance and noise of the stepper motor, while improving the resolution of the stepper motor. This will ensure that the stepper motor can be used to engrave fine resolution designs without the noise and missed steps. It should be noted that microstepping does not influence the accuracy of the system, only the resolution. Therefore, a trade-off should be made between the total mass the system can handle as a load, the top speed and the resolution of the system. Depending on the tolerance of the gearbox, the accuracy of the stepper motor and gearbox system can be improved. The $MotorIncrementalTorque$ of each motor can be calculated using equation (13).

$$MotorIncrementalTorque = MotorHoldingTorque \times IncrementalTorquePercentage \tag{13}$$

The $IncrementalTorquePercentage$ is dependant on the order of microstepping used and can be viewed in Table 19.

Table 19: Effects of Microstepping Order on the Incremental Torque of the Stepper Motor

Microstepping Order	$\boldsymbol{IncrementalTorquePercentage}$ (%)
1	100.00
2	70.71
4	38.27
8	19.51
16	9.80
32	4.91
64	2.45
128	1.23
256	0.61

Now, the required torque can be calculated with respect to the corresponding incremental torque effects due to the choice in microstepping. These required torque values can then be used to calculate the required gear ratio to overcome this tilted load torque. Also, since a resolution of 0.5 mm at the full extended arm length of 470 mm is desired, equation can be used to calculate the required gear ratio to achieve the desired resolution, given the microstepping order and stepper motor $StepAngle_{Deg} = 1.8°$.

(14)

$$RequiredGearRatio = \frac{StepAngle_{Deg} \times TotalArmLength_{mm} \times \pi}{MicrosteppingOrder \times DesiredResolution_{mm} \times 180°}$$

The required gear ratio to overcome the load torque can be anything higher than the values calculated in Table 20, and should at least be higher than the required gear ratio for the required resolution. These acceptable gear ratios are highlighted in Table 20.

Table 20: Calculated Gear Ratios to Adhere to the Load Torque and Resolution Requirements

Motor Option			1	2	3	4	5
Micro-stepping Order	**Required Torque (Nm)**	**Required Gear Ratio for Resolution (1:GR)**	**Required Gear Ratio to Overcome the Load Torque (1:GR)**				
1	1.21	29.5310	2.51	2.68	2.68	2.74	3.01
2	1.70	14.7655	3.55	3.79	3.79	3.87	4.26
4	3.15	7.3827	6.56	7.00	7.00	7.16	7.87
8	6.18	3.6914	12.87	13.73	13.73	14.04	15.44
16	12.30	1.8457	25.62	27.33	27.33	27.95	30.74
32	24.55	0.9228	51.14	54.55	54.55	55.78	61.36
64	49.19	0.4614	102.48	109.31	109.31	111.80	122.98
128	97.98	0.2307	204.13	217.74	217.74	222.69	244.95
256	197.57	0.1154	411.60	439.04	439.04	449.02	493.93

From Table 20, it is observable that microstepping the stepper motors below an order of 8 will cause the system not to meet the requirements and any order higher than this will improve the resolution and torque capabilities of the system. However, the higher the gear ratio of the system, the smaller the diameter of the sun gear will become and cause the gearbox parts to become too petite and therefore, fragile. Also, the higher the gear ratio, the slower the system will become for the same computational frequency. Also, increasing the stepping order will increase computational overhead even more. To choose a sensible gear ratio from these proposed ratios, the resulting speed of the system and size of the sun gear should be considered.

The required speed of the system (according to Appendix A: The Systems Requirements Document) is 100 mm/s along the arc of the full extent of the arm of the SCARA robot. Therefore, the required degrees per second of the system can be calculated using equation (15) .

(15)

$$DesiredSpeed_{Degrees/s} = \frac{DesiredSpeed_{mm/s} \times 180°}{TotalArmLength_{mm} \times \pi}$$

This is calculated to be 12.1906 °/s that the stepper motor and gearbox system should be able to turn to achieve the desired speed. The theoretical maximum speed of the system, given the choice in gearbox ratio and maximum speed (in revolutions per second) of the setup, can be calculated using equation (16).

$$MaximumSpeed_{Degrees/s} = \frac{MaximumSpeed_{Revolutions/s} \times 360°}{GearRatio} \tag{16}$$

The result is Table 21, indicating the limits for choosing the gear ratio of the gearbox given that the gearbox ratio corresponds to the ratios calculated previously with respect to the order of microstepping and motor option. The microstepping, gear ratio and motor option combinations, adhering to the required speed of the system, is once again highlighted in the table.

Table 21: Corresponding Maximum Speed of the Stepper Motor and Gearbox Ratios

Motor Option	**1**	**2**	**3**	**4**	**5**
Micro-stepping Order	**Maximum Speed of Stepper Motor and Gearbox System (°/s)**				
1	192.03	217.98	147.66	139.02	110.63
2	135.78	154.13	104.41	98.30	78.23
4	73.49	83.42	56.51	53.20	42.34
8	37.46	42.53	28.81	27.12	21.58
16	18.82	21.36	14.47	13.62	10.84
32	9.43	10.70	7.25	6.83	5.43
64	4.70	5.34	3.62	3.41	2.71
128	2.36	2.68	1.82	1.71	1.36
256	1.17	1.33	0.90	0.85	0.67

These results show that if a microstepping order of 8 or 16 is to be implemented, the system can meet the load torque, speed and resolution requirements for any of the stepper motor options (with the exception of option 5 only meeting said requirements for an order of 8). Also, that said requirements will theoretically meet if the gear ratio is chosen to be between 12.87 and 27.95 for an order of 8, or if the gear ratio is chosen to be between 25.62 and 27.95 for a microstepping order of 16.

Finally, the gear ratio can be chosen as to maximise the durability of the gears of the gearbox. This can be achieved by choosing the ratio resulting in the maximum size of planet and ring gear diameters. Since the maximum diameter of the annular or ring gear is 36 mm (larger diameter causes the gearbox to become larger than the face of the stepper motor), the desired diameter for the sun and planet gears should be a third of this, which is 12 mm. According to equation (5), this means that the gear ratio should be as close to 4 as possible. However, the design does not allow for this to be plausible and therefore, the planetary gearbox should become a stacked one. This means that gearbox ratios of 4, 16, 64 and so forth becomes possible. Looking at the available ranges, this means that a gear ratio of 16 (two stacked planetary gearboxes of 4 each), is the acceptable optimised solution. This will lead to all the system requirements to still meet and cause the microstepping order of 8 to be the only valuable option.

Therefore, it can be concluded that if a stacked planetary gearbox with gear ratio of 16 is implemented, the gearbox will have an optimised durability (regarding gear sizes) and the system will theoretically achieve the following requirements for the five stepper motor options, given that the microstepping order is equal to 8 (see Table 22).

Table 22: Calculated Theoretically Achieved Requirements of each Stepper Motor Option for a Gear Ratio of 16 and Microstepping Order of 8

Requirement Description	Stepper Motor Option				
	1	2	3	4	5
Expected Mass of Load Handleable (kg)	3.7298	3.4967	3.4967	3.4190	3.1082
Expected Top Speed Achievable (°/s)	30.1339	36.4865	24.7159	23.7981	20.8333
Expected Resolution Achievable (mm)	0.1154	0.1154	0.1154	0.1154	0.1154

Table 22 shows that the expected handleable mass of all the options surpasses the requirement of 3 kg at 5° and that they follow the same order as that of the technical rank from Table 16. It also shows that the expected max speed of the system for any option is also faster than the 12.1906 °/s required with option 2 taking the lead. Also, they all have the same expected resolution of 0.1154 mm at the fully extended arm length of 470 mm, which should have been anything less than 1.5 mm. This means that if a stepper motor driver exists that can handle a continuous current of 2.0 A/phase, the preferred options should still follow the rank (numbers) of the options.

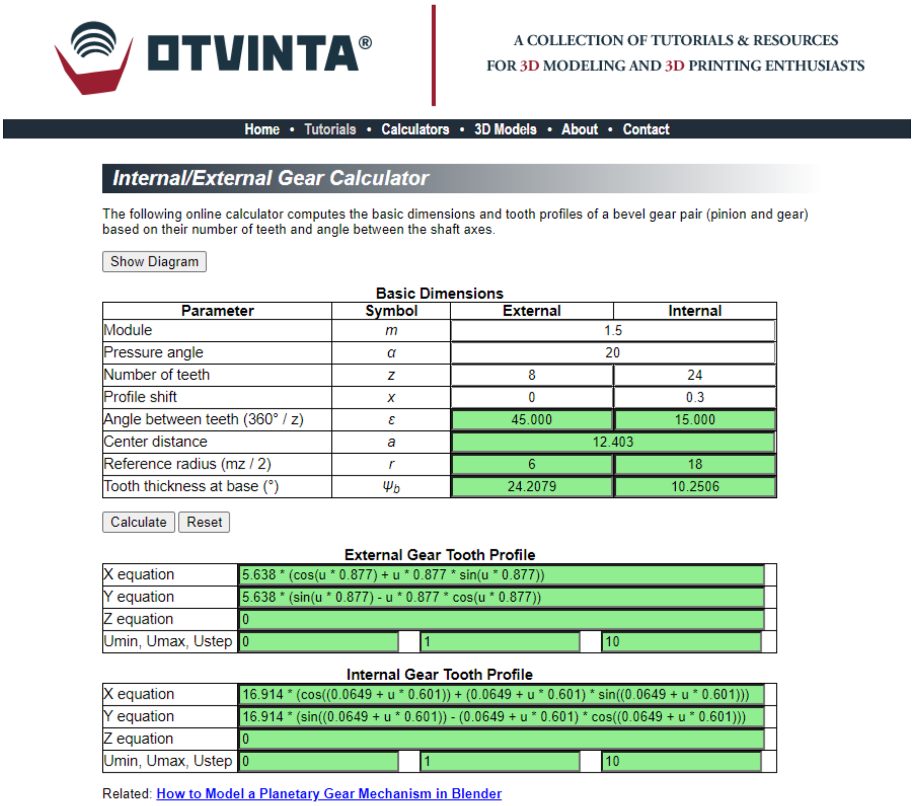
3.2.3.7 Designing the Planetary Gearbox

As mentioned before, www.otvinta.com is a website that hosts an online calculator for determining the gear profile required in the form of involve equations given by equations (8) and (9). In the calculator tab on the left-hand side, the "Internal/External Gear Calculator" can be used to calculate the involve curves for the gear profiles of the annular and planet gears. The calculator requires the desired module, pressure angle, and the number of teeth and profile shifts for both the annular and planet gears. The module can be calculated using equation (6), given that the diameter and number of teeth are provided.

The number of teeth should preferably be a factor of the number of expected planetary gears, so that the load is spread between all the planetary gears at any given time. A factor of half the amount of expected planetary gears will also spread the load evenly, given that the amount of planetary gears is even.

Furthermore, the Herringbone pattern ensures that every planetary gear handles the same amount of load. Given that the annular ring has a diameter of 36 mm and the planetary and sun gears to have a diameter of 12 mm (planetary gear ratio of 4), the maximum amount of planetary gears expected to fit in between the sun and annular gears, without interfering with each other, are 4 gears. Therefore, teeth possibilities of 4, 6, 8, 10, 12 etc. are preferred. After some iterations, it was clear that 10 teeth were too many for the size of the gears and that 8 teeth should be used. As mentioned previously, a pressure angle of 20° causes minimal noise and vibrations.

The online calculator was populated as can be seen below in Figure 32. The calculator warns the user when interference is expected, which indicates that the phase shift of the internal gear (annular gear) should be increased. First, the annular phase shift of 0.3 was introduced, and the involve curves for the annular and planetary gears were generated. Using these equations together with a CAD software package such as NX12 enables the designer to study the profiles to see if the gears still interfere.



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Internal/External Gear Calculator

The following online calculator computes the basic dimensions and tooth profiles of a bevel gear pair (pinion and gear) based on their number of teeth and angle between the shaft axes.

Show Diagram

Basic Dimensions

Parameter	Symbol	External	Internal
Module	m	1.5	
Pressure angle	α	20	
Number of teeth	z	8	24
Profile shift	x	0	0.3
Angle between teeth (360° / z)	ε	45.000	15.000
Center distance	a	12.403	
Reference radius (mz / 2)	r	6	18
Tooth thickness at base (°)	ψ_b	24.2079	10.2506

Calculate Reset

External Gear Tooth Profile

X equation	5.638 * (cos(u * 0.877) + u * 0.877 * sin(u * 0.877))		
Y equation	5.638 * (sin(u * 0.877) - u * 0.877 * cos(u * 0.877))		
Z equation	0		
Umin, Umax, Ustep	0	1	10

Internal Gear Tooth Profile

X equation	16.914 * (cos((0.0649 + u * 0.601)) + (0.0649 + u * 0.601) * sin((0.0649 + u * 0.601)))		
Y equation	16.914 * (sin((0.0649 + u * 0.601)) - (0.0649 + u * 0.601) * cos((0.0649 + u * 0.601)))		
Z equation	0		
Umin, Umax, Ustep	0	1	10

Related: How to Model a Planetary Gear Mechanism in Blender

Figure 32: Populated Parameters for Internal Profile shift of 0.3

This resulted in the gaps of the planetary gear to still interfere with the annular gear (see Figure 33).

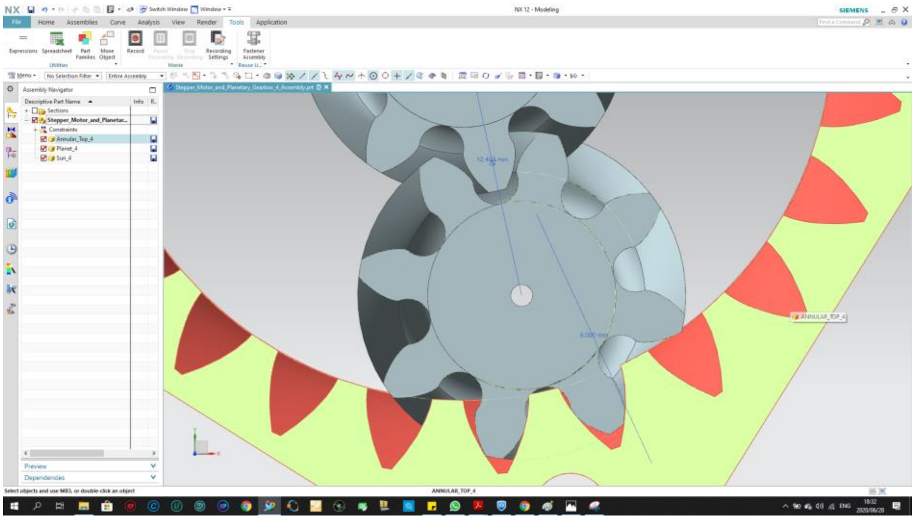
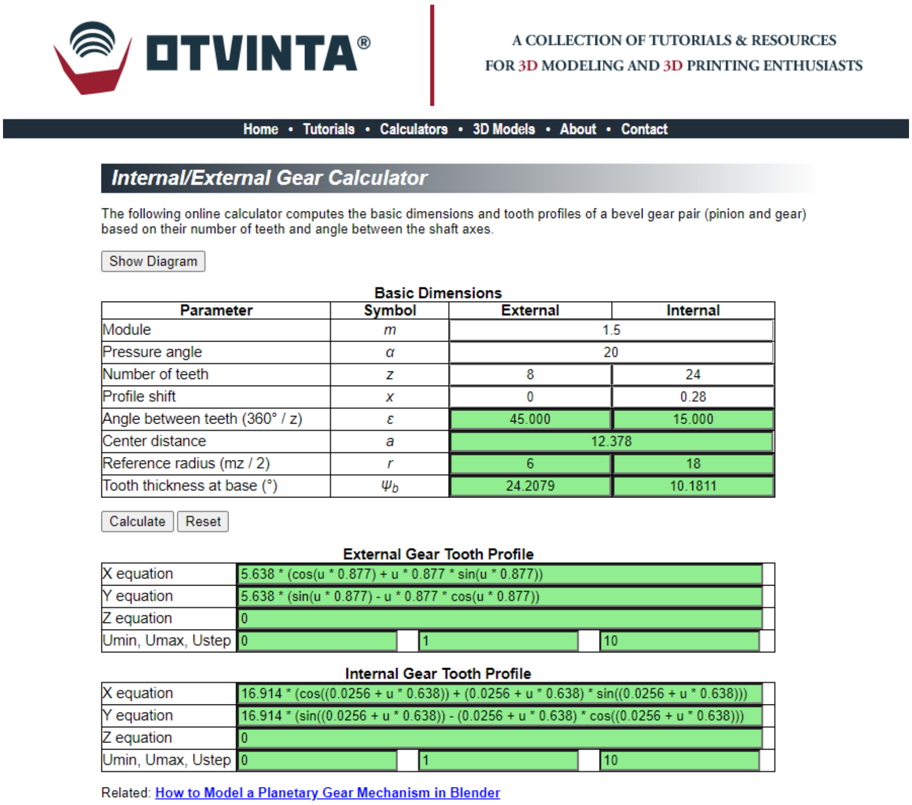


Figure 33: CAD Model of Interfering Gear Profiles with Inner Phase Shift of 0.3

The inner phase shift was reduced to 0.28 and the parameters were populated into the calculator (see Figure 34).



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Internal/External Gear Calculator

The following online calculator computes the basic dimensions and tooth profiles of a bevel gear pair (pinion and gear) based on their number of teeth and angle between the shaft axes.

Show Diagram

Basic Dimensions

Parameter	Symbol	External	Internal
Module	m	1.5	
Pressure angle	α	20	
Number of teeth	z	8	24
Profile shift	x	0	0.28
Angle between teeth (360° / z)	ε	45.000	15.000
Center distance	a	12.378	
Reference radius (mz / 2)	r	6	18
Tooth thickness at base (°)	Ψ_b	24.2079	10.1811

Calculate Reset

External Gear Tooth Profile

X equation	5.638 * (cos(u * 0.877) + u * 0.877 * sin(u * 0.877))
Y equation	5.638 * (sin(u * 0.877) - u * 0.877 * cos(u * 0.877))
Z equation	0
Umin, Umax, Ustep	0 1 10

Internal Gear Tooth Profile

X equation	16.914 * (cos((0.0256 + u * 0.638)) + (0.0256 + u * 0.638) * sin((0.0256 + u * 0.638)))
Y equation	16.914 * (sin((0.0256 + u * 0.638)) - (0.0256 + u * 0.638) * cos((0.0256 + u * 0.638)))
Z equation	0
Umin, Umax, Ustep	0 1 10

Related: How to Model a Planetary Gear Mechanism in Blender

Figure 34: Populated Parameters for Internal Profile shift of 0.28

This resulted in the gaps of the planetary gear to still, but only slightly, interfere with the annular gear (see Figure 35).

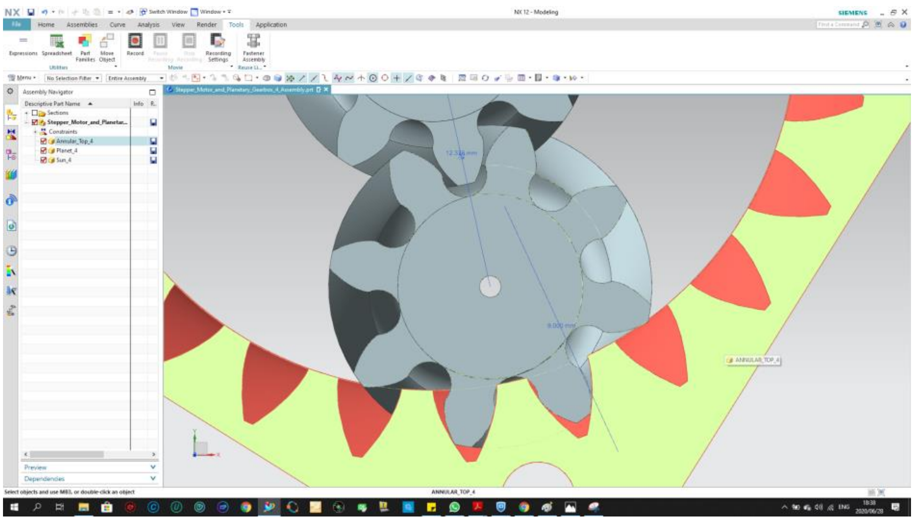
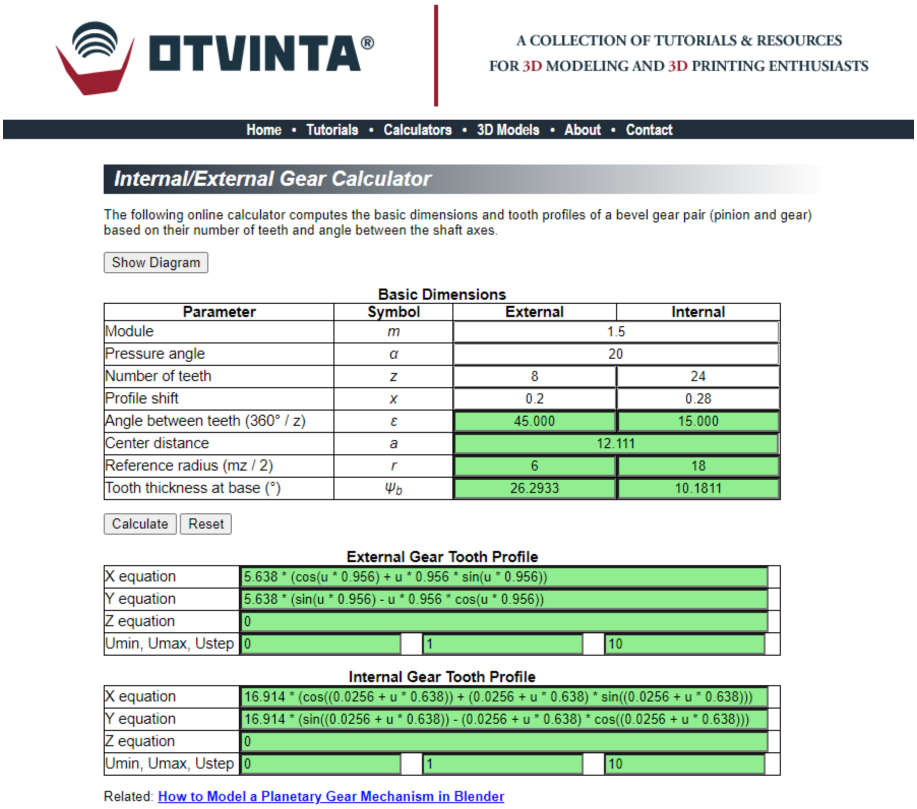


Figure 35: CAD Model of Interfering Gear Profiles with Inner Phase Shift of 0.28

The inner profile shift of 0.28 was the lowest is could go and therefore, the external profile shift had to be tweaked next. This resulted in an external profile shift of 0.2 and the parameters were populated as seen in Figure 36.



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Internal/External Gear Calculator

The following online calculator computes the basic dimensions and tooth profiles of a bevel gear pair (pinion and gear) based on their number of teeth and angle between the shaft axes.

Show Diagram

Basic Dimensions

Parameter	Symbol	External	Internal
Module	m	1.5	
Pressure angle	α	20	
Number of teeth	z	8	24
Profile shift	x	0.2	0.28
Angle between teeth (360° / z)	ε	45.000	15.000
Center distance	a	12.111	
Reference radius (mz / 2)	r	6	18
Tooth thickness at base (°)	ψ_b	26.2933	10.1811

Calculate Reset

External Gear Tooth Profile

X equation	5.638 * (cos(u * 0.956) + u * 0.956 * sin(u * 0.956))		
Y equation	5.638 * (sin(u * 0.956) - u * 0.956 * cos(u * 0.956))		
Z equation	0		
Umin, Umax, Ustep	0	1	10

Internal Gear Tooth Profile

X equation	16.914 * (cos((0.0256 + u * 0.638)) + (0.0256 + u * 0.638) * sin((0.0256 + u * 0.638)))		
Y equation	16.914 * (sin((0.0256 + u * 0.638)) - (0.0256 + u * 0.638) * cos((0.0256 + u * 0.638)))		
Z equation	0		
Umin, Umax, Ustep	0	1	10

Related: How to Model a Planetary Gear Mechanism in Blender

Figure 36: Populated Parameters for Internal Profile shift of 0.28 and External Profile Shift of 0.2

This resulted in no interference between the annular and planet gears (as can be seen in Figure 37).

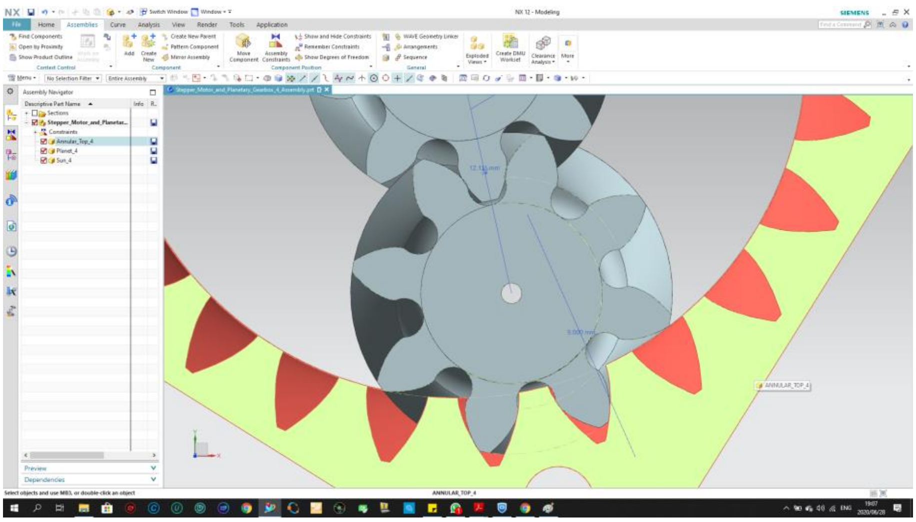
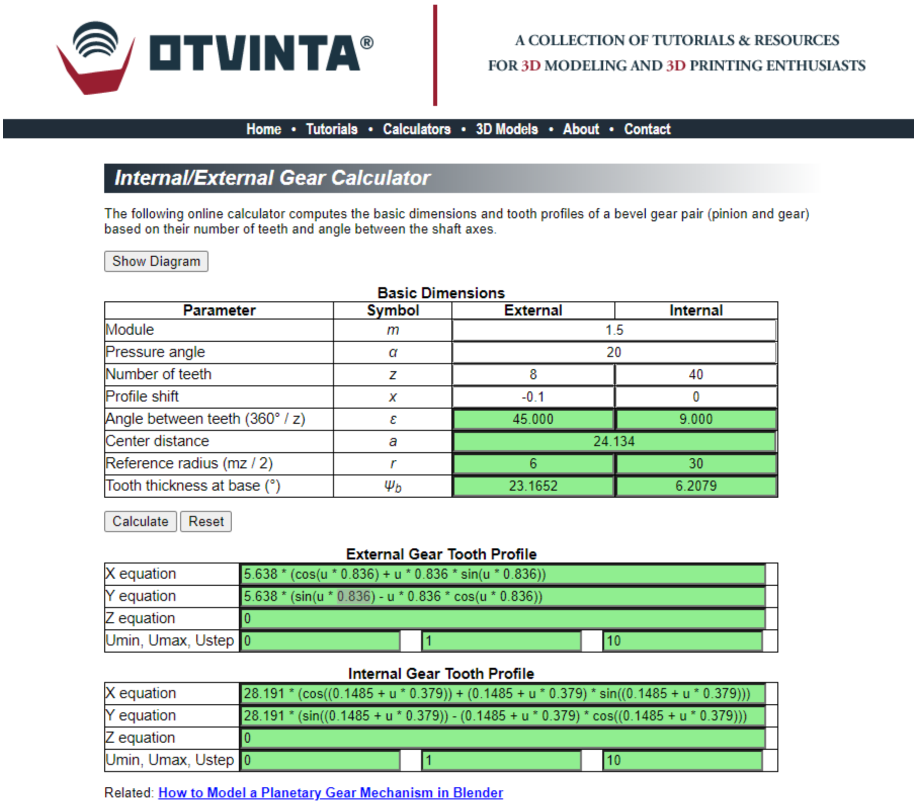


Figure 37: CAD Model of No Interference of the Gear Profiles with Internal Phase Shift of 0.28 and External Phase Shift of 0.2

Now, the sun gear can be designed using the same calculator. It is recommended that the internal parameters are set as seen in Figure 38 and the sun gear should be interpreted as the external gear with the same module for proper meshing of the gears. The profile shift was set to -0.1.



Internal/External Gear Calculator

The following online calculator computes the basic dimensions and tooth profiles of a bevel gear pair (pinion and gear) based on their number of teeth and angle between the shaft axes.

Show Diagram

Basic Dimensions

Parameter	Symbol	External	Internal
Module	m	1.5	
Pressure angle	α	20	
Number of teeth	z	8	40
Profile shift	x	-0.1	0
Angle between teeth (360° / z)	ε	45.000	9.000
Center distance	a	24.134	
Reference radius (mz / 2)	r	6	30
Tooth thickness at base (°)	ψ_b	23.1652	6.2079

Calculate Reset

External Gear Tooth Profile

X equation	5.638 * (cos(u * 0.836) + u * 0.836 * sin(u * 0.836))		
Y equation	5.638 * (sin(u * 0.836) - u * 0.836 * cos(u * 0.836))		
Z equation	0		
Umin, Umax, Ustep	0	1	10

Internal Gear Tooth Profile

X equation	28.191 * (cos((0.1485 + u * 0.379)) + (0.1485 + u * 0.379) * sin((0.1485 + u * 0.379)))		
Y equation	28.191 * (sin((0.1485 + u * 0.379)) - (0.1485 + u * 0.379) * cos((0.1485 + u * 0.379)))		
Z equation	0		
Umin, Umax, Ustep	0	1	10

Related: How to Model a Planetary Gear Mechanism in Blender

Figure 38: Populated Parameters for External Profile Shift of -0.1

This resulted in no interference between the sun and planet gears (as can be seen in Figure 39).

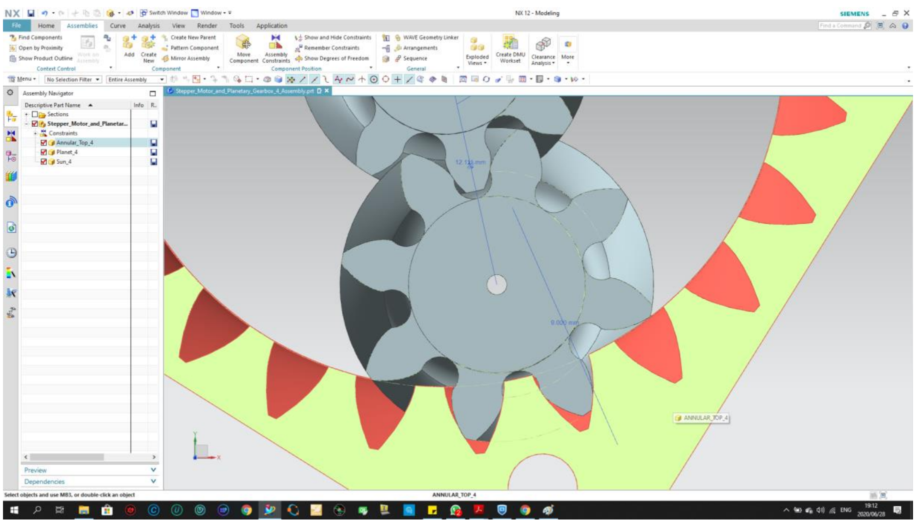


Figure 39: CAD Model of No Interference of the Gear Profiles between the Sun Gear and Planet Gears with an External Phase Shift of -0.1

There was, however, concern that the teeth of the annular gear will get pinched between the gaps of the planet gears (see Figure 40).

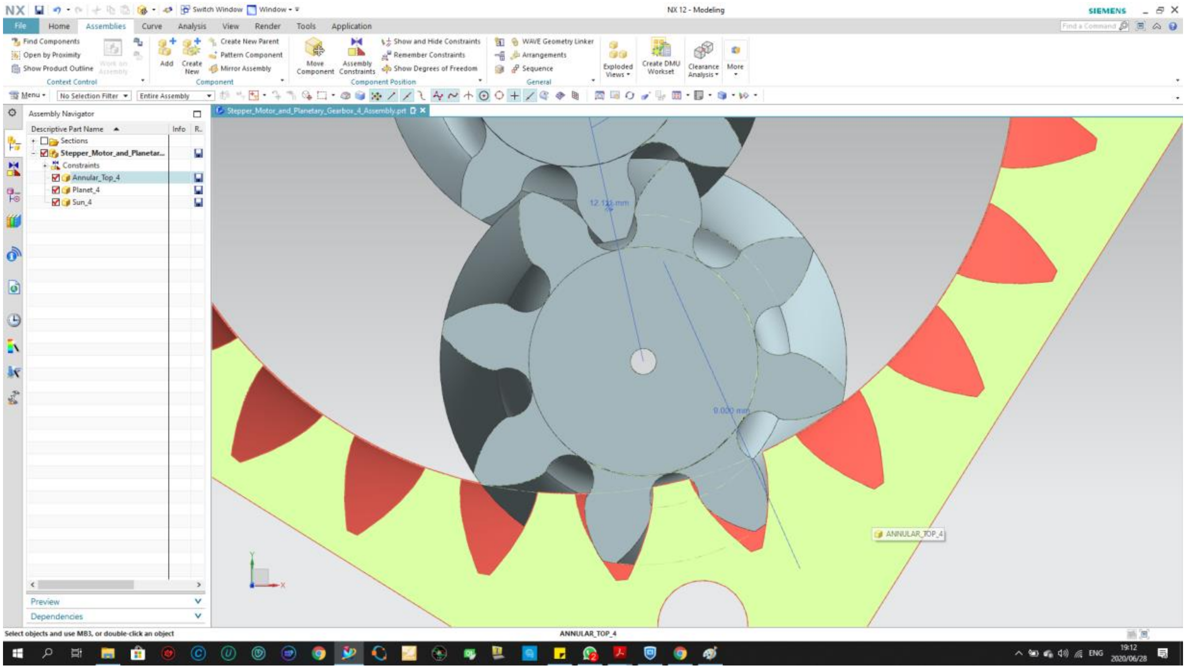


Figure 40: Possible Pinching Effect of Annular Gear's Teeth in between the Planet Gear's Gaps

This led to the gaps of the planet gears to get slightly increased to leave room for the teeth of the ring gear to freely move in between these gaps (see Figure 41).

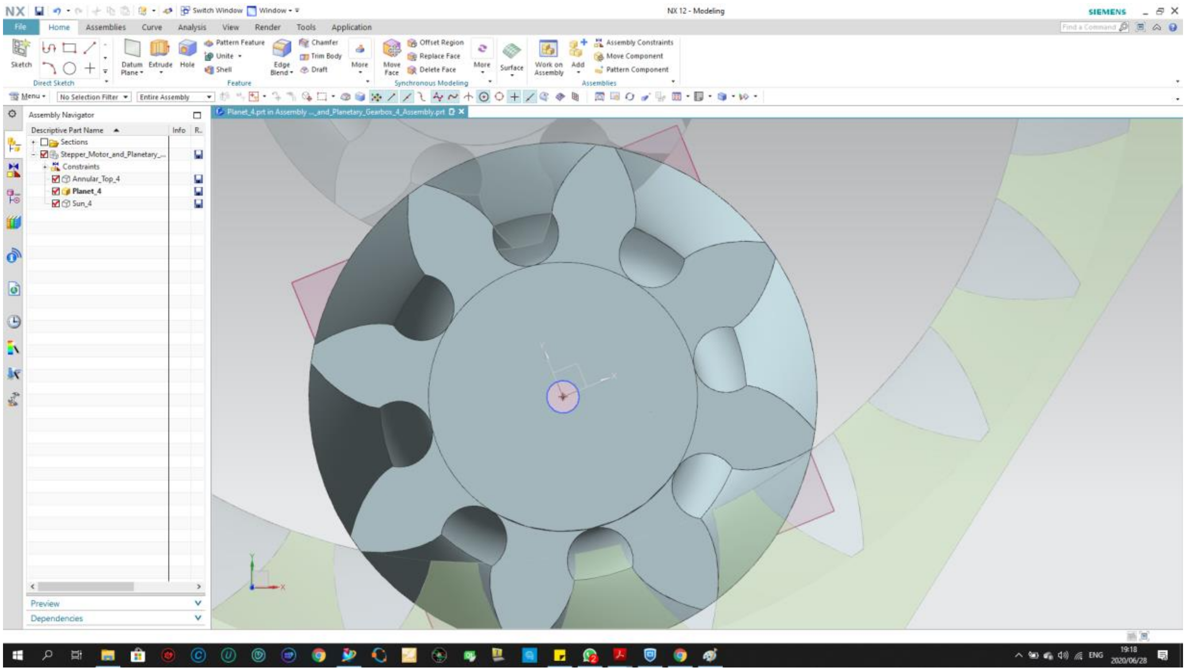
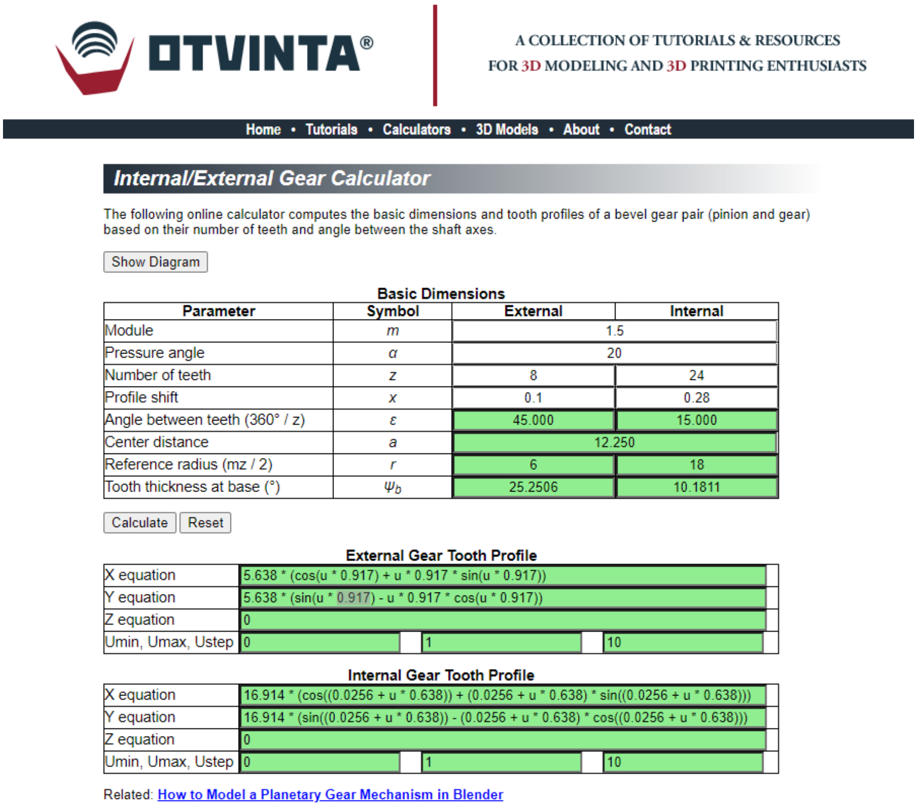


Figure 41: Increased Planet Gear Gaps to Avoid Possible Pinching Effect

Furthermore, now that these gears align perfectly, room for practical printing error (a printing tolerance) should be accounted for. Therefore, the phase shift of the planet gears was slightly decreased, and the distance from the centre of the sun gear was kept constant. This caused the planet gear's diameter to reduce slightly (See Figure 42 and Figure 43).



Internal/External Gear Calculator

The following online calculator computes the basic dimensions and tooth profiles of a bevel gear pair (pinion and gear) based on their number of teeth and angle between the shaft axes.

Show Diagram

Basic Dimensions

Parameter	Symbol	External	Internal
Module	m	1.5	
Pressure angle	α	20	
Number of teeth	z	8	24
Profile shift	x	0.1	0.28
Angle between teeth (360° / z)	ε	45.000	15.000
Center distance	a	12.250	
Reference radius (mz / 2)	r	6	18
Tooth thickness at base (°)	ψ_b	25.2506	10.1811

Calculate Reset

External Gear Tooth Profile

X equation	5.638 * (cos(u * 0.917) + u * 0.917 * sin(u * 0.917))		
Y equation	5.638 * (sin(u * 0.917) - u * 0.917 * cos(u * 0.917))		
Z equation	0		
Umin, Umax, Ustep	0	1	10

Internal Gear Tooth Profile

X equation	16.914 * (cos((0.0256 + u * 0.638)) + (0.0256 + u * 0.638) * sin((0.0256 + u * 0.638)))		
Y equation	16.914 * (sin((0.0256 + u * 0.638)) - (0.0256 + u * 0.638) * cos((0.0256 + u * 0.638)))		
Z equation	0		
Umin, Umax, Ustep	0	1	10

Related: How to Model a Planetary Gear Mechanism in Blender

Figure 42: Parameters of Reduced External Profile Shift of Planet Gears to 0.1 for Tolerance

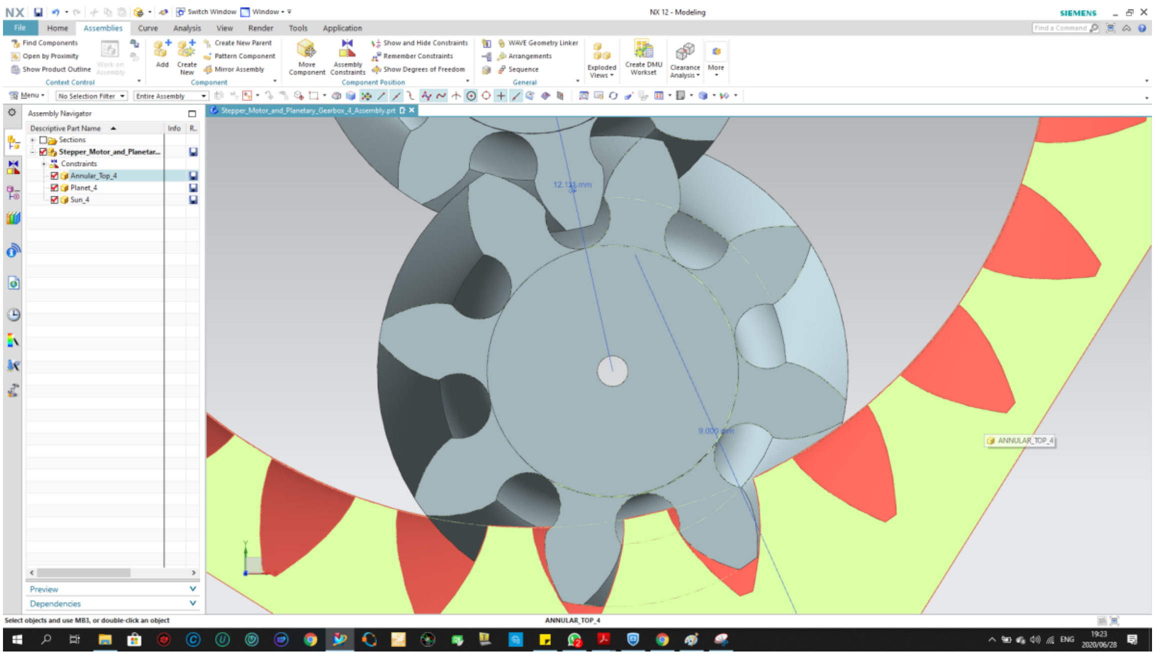


Figure 43: Final Meshing Profile of Annular, Planet and Sun Gear

The gears were finally extruded with a Herringbone pattern (see Figure 44), four planet gears were inserted in between the sun and annular gear (see Figure 45) and the casing of the stacked gearbox was designed to fit on a NEMA 17 Stepper Motor (see Figure 46).

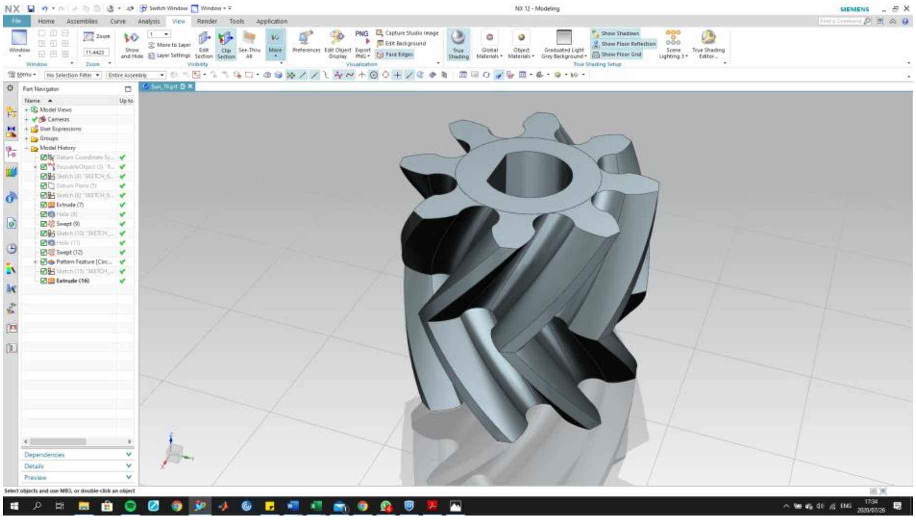


Figure 44: Sun Gear with Herringbone Profile

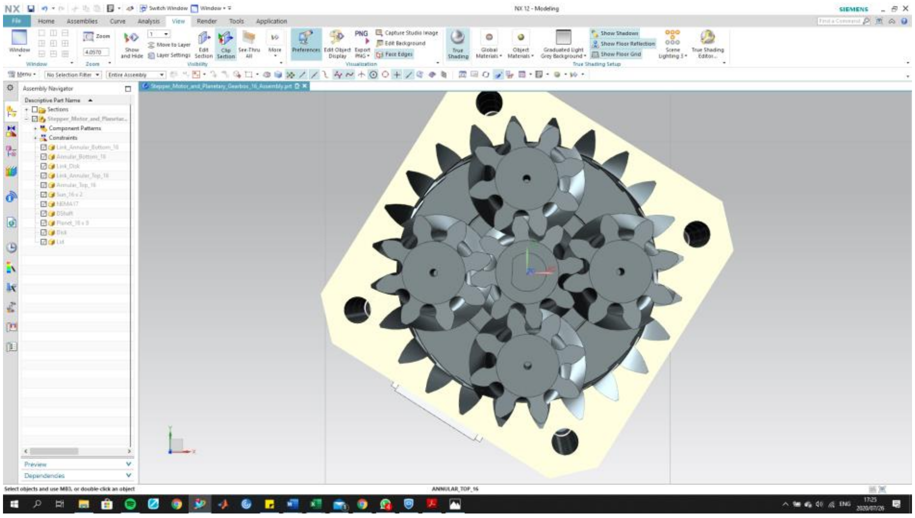


Figure 45: Top Full-Cut View of 1:16 Gearbox with 4 Planet Gears

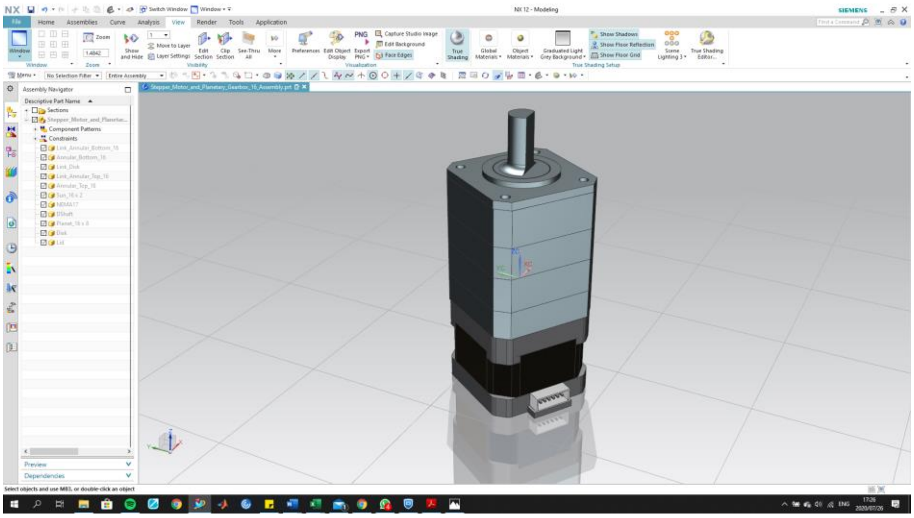


Figure 46: Final Stacked 1:16 Planetary Gearbox made to Fit a NEMA 17 Stepper Motor

3.2.3.8 Homing System

Stepper motors are normally open loop systems; therefore, the system will have no idea of its position when power gets turned off. Files can be stored on the system to remind the system where it was before, however, the system could be tampered with while it is turned off and will therefore not suffice. If the system has a false interpretation of where it is located, the system will not be able to operate correctly and could damage itself by crashing into itself.

To overcome this problem, a homing system is proposed. One which can limit the system from crashing into walls (limiting sensors), that knows its location at any time for smarter homing paths (positioning sensors) and one that could accurately reset the system (initialising sensors).

Possible collision points of the arm are marked with red crosses and should be the ideal positions for sensors (see Figure 47 and Figure 48). Notice that the mirror thereof should also be accounted for.

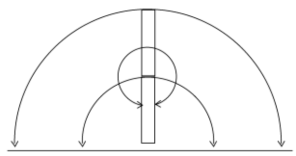


Figure 47: Illustration of the Space for Free Motion

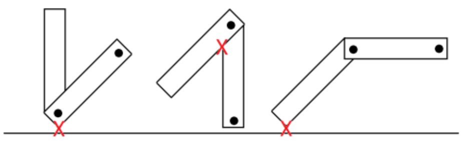


Figure 48: Possible Points of Collision with the System Walls

Some sensor options for the homing system are

- Conventional Switches (Micro Switches)
- Optical Source Sensors (IR)
- Hall-Effect Sensors
- Inductive Sensors
- Potentiometers
- Absolute Rotary Encoders

These sensors can also be used to initialise the system when turning on or in-between cycles if steps were missed. This will also allow for the calibration of the manufacturing mechanism in different environments by performing a sweep and counting the steps of the stepper motors.

Conventional switches wear mechanically over time and have undesirable debouncing effects. Optical source sensors work with infrared signals, which means that sunlight or possible laser module upgrades could interfere with the system. Hall-Effect sensors are valuable solutions but require magnets to trigger the sensors and therefore could become expensive to install depending on the setup. Inductive sensors work on almost the same principal as the hall-effect sensors; however, the sensor acts as the magnetic field source and the system need only have a metal plate installed at collision points.

Potentiometers could be used to give a rough estimation of the location of the system at any time, which should be enough to follow a smarter homing path. Absolute rotary encoders can do the same but are more accurate and more sophisticated and therefore much more expensive than potentiometers.

The best solution should be to use a combination of potentiometers and hall-effect sensors. The potentiometers can be used for continuous position acquisition with rough accuracy. Accuracy during the continuous position acquisition is not as important as the initialisation accuracy and should therefore suffice for this part of the homing system. Its alternative, the absolute rotary encoder is also much more expensive. For the initialisation part of the homing system, two analogue hall-effect sensors, one at each left-side end of the manipulator's arms, together with small Neodymium magnets mounted on the wall of the system at the initialisation position, should suffice.

Hall-Effect sensors are magnetic field sensors. It consists of a plate connected to a constant current source and voltmeter. When no magnetic field is present, the current finds the least resisting path through the plate and therefore moves in a straight line. This means that no voltage reading is present. When a magnetic field is brought closer to the plate, eddy currents occur and the path of least resistance changes into curved lines, usually bent into one direction, causing uneven charge across the plate and therefore, a non-zero voltage reading, which can signal the MCU with an ADC interface (see Figure 49).

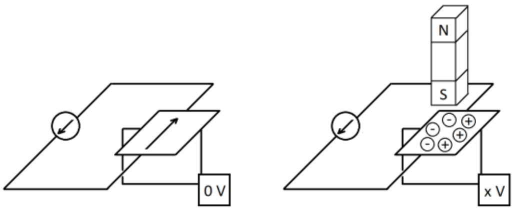


Figure 49: Basic Principle of Hall-Effect Sensor

They are relatively inexpensive and can even be pared with an operational amplifier and potentiometer as a variable proximity sensor. See Figure 50 and Figure 51 for the basic circuitry and photo of a variable proximity sensor, respectively.

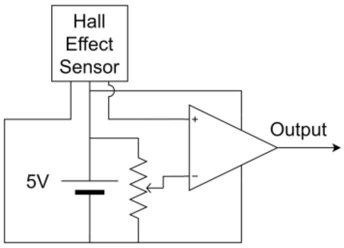


Figure 50: Circuit Diagram of Variable Hall-Effect Proximity Sensor

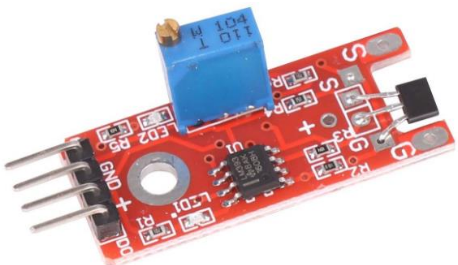


Figure 51: Photo of Variable Hall-Effect Sensor

3.2.3.9 Stepper Motor Drivers

Stepper motors can be easily implemented with minimal effort. However, the way a stepper motor is driven can improve its precision, resolution, speed, torque and noise (i.e. if done properly). This can be accomplished my means of microstepping, implementing H-bridges and PWM current chopper drivers.

Microstepping Sequencer

A microstepping sequencer is a microcontroller chip that can supply different levels of microstepping sequences (i.e., 4, 8, 16, up until 256 amplitude sampled sinusoidal (see Figure 52)), which are used together with an H-bridge to drive a stepper motor. The programmer usually specifies the microstep level (or mode) by setting two or three onboard digital input pins to the respective sequence found in the datasheet of the controller. The microcontroller transfers from one step to the next at a rate that is synchronised with the input clock pin. The sequencer also has a digital input pin for generating the proper sequence signals to turn the stepper motor in the desired direction. The higher the order of microstepping, the better the resolution and resonance (which can cause missed steps) and thus less noise, however, this means that the top speed and torque of the motor decreases and the computational overhead increases.

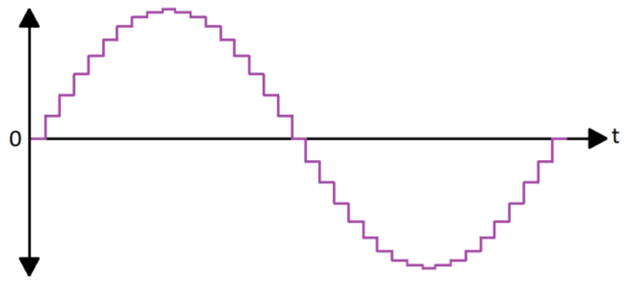


Figure 52: Signal Waveform of a Sampled Sinusoidal for Microstepping

H-Bridge

An H-bridge is a circuit that provides the means for changing the current direction through a load. This is accomplished by implementing PNP and NPN MOSFETS in a configuration as can be seen in Figure 53.

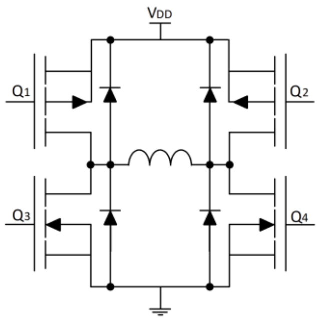


Figure 53: Circuit Diagram of Full-H-Bridge Setup using MOSFETS

To drive current through the load in one direction, MOSFETS Q1 and Q2 can be driven as short circuits and with Q2 and Q3 as open circuits. To change the direction, the mirror thereof is implemented. The shunt diodes are used to protect the power supply from damage due to back-emf being induced when a spinning motor loses its supply current.

PWM Current Chopper Driver

A PWM current chopper driver generates a PWM signal, which is used to switch a current source beyond ultrasonic frequencies (above 20 kHz) to match the average current through an inductive load to the target current. Because the load is an inductive one, the current in the windings does not instantaneosly rise to its maximum value. This slow rising in current makes it possible to measure the instantaneous current with a sensing resistor and compare it with the predefined target current. The output of the comparator is used to switch the current supply to achieve a reasonably constant current through the inductive load (see Figure 54).

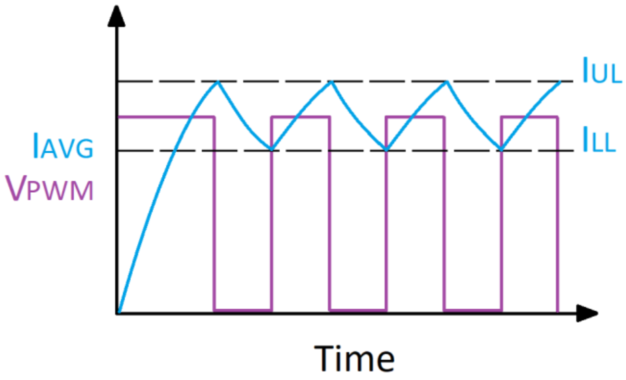


Figure 54: Graph of Average Current Through an Inductive Load using a Current Chopper Driver

Current Decay

When these three drivers are used in conjunction, the speed ringing and noise of the motor can be improved by implementing the correct type of current decay (i.e. fast or slow current decay). Slow decay happens when Q3 and Q4 from is shorted and the other two, opened. Fast decay happens when the direction in current is changed while current was flowing in the other direction. Since a stepper motor is an inductive load, current through the phases cannot change instantaneously. This is a problem when implementing high frequency microstepping since the current may not decrease at the desired rate (slow decay) and cause a distorted sinusoidal microstepping output (Figure 55 (a)). Because the H-bridge can change the direction of current through the load, it allows for a faster current decay option (Figure 55 (b)). These two signals in the figure cause resonance and can lead to missed steps. Therefore, mixed decay is introduced in stepper motor drivers to control the speed of current decay by switching between the two at the proper duty cycle for a proper sinusoidal output and less noise.

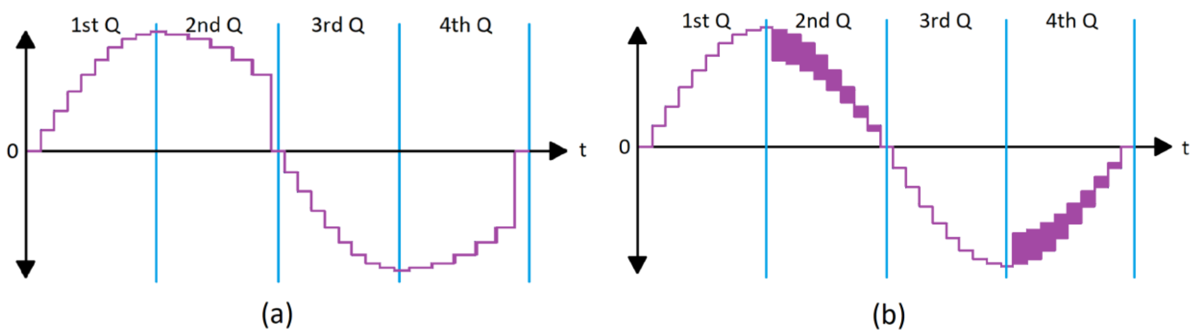


Figure 55: Microstepping Control Signal with (a) Slow Decay and (b) Fast Decay

Standard Stepper Motor Driver Boards

Next, the most common stepper motor drivers are considered for NEMA 17 stepper motors. These drivers are relatively cheap and the design thereof from first principles could be considered a final year project in its own right. Therefore, these drivers can be bought and integrated into a master PCB for controlling the manufacturing mechanism.

1. L293d

The L293d stepper motor driver (see Figure 56) is a quadruple half-H-bridge circuit. Therefore, no microstepping or current limiting is provided. Microstepping and current limiting can still be achieved by means of a shunt resistor and algorithms in the master MCU controlling the stepper drivers. However, this will cause a lot of calculation overhead and unnecessary problems to solve regarding decay and limited I/O pins.

Figure 56: Photo of the L293d Stepper Motor Driver Board

2. L298N

The L298N stepper motor driver (seeFigure 57) is a dual full-h-bridge circuit. It does not have inherited microstepping and current chopping capabilities, but can be paired with its counterpart, the L297, to achieve these capabilities (see Figure 58). However, these are normally sold separately and there exist more compact and better integrated driver boards that have the same current output limits and other performance characteristics.

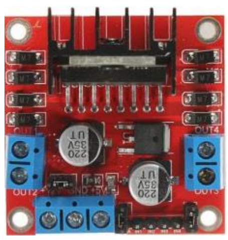


Figure 57: Photo of the L298N Stepper Motor Driver Board

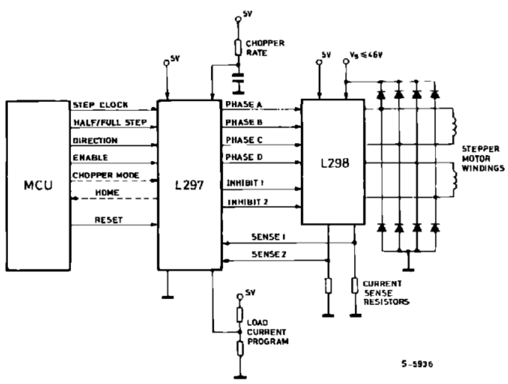


Figure 58: Schematic of the Integrated Setup of the L298N and L297 ICs

3. Easy Driver

The Easy Driver series (see Figure 59) has a microstepping sequencer (1/2, 1/4 and 1/8 stepping capabilities), onboard dual full-H-bridge, variable PWM current chopper driving and variable current decay speed capabilities. This is truly a fully integrated stepper motor driver, but it has one serious drawback. The maximum output current rating per phase for this series ranges from 150 mA to 750 mA. This is too low for most NEMA 17 stepper motors with holding torques of more than 0.4 Nm, which range from 1.2 A/phase (most popular being 1.7 A/phase) for full utilisation of torque.

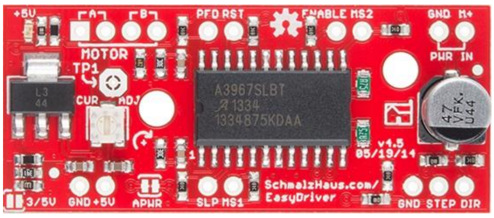


Figure 59: Photo of the Easy Driver Stepper Motor Driver Board

4. A4988

The A4988 driver (see Figure 60) is a compact PCB with header pins, making it suitable for easy maintenance master circuit integration with the use of female header pins. This driver is capable of 1/2, 1/4, 1/8 and 1/16 microstepping, has an onboard dual full-H-bridge, variable PWM current chopper driving and variable current decay speed capabilities. It can handle power supply voltages from 8 V to 35 V, has a maximum continuous current per phase of 1 A to 1.2 A and peak current per phase of 2 A (with heat sink and proper air flow).

Figure 60: Photo of the A4988 Stepper Motor Driver Board

5. DRV88XX (25, 34 or 80)

The DRV88XX driver series (see Figure 61) has the same physical dimensions and layout as the A4988.

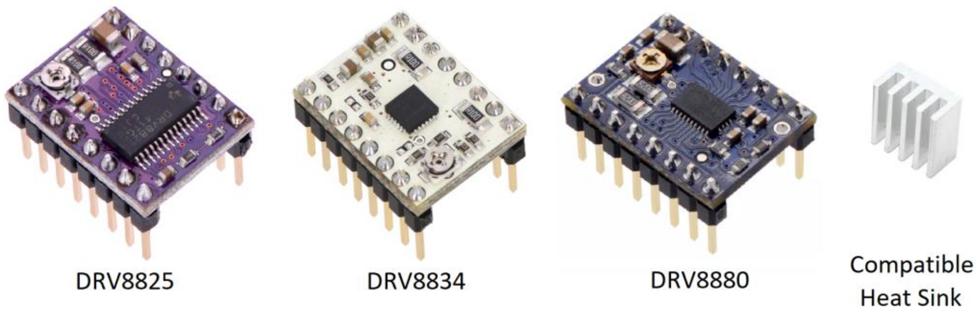


Figure 61: Photos of the DRV88XX Stepper Motor Driver Series

This driver series is capable of 1/2, 1/4, 1/8 and 1/16 microstepping (with the DRV8825 and DRV8834 capable of an additional 1/32 option), has an onboard dual full-H-bridge, variable PWM current chopper driving and variable current decay speed capabilities. The DRV8825, DRV8834 and DRV8880 can handle power supply voltages from 8.2 V – 45 V, 2.5 – 10.8 V and 6.5 – 45 V, respectively. They also have a maximum continuous current per phase of 1.5 A, 1.5 A and 1 A, respectively. Also, a peak current per phase of 2.2 A, 2 A and 1.6 A (with heat sink and proper air flow), respectively.

6. MP6500 (Potentiometer or Digital Current Control)

Again, the MP6500 series (see Figure 62) has the same physical dimensions and layout as the A4988.

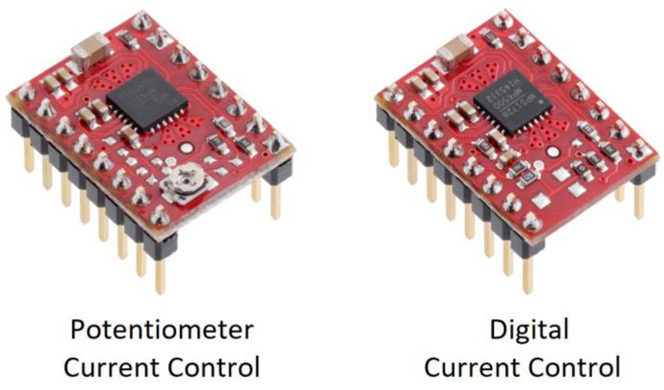


Figure 62: Photos of the MP6500 Stepper Motor Driver Series

This driver series is capable of 1/2, 1/4 and 1/8 microstepping, has an onboard dual full-H-bridge, variable PWM current chopper driving (pot. or digital reference control) and variable current decay speed capabilities. The MP6500 Pot. CC and Digital CC can handle power supply voltages from 4.5 V to 35 V. They also have a maximum continuous current per phase of 1.5 A and a peak current per phase of 2.5 A and 2 A (with heat sink and proper air flow), respectively.

7. TB67S249-FTG

Finally, the last stepper driver worth mentioning for the NEMA 17 stepper range is the TB67S249-FTG (see Figure 63). It has a microstepping capability of 1/2, 1/4, 1/8, 1/16 and 1/32, has an onboard dual full-H-bridge, variable PWM current chopper driving and variable current decay speed capabilities. It can handle power supply voltages from 10 V to 47 V, has a maximum continuous current per phase of 1.6 A and a peak current per phase of 4.5 A (with heat sink and proper air flow).

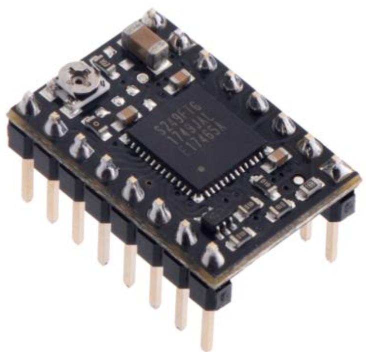


Figure 63: Photos of the TB67S249-FTG Stepper Motor Driver Series

Stepper Motor Driver Design Decision

The last four stepper motor drivers have all the necessary driver technologies to make a powerful, yet compact master CNC PCB, with the header pins improving maintenance capability to the PCB. Since the power supply voltage of the system will probably be a 12 V or 24 V power supply, the DRV8834 is omitted. The average 1.5 A/phase rating of the NEMA 17 stepper motor omits the A4988 and DRV8880 drivers. Therefore, the DRV8825, MP6500 and TB67S249-FTG drivers are the remaining options. Since the stepper motor will be microstepped at 1/8, all four options remain. The two last criteria that will be used, is the maximum current per phase ratings and the price of the drivers. Research regarding available drivers emits the lockdown implications, due to Covid-19, and the price of the modules, were done. The results were recorded in Table 23.

Table 23: Comparing the Current Limits per Phase and Prices of Available Stock in SA

Driver Board	Max Continuous Current w/o Cooling [A/phase]	Peak Current [A/phase]	Lowest Price Available (tax incl.)	Supplier
DRV8825	1.5	2.2	R 47.40	PiShop
MP6500 Pot. CC	1.5	2.5	Not Available in SA at The Time	
MP6500 Digital CC	1.5	2.0	R 138.00	MicroRobotics
TB67S249-FTG	1.6	4.5	R 91.64	Digi-Key

The TB67S249-FTG is the best driver between the four, however, only the IC's are available and therefore, specialised equipment such as a heating bed is needed. This equipment is unfortunately not available during this covid-19 lockdown period and is therefore not an option.

The second-best option is the DRV8825 driver, which is also the cheapest of the lot, since it is a very generic driver for NEMA 17 stepper motors.

Therefore, the DRV8825 microstepping driver will be used in this project. And since this allows for any of the 5 stepper motor options to be implementable (and option 1 was out of stock at the time), option 2 (with the bonus of the lowest price and highest speed) will be used in this project.

3.2.3.10 Vacuum Pickup Tool

The vacuum pickup tool should at least be able to lift an item with a weight of 2 N and should have a maximum surface of 40 mm diameter. This can be achieved by means of a miniature vacuum air pump, hoses and a suction cup. Since the items engraved will have imprints on them, it will be a bit difficult to calculate the required negative pressure of such a pump. Therefore, the pump should either be more than capable of lifting a 2 N item and control the pressure thereof by means of a PWM signal, or a special type of suction cup should be used that is capable of sealing of the leakage air.

First, let us consider the basic physics of calculating the required negative pressure by studying equation (17).

$$Pressure = \frac{Force}{Area}, \tag{17}$$

where $Force$ is in Newtons, $Area$ in square meters and $Pressure$ therefore in Pascal.

Substituting 5 N and 20 mm diameter circular area (314.159 mm^2), the required pressure calculates to 15.9155 kPa.

After some research, it was evident that this could be attainable with a vacuum gripper system from piVAC Africa (paid distributers in Africa) and miniature vacuum air pump configuration.

Piab specialises in manufacturing industrial vacuum pumps, suction cups and composed vacuum gripper tools. The latter has a wide variety of negative pressure capabilities, module sizes and suction cup diameters. The cups also feature their own series of subcomponents such as the bellows used, cup material, gaskets and other links. The material of the cup itself, determines the tolerance on the roughness of the surface of the item to be picked up, which will help create a proper seal on the engraved surfaces. The BX25P (Figure 64 (a)) is capable of handling very rough surfaces such as rocks.

Piab also sells miniature vacuum gripper systems that allows for an easy tool handling experience. The VGS™2010 (see Figure 64 (b)) is a vacuum gripper system series appropriate for handling loads with contact areas from 10 – 80 mm diameters and can achieve negative pressures of up to 90 kPa. This means that for a 26 mm diameter cup, the vacuum gripper system will theoretically be able to lift load capacities of 47.784 N (or 4.873 kg). However, this is only theoretical and a more practical value (due to decrease in vacuum contact area) will be closer to half of this at about 20 N (or about 2 kg). The quick release atmosphere valve will improve time efficiency.

Furthermore, a miniature vacuum air pump should be sourced. Unfortunately, Piab does not sell miniature electrical pumps (only pneumatic pumps) and so does no other reliable online store in South Africa. Therefore, this 12 V, 6 W with 65 -kPa miniature vacuum pump (Figure 64 (c)), must be sourced from amazon, due to no local alternatives.

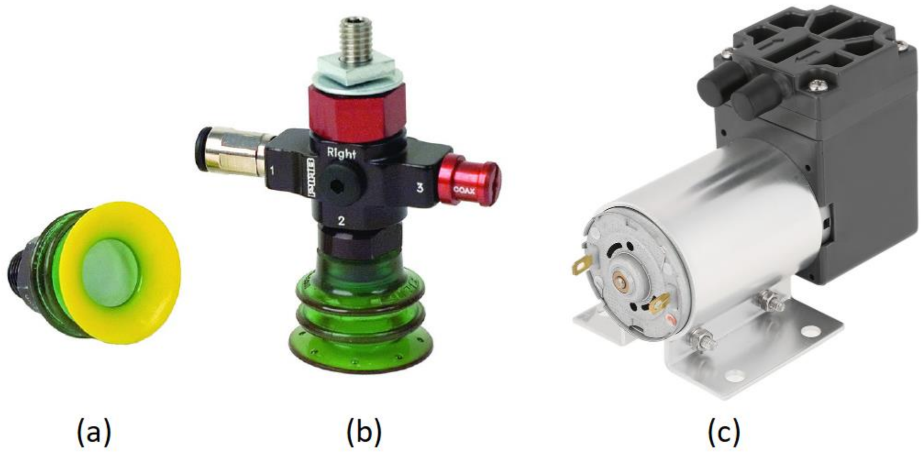


Figure 64: Photo of the VGS™2010 Vacuum Gripper System

3.2.3.11 Engraving Tools

The engraving tool type will directly affect the quality of the end-product, i.e. the engraved item. Also, users and customers rarely appreciate all the effort behind the scenes and only care about the end-product. Therefore, to ensure that the Keybot leaves a long-lasting impression on the prospective student and their parents, this choice should mainly be based on the quality of the engraved impression left on the item. A few options were previously considered regarding the type of engraving process to be executed, which only ruled out etching as an engraving technique. Mechanical rotary engraving and laser engraving were still considered valuable options. Now, electrical- and pneumatic impact engraving as well as diamond spring-loaded drag engraving is added to the list of options and a choice must be made regarding which method(s) should be implemented.

3.2.3.11.1 PNEUMATIC IMPACT ENGRAVING

Pneumatic impact engravers use air flow to pulse an engraving bit in and out of a guide at high frequencies. This process mimics the physical traditional engraving process of a hammer and chisel setup. However, this requires that the system should have an airflow pump/regulator with hoses, which makes the system bulkier. The vibrations at high speeds also cause high pitched noise levels.

3.2.3.11.2 ELECTRICAL IMPACT ENGRAVING

Electrical impact engraving uses a motor with an imbalanced locus, which knocks the engraving bit in in and out of a guide at high frequencies. Therefore, it also introduces a high-pitched frequency noise, and the vibrations can cause the rest of the system to behave unexpectedly. However, this is a superior option to pneumatic impact engravers since the tool does not require hoses and an expensive, heavy and bulky air regulator. Some electrical impact engravers also utilise DC motors and could thus interface easier with the DC power supply of the Keybot system.

3.2.3.11.3 LASER ENGRAVING

Laser engravers come in many different types, including CO_2 (gas) lasers, fiber lasers and diode lasers (see Figure 65). CO_2 lasers can engrave and cut almost any type of material except metals. Fiber lasers are much more concentrated and can be used for even metal engraving and require much less maintenance. However, CO_2- and fiber lasers are mainly used in industrial applications, since the output power is in the kilowatt range. The diode lasers can also be used to engrave metals, but lower non-industrial modules are available for the public to use. Class IV diode lasers are amongst these and are normally available with output power ratings from 500 mW to as much as 15 W. These lasers, however, have a shorter lifespan of about 8000 hours, which is still much for a system such as the Keybot system.

The downsides to the use of laser engravers are that they are relatively expensive (about R 600.00 per Wattage). Diode lasers can be used for marking metals, only if the output power exceeds 4 W. Therefore, a laser module capable of marking metals will already cost more than R 2 400.00 every 8 000 working hours. Not only that, but laser engraving can cause toxic fumes, permanent damage to the human eye and will most probably not engrave metals to a satisfactory degree.

Therefore, diode lasers should only be considered if the necessary funds are available and proper safety measures can be properly implemented. These measures include the limiting of contact or power density of the laser to human eyes. This can be achieved by means of non-reflective materials in the engraving area, laser protection windows with an OD4+ rating, OD4+ safety glasses (see Figure 65) and proper directional air flow away from direct air consumption of humans. The choice of material can also eliminate the production of toxins.

Figure 65: Photo of Laser Protective Glasses and 2.5 W Violet Diode Laser Module

An OD4+ rating and higher will filter the power density of the laser at specific wavelengths, lowering the radiation to safe levels. To look directly into lasers with a wattage over 500 µW can cause minor injuries after 10 seconds. However, since the laser will be pointed downward onto a non-reflective surface, direct contact is not supposed to be possible. Nonetheless, the laser should be treated as such since the laser could fall from its mounting position while being electrically connected. Therefore, an OD4+ rating will lower the power density with an order of four, reducing the wattage from 5 W to 500 µW, which should allow for enough time to switch off the laser with an emergency stop button. This can already be deemed enough protection since laser pointers usually outputs ten times this amount. However, with the use of additional protective glasses, this level can be reduced significantly.

This means that people wearing the glasses will be more than fully protected and passers-by will also be sufficiently protected even if the laser point directly at someone. This, however, requires that the protective window fully isolates the laser from the on-looker's eyes. This can become quite expensive, since no company exist in South Africa that sells these windows. Imported windows filtering the 450 nm range (typical violet diode laser wavelength) with a size of 12-inch x 12-inch panel and OD4+ rating can cost as much as R 1,000.00 without delivery costs. The glasses, however, are available in South Africa and can be bought at DIY Electronics for R 69.95 a pair. Over a hundred modules were compared to one another and the best option, considering the price per wattage (R 526.00/W), output power (4 W), efficiency (16.7%) and expected working hours (<10,000 hours), is found online at Racer Gadgets. This proves that a diode laser engraver can still be considered a valuable solution if the funds allow for the proper safety precautions to realize.

This option will improve the UX of the demonstration platform more than any other engraving option. That being said, the safety of humans should always be the highest priority in any engineered system and although the risks are theoretically eliminated, Murphy's Law can always find its way.

3.2.3.11.4 MECHANICAL ROTARY ENGRAVING

Mechanical rotary engraving works on a chipping principle. A DC motor is connected to an engraving bit with a mini drill chuck or collet with collet holder (see Figure 66).

Figure 66: Photos of (a) Generic 775 DC Motor (b) Collets and Collet Holder and (c) Mini Drill Chuck

When these components are connected, the configuration is called a DC spindle (with the addition of some attached cooling system). These products are also sold separately, which reduces the cost thereof from an average of R 1,200.00 to R 500.00. The 775 DC motor seen in Figure 66 (a) is a compact (42 mm diameter) generic 12 V to 24 V DC motor capable of speeds between 13 000 and 15 000 rpm.

The mini drill chuck accepts engraving bits with diameters from 0.3 mm to 4.0 mm and has a sleeve for a 5 mm motor shaft, which means that it is compatible with the 775 motor.

The collets have a wide variety of sizes and the popular miniature collet holder type from Dremel® can be bought for R 106.70 from Communica.

3.2.3.11.5 DIAMOND SPRING-LOADED DRAG ENGRAVING

Diamond spring-loaded drag engraving might be the option with the least possible physical issues. This is a very easy, clean-cut and eco-friendly engraving technique. An engraving bit with a very sharp and small diamond attached to the tip is inserted into a spring-loaded holder (see Figure 67). This configuration eliminates the relative height and pressure issue when it comes to lowering the engraving tool to the item's surface height. When the tool is lowered more than necessary, the spring will automatically alleviate the pressure that the item and bit experience. Also, the engraving profile created is more continuous, precise and adjustable. The best part is that this tool does not require any electrical power, rotational- or vibrating movement, only a drag movement, which is in any case is required for the other options. However, this product is somewhat expensive (averaging about R 1,200.00) and unfortunately not available at South African online stores.

Figure 67: Photo of Diamond Spring-Loaded Drag Engraving Tool

All the mentioned engraving tool options present their own pros and cons.

The pneumatic- and electrical impact engravers produce a lot of mechanical vibrations and high-pitched noise, which can irritate the crowd and prospective students. This can also distract the marketer from effectively presenting the demonstration platform.

The laser engraving module will leave quite the impression and attract a lot of attention at demonstration events. However, this pro can also be interpreted as a con, since more people will stare at the laser during engraving, which means that a lot of protection glasses need to be purchased for all spectators to experience the same level of protection. However, if a protection window is installed together with some air regulation (or even non-toxic materials are engraved), the laser engraving option can still be proven to be a valuable solution. Also, this is probably the most expensive solution, with an expected cost of around R 3,500.00 for the laser module, protection window and a few glasses.

The mechanical rotary engraver is most probably the most practical solution at the time of design since the cost will not exceed R 500.00 and the implementation thereof is relatively straight forward. These components are also available in South Africa (other than the drag engraver option).

The laser-, mechanical rotary- and diamond spring-loaded engraving techniques could technically all be perused and should all feature in future versions of the Keybot system. However, since the mechanical rotary engraving technique is deemed the most practical solution, this technique will be the primary one perused for the first version of the Keybot system (even if it is the most power intensive option of about 150 W).

If the rotary engraver implementation is successful, the other two techniques should be easily implementable in future versions, and therefore, the Keybot will follow a generic multitool accommodation design with a database of materials listing the techniques appropriate for a material.

3.2.3.12 Power Supply

Since the system will use most of its power during the engraving process, the requirements for the power supply will be specified for this stage. During the engraving stage, the Raspberry Pi, touchscreen, four stepper motors and DC motor will consume almost all the power consumed at the time. The Raspberry Pi and touchscreen will consume about 15 W. The stepper motors will at most draw 1.7 A per phase, which means that with a microstepping order of 8, will consume a combined 140% of the rated phase current between the two phases. There are four stepper motors and therefore, together with the current chopping process of 12 V supply, will consume about 115 W.

Finally, the DC motor used for the mechanical engraving will consume about 150 W, which adds up to about 280 W consumable by the system. At 12 V, this means that system should at the very least be able to provide 23 A output current. Since generic power supplies of 12 V only comes in 5 A, 10 A, 20 A, 30 A, 40 A and 50 A, a 30 A power supply should be able to provide the necessary power to the system. This leaves the system at 78% maximum power usage, which will account for leakage currents, negligible components and an imperfect power supply.

Since we have a very precise specification for the power supply, it was easy to find the best deal at the time, which was a deal on Takealot at the following link for R495.00.

Figure 68: Photo of 12 V 30 A DC Switch Mode Power Supply

3.2.3.13 DC-to-DC Converter

Since not all the components will be compatible with the 12 V DC power supply, other generic voltage levels such as 5 V and 3.3 V should be introduced into the system.

Two easy solutions exist for this problem; use linear voltage regulators (see Figure 69 (a)) or buck-converters (see Figure 69 (b)). The amount of output current required to pass through the converter will determine if a voltage regulator such as the LM7805 (5 V) and LM1117 (3.3 V) are valuable options, since this is the lesser efficient option, causing large power dissipation in the form of unnecessary heat at as low as 500 mA output current. The buck converter is a much more efficient alternative and it is yet to be determined by the moderator whether one must be designed from scratch (to demonstrate electronics design) or if simply purchasing a few buck converters for R 29.00 each, will be allowed.

(a) (b)

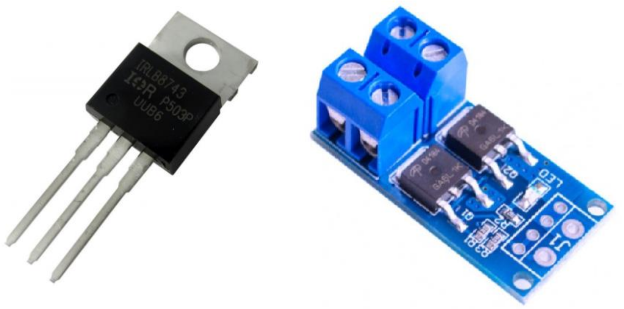
Figure 69: Photos of (a) Generic LM7805 Linear Voltage Regulator (b) Generic Buck Converter

3.2.3.14 MOSFET Trigger Switch Driver Module

Since the chosen engraving tools might have to undergo power regulation for improved control and performance, a power switching circuit must be considered.

The 12 V 775 DC motor will be the most power intensive at 150 W (or 12.5 A rated current). Therefore, a power switching circuit capable of handling 15 A, or more, will be ideal.

Below in Figure 70 (a), is photo of a power MOSFET, which is capable of up to 150 A DC loads and (b) is a photo of a generic driver module capable of 15 A DC loads. Both can be used, either directly, or with a bit of circuit design, to drive DC loads from a PWM signal originating from an MCU. This will ensure that the choices of the above tools will have a controllable output power, which can be used to better integrate the system.



(a) (b)

Figure 70: Photos of (a) Power N-Channel IRLB8743 MOSFET 30 V/150 A and (b) Generic MOSFET Trigger Switch Driver Module

3.2.3.15 ISO Wiring

Since some loads will draw around 12.5 A, it is important to consider which wires will be able to transfer this current without overheating. One standard for determining this, is the AWG rating (American Wire Gauge), which indicates how much current is manageable by what size of wire. The ISO rating is the International Standard Organisation, which can be derived rom the AWG rating. However, since most stores sell the wires with the AWG rating, we will focus on this rating system.

According to [25], the smaller the AWG rating, the larger the area of the wire, lowering the resistance and increasing the capacity for current (referred to ampacity). Also, the higher the ambient temperature, the higher the resistance, which means less current may flow through the wire. Finally, the longer the wire, the higher the resistance and even less current is manageable.

It is clear that a few factors need to be considered, so we will make some assumptions to simplify the calculations. Since the wire will have to be longer than 2 m, we will assume that we are working with a total maximum length of four meters. Also, since the requirement document specified that the Keybot need not be able to operate at ambient temperatures higher than 50 °C, we will adjust the ampacity table from [25] with 0.58. Finally, we will assume that the wire will be manufactured from standard annealed solid copper with PVC insulation.

Now, we can use Ohm's Law (18) to calculate the voltage drop for 12.5 A through the power cable, to be able to calculate the maximum motor power percentage (see Table 24).

$$V = I \times R \tag{18}$$

Table 24: Max. Motor Power and Wire Ampacity for AWG Sized, PVC Insulated, Copper Cables @ 45 – 50 °C Ambient Temperatures

AWG	Diameter [mm]	Resistance Copper [Ω/4 m]	Voltage Drop [V]	Max. Motor Power [%]	Typical Max. Current Load Ratings [A] of Copper Cable @ 45 - 50°C Ambient					
					1 Core	2 – 3 Cores	4 – 6 Cores	7 – 24 Cores	25 – 42 Cores	43+ Cores
24	0.51	0.352	4.400	63.33	2.03	1.16	0.93	0.81	0.70	0.58
22	0.64	0.208	2.600	78.33	2.90	1.74	1.39	1.22	1.04	0.87
20	0.81	0.136	1.700	85.83	3.48	2.90	2.32	2.03	1.74	1.45
18	1.00	0.084	1.050	91.25	5.51	4.06	3.25	2.84	2.44	2.03
16	1.30	0.052	0.650	94.58	8.70	5.80	4.64	4.06	3.48	2.90
14	1.60	0.033	0.410	96.58	13.92	8.70	6.96	5.80	5.22	4.35
12	2.10	0.021	0.260	97.83	19.72	11.60	9.28	8.12	6.96	5.80
10	2.60	0.013	0.165	98.63	30.16	17.40	13.92	12.18	10.44	8.70
8	3.30	0.008	0.105	99.13	43.50	23.20	18.56	16.24	13.92	11.60
6	4.10	0.005	0.065	99.46	55.10	31.90	25.52	22.04	19.14	15.66
4	5.20	0.003	0.041	99.66	69.60	40.60	32.48	28.42	24.36	20.30
2	6.50	0.002	0.026	99.79	98.60	55.10	44.08	38.28	33.06	33.06

Table 24 also highlights the AWG sizes capable of handling the 12.5 A current for different amounts of cores. Aluminium was not considered since its resistance is more than Copper's. Therefore, Aluminium would have even less capacities than the listed Copper cables. Also, the more cores, the more flexible the wire, but the less its ampacity.

Before choosing the AWG rating for the Keybot, clarity needs to be obtained regarding the definition of single and multicore wires. According to [26], single core cables can be solid (Figure 71 (a)) or stranded (Figure 71 (b)). The so-called multicore is individually insulated single cores (Figure 71 (c)).

Since the cable will run down the Keybot's arms, it will be better to use stranded wires, since solid wires are not as flexible and will add to the resistance in movement of the arm. Also, solid cores tend to break easier after bending multiple times.

To supply power to the 12.5 A DC motor load (largest current load for an engraving tool), a single, stranded, copper wire of 14 AWG (1.6 mm diameter) or less (larger diameter) will be acceptable. Or, if a dual core cable is desired to keep the positive and negative wires bundled, a 10 AWG or less will be sufficient. To supply 3 A to the Raspberry Pi, which in turn powers the touchscreen, a 20 AWG or lower will be acceptable. Finally, to supply 1.7 A per phase to the stepper motors, a single core configuration will demand a 24 AWG wire. If the four wires per stepper is desired to be kept together, a 20 AWG wire will be required.

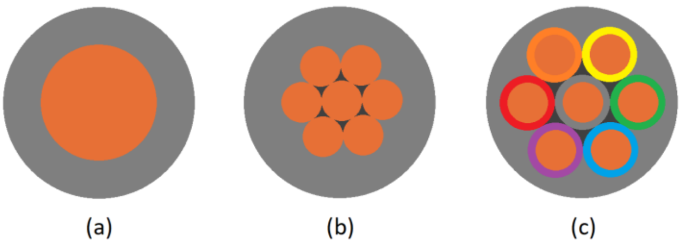


Figure 71: Illustration of (a) Single, Solid Core, (b) Threaded Single Core and (c) Multicore Cables

3.2.3.16 Designing the Electrical Enclosure and Manufacturing Mechanism Structure

The electrical enclosure will have three different compartments (Figure 72). The first will allow for the palette to be placed in. Here, any depth of the cavities below 60 mm (even deeper for possible future expansions such as stacking items in single cavities) can easily be achieved without colliding with other parts of the system. For the smallest allowable item of 30 mm radius (described in the requirement documentation), 12 items can be loaded (four rows and three columns). Also, for the largest allowable item of 70 mm radius, 2 items can be loaded in this area at the same time.

The second compartment (inside the electrical enclosure) is the location of the main drawer hosting all the electronics for demonstration purposes. Here, the power supply, controller board of the controlling mechanism and electronics of the interface mechanism will be stored away for protection. This drawer can host a maximum boxed volume of 366 x 336 x 80 mm. This compartment also hosts the base (70 mm Ø) of the Keybot's arm, wherein the first stepper motor with its gearbox will reside. The rails for this drawer exhibits push to open technology to allow for the enclosure's size to be maximised without violating the maximum breadth of the Keybot.

The third compartment is the second drawer wherein the post-engraved item will be dispensed for collection by the user. The drawer will feature a drawer stop and two magnetic strips to add some resistance for opening and closing the drawer at its limits. The stop will also keep the Keybot from dispensing items without being caught in the drawer. Also, if the drawer is fully open when the Keybot releases an item, the user just needs to close the drawer fully to let the stopper shift the item forward. Thereafter, the user can retrieve the previously misplaced item next time the drawer is opened.

As seen in Figure 72, the maximum length of the Keybot is exactly 1 m. This falls well within the requirements of 1.1 m. This was achieved by designing the inside of the enclosure to achieve the total length. It can also be seen that the drawer's size is designed to be at its maximum allowed space as to not collide with other compartments. The walls inserted to hoist the rails on, serves a dual purpose, i.e. to also strengthen the structure of the enclosure even more. They are also placed in a symmetrical manner for a more attractive outside view.

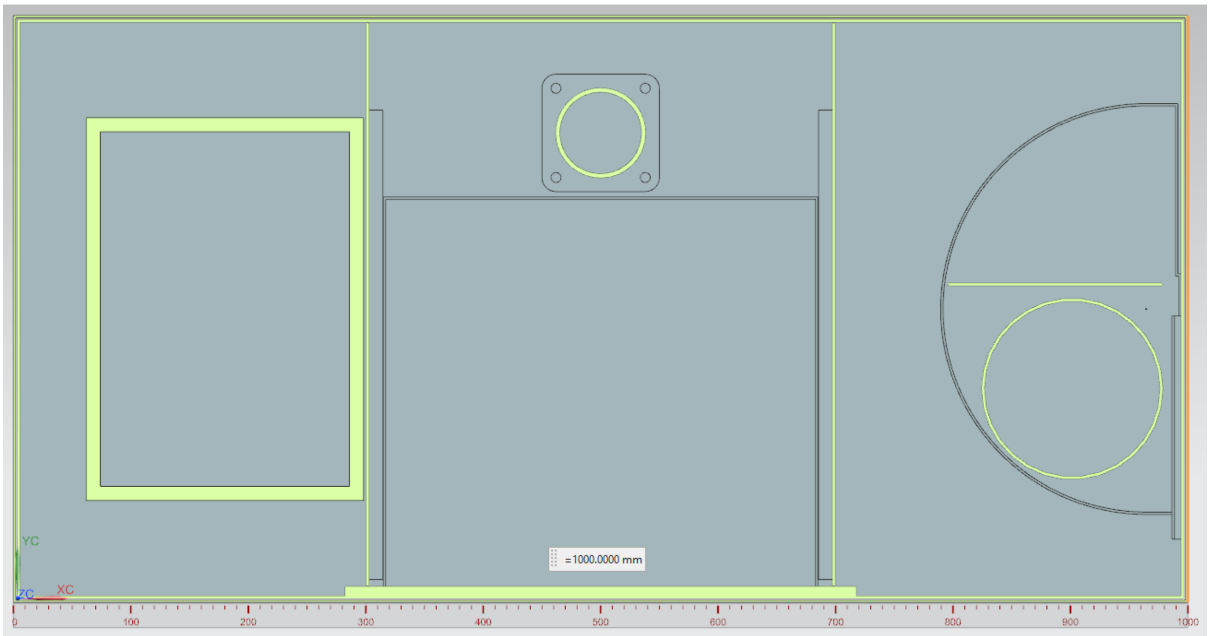


Figure 72: CAD View of Realised Compartments and Measured Length of Electrical Enclosure

Figure 73 illustrates all the necessary details for the measurements of the compartments as well as the area that will be reachable by the arms of the Keybot. As mentioned before, the total arm length will be 470 mm (235 mm per arm). This means that the arms will have to be intelligently controlled to prevent it from crashing into the see-trough, acrylic enclosure. Therefore, a clearance banner of 100 mm is introduced to the system to allow for arm overhang to not collide with this acrylic enclosure.

The length of the arms was specially designed to allow for all 12 of the smallest allowable items to be collectible by the Keybot's arms, as well as to allow for the Keybot to dispense the item into the dispensing drawer on the front side of the Keybot to enhance UX. It is also vital that the arms should be able to be fully extended at the corners to allow for the arms to be able to point in in different directions. Without the latter design decision, the arms would have always pointed in one direction, which would have limited the reachable area of the arms even more.

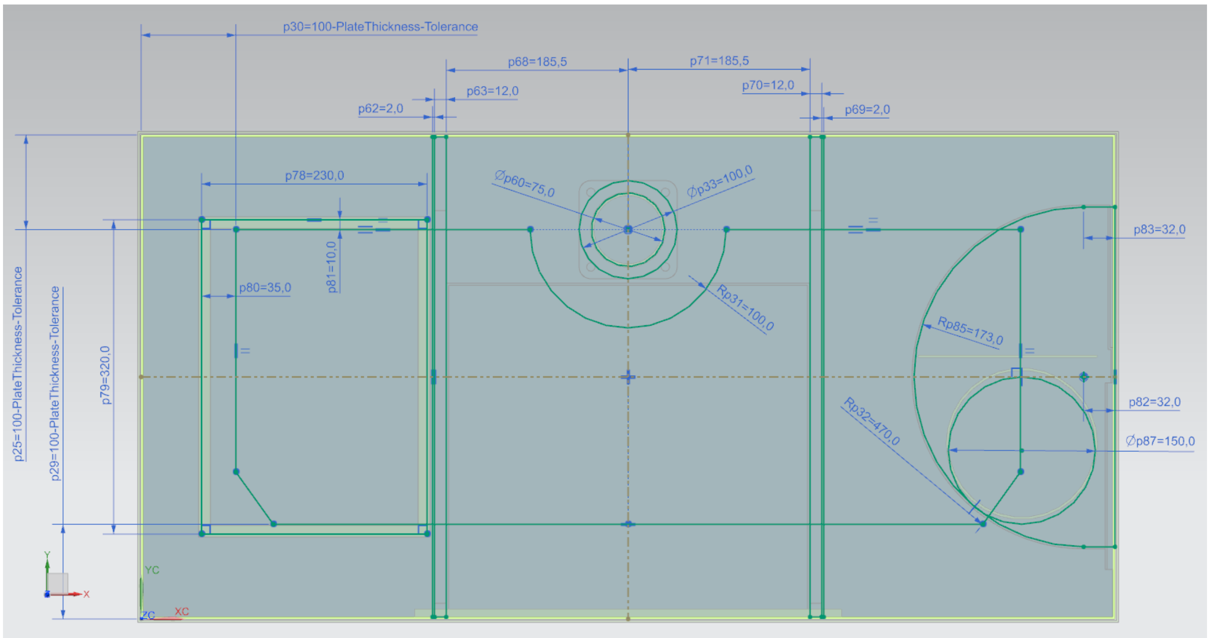


Figure 73: CAD View of Details of Electrical Enclosure Compartment Measurements

Figure 74 Illustrates the breadth, height and isometric views of the Keybot with and without the lid.

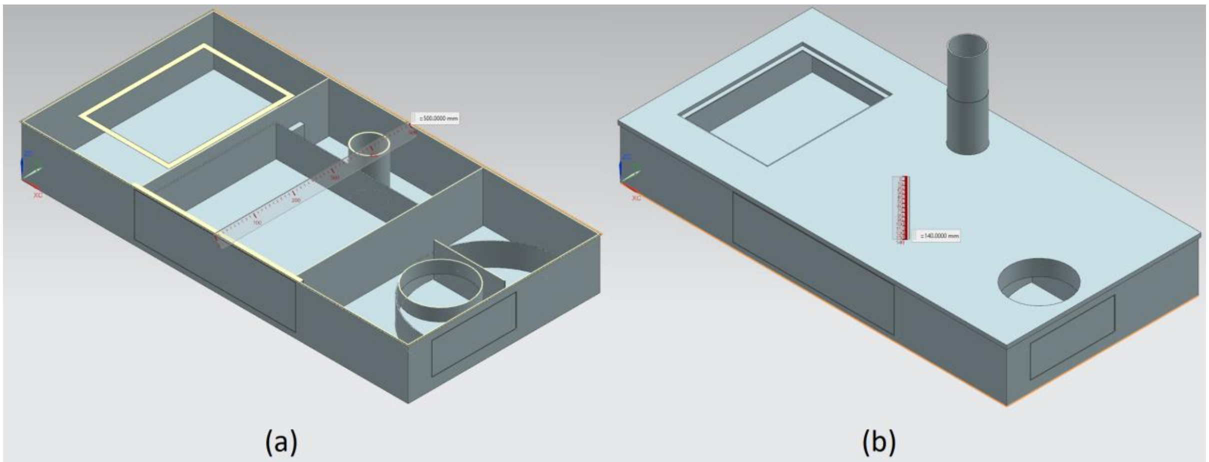


Figure 74: CAD View of Enclosure (a) Without Lid and Breadth Measurement and (b) With Lid and Height Measurement

3.2.3.17 Selective Compliance Articulated Robot Arm (SCARA)

There were a lot of considerations when it came to designing the actual SCARA mechanism. This included the housing of the tool needed to perform both the pick and place action and the engraving action, overloading the mechanism, degrees of freedom and the number of actuators needed, which would increase cost.

Two high-level ideas of the architectural design were considered. The first was to mount both the engraving tool and the pickup tool on the second arm. For this option, two solutions were considered, i.e., mounting the tools side by side at the same distance from the joint of the two-arm links. The second was to mount the two tools on a swivel that can rotate between the two tools as needed. There were some concerns regarding these two solutions from this first high-level idea. The first was the unnecessary weight that would be always carried by the SCARA since only one tool will be used at any given time. The other issue was that the dangling excessive tool would most probably get in the way of the natural flow of the motions of the arm as it could crash into other objects and would restrict the angle of rotation between the two arms. The third issue with this solution was that the items to be engraved needed an additional degree of freedom, which was to orientate the item the appropriate way for it to be fixable by the customizable cavity at the engraving station, this meant that the number of stepper motors needed would increase and overload the arm. Therefore, this first high-level idea would not have sufficed.

The second high-level idea was to make the tools exchangeable by automating the SCARA to uninstall and install both the tools as required. This solved all three of the issues with the previous idea since no unnecessary weight would have been carried at any given time, no unnecessary restrictions to the motion of the arm would be present and the number of stepper motors needed to achieve this design was reduced, thereby making it lighter and cheaper. There was, however, a few drawbacks that came with the design. The first was the new desire for a tool post where the tools could be uninstalled and installed in an automated way. The second issue was that the engraving tool and pickup tool, respectively needed to be electrically and pneumatically linkable. Although a bit more complex, this high-level idea was more reasonable than an overloaded SCARA mechanism.

Once this was decided, two designs for the placement of the components and the integration thereof were weighed against one another. The first was to stack the stepper motors to minimise the moment created by the hanging arm (see Figure 75 (a)). The other was to rather increase the z-axis travel capability by not stacking the motors (see Figure 75 (b)). The latter was chosen to accommodate for both the restricted height of the Keybot and the height of items as specified in the requirements.

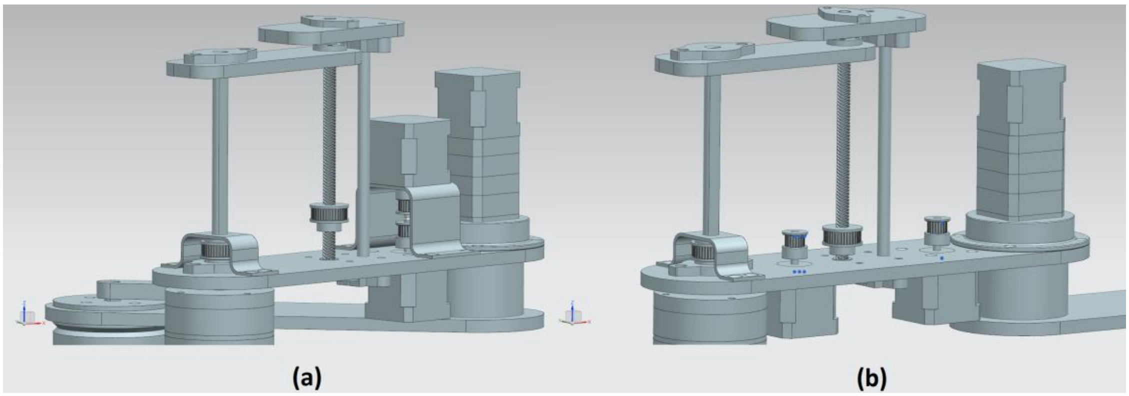


Figure 75: CAD Assembly Models of (a) The Stacked Stepper Motor Approach and (b) The Z-Axis Bias Approach

3.2.4 Detailed Architecture

The architectural design helps to determine all the components necessary to perform the functions of the FFBD and identify the interfaces required for a fully compatible setup. It consists of levels 0 to 2, which contributes to the final level (level 3), which is the detailed architectural design. The descriptions for the interfaces can be found at the end of the document in Appendix C: Interfaces.

3.2.4.1 Level 0

Figure 76 shows all the stakeholders that will interact with the system, which are outside the scope of the system. The Keybot will, however, interact with these stakeholders and thus, the necessary interfaces should be considered when designing the system.

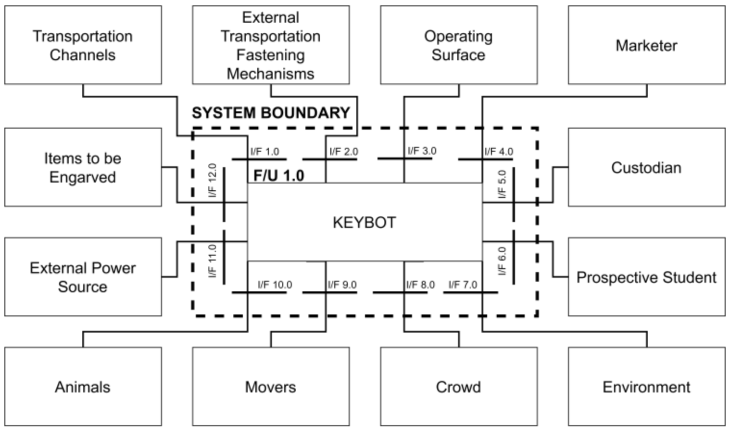


Figure 76: Architectural Design Level 0

3.2.4.2 Level 1

Level 1 of the Keybot system has five macro functional units. These are the supporting and encapsulating structure, the main power supply system, interface mechanism, controlling mechanism and manufacturing mechanism. Study Figure 77 to see which macros interface with each other and with the external stakeholders.

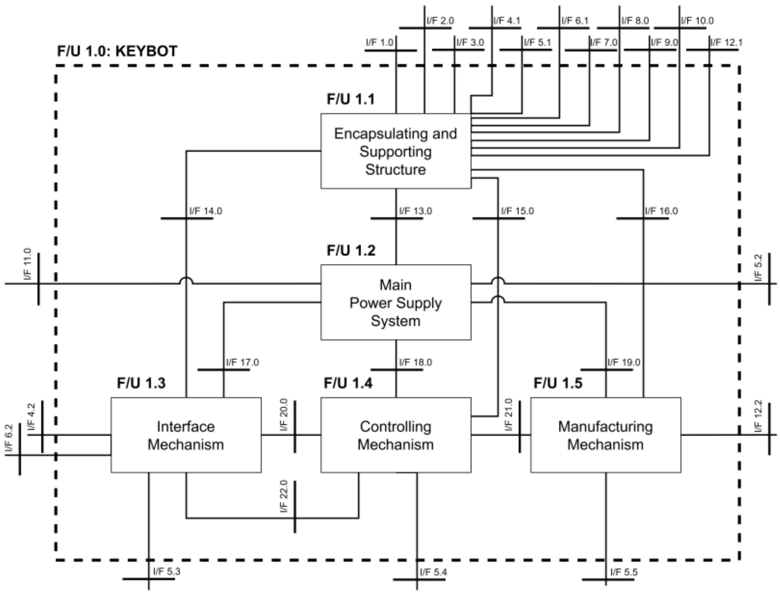


Figure 77: Architectural Design Level 1

3.2.4.3 Level 2

Level 2 of the Keybot system takes a deeper look into the five macro functional units (F/U). F/U 1.1 (structure) comprises of eight sub functional units (see Figure 78). The surrounding see-through enclosure acts as a barrier that protects the users and the SCARA robot from one another. The transport fastening mechanism is used to fasten the system with safety belts while being transported. The item loading station is where the palette is located wherein the items are placed for pickup by the SCARA robot. The manufacturing station is the area on which the items are engraved. The item dispensing station is a drawer wherein the engraved items are placed for collection by the user. The base enclosure of the demonstration platform is the electrical enclosure that protects the electronics from dust and liquids. The internal system storage is used to house the electronics and HMI. The adjustable feet are used to level the system for optimal torque performance by the motors.

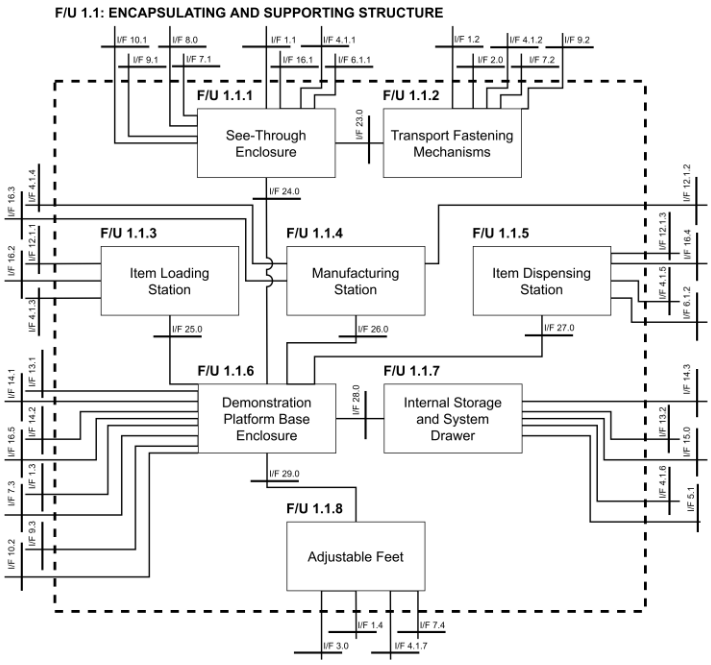


Figure 78: Architectural Design Level 2 Functional Unit 1.1

F/U 1.2 (power supply) comprises of four sub functional units (see Figure 79). It consists of the main AC to DC power supply, and three stations capable of delivering 12 V and two 5 V levels (one is dedicated to the Interface Mechanism and the other to the Controlling Mechanism).

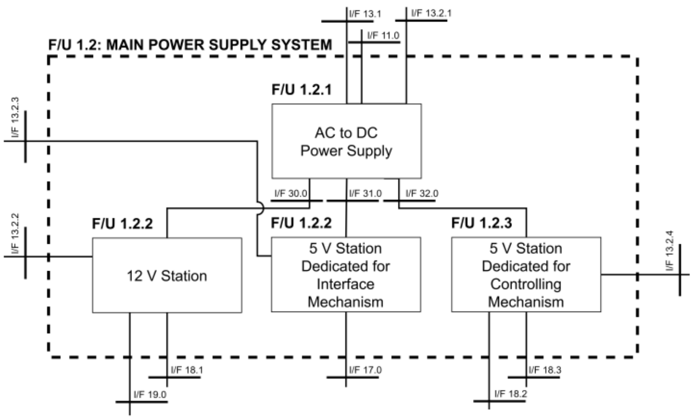


Figure 79: Architectural Design Level 2 Functional Unit 1.2

F/U 1.3 (interface mechanism) comprises of five sub functional units (see Figure 80). It consists of an LCD screen, capacitive touch overlay, Raspberry Pi, SD card and an emergency stop button.

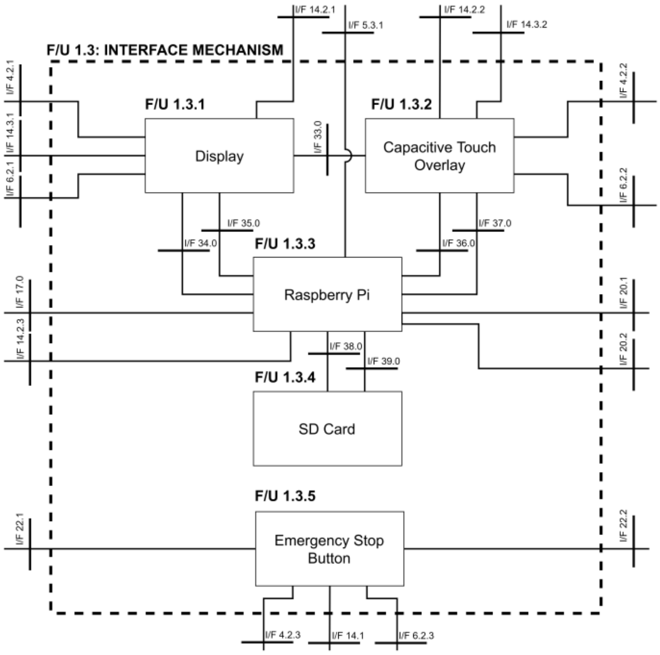


Figure 80: Architectural Design Level 2 Functional Unit 1.3

F/U 1.4 (controlling mechanism) comprises of seven sub functional units (see Figure 81). It consists of an STM MCU, four stepper motor drivers and two MOSFET drivers (one for the motor for the pickup tool and another for the motor of the engraving tool).

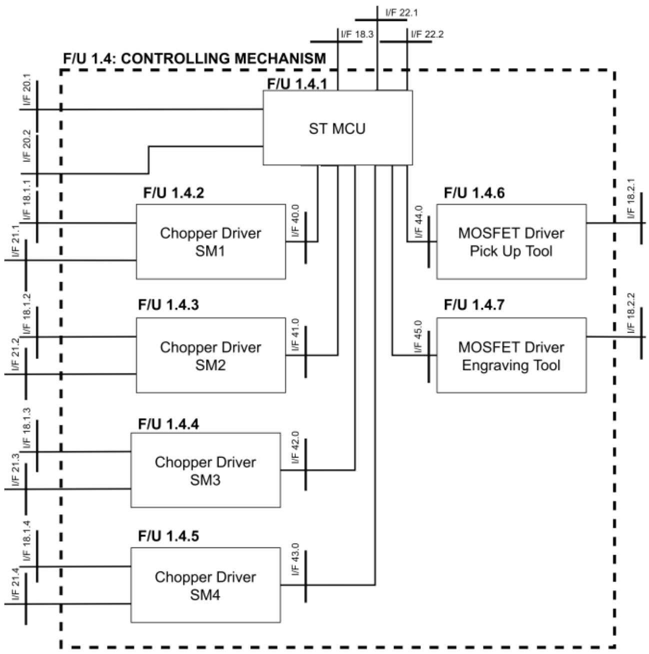


Figure 81: Architectural Design Level 2 Functional Unit 1.4

F/U 1.5 (manufacturing mechanism) comprises of fourteen sub functional units (see Figure 82). It consists of a base, four hybrid bipolar stepper motors, two gearboxes, a homing system, two aluminium arm links, a rotary to linear motion converting mechanism, an engraving tool, miniature pump and smart suction cup.

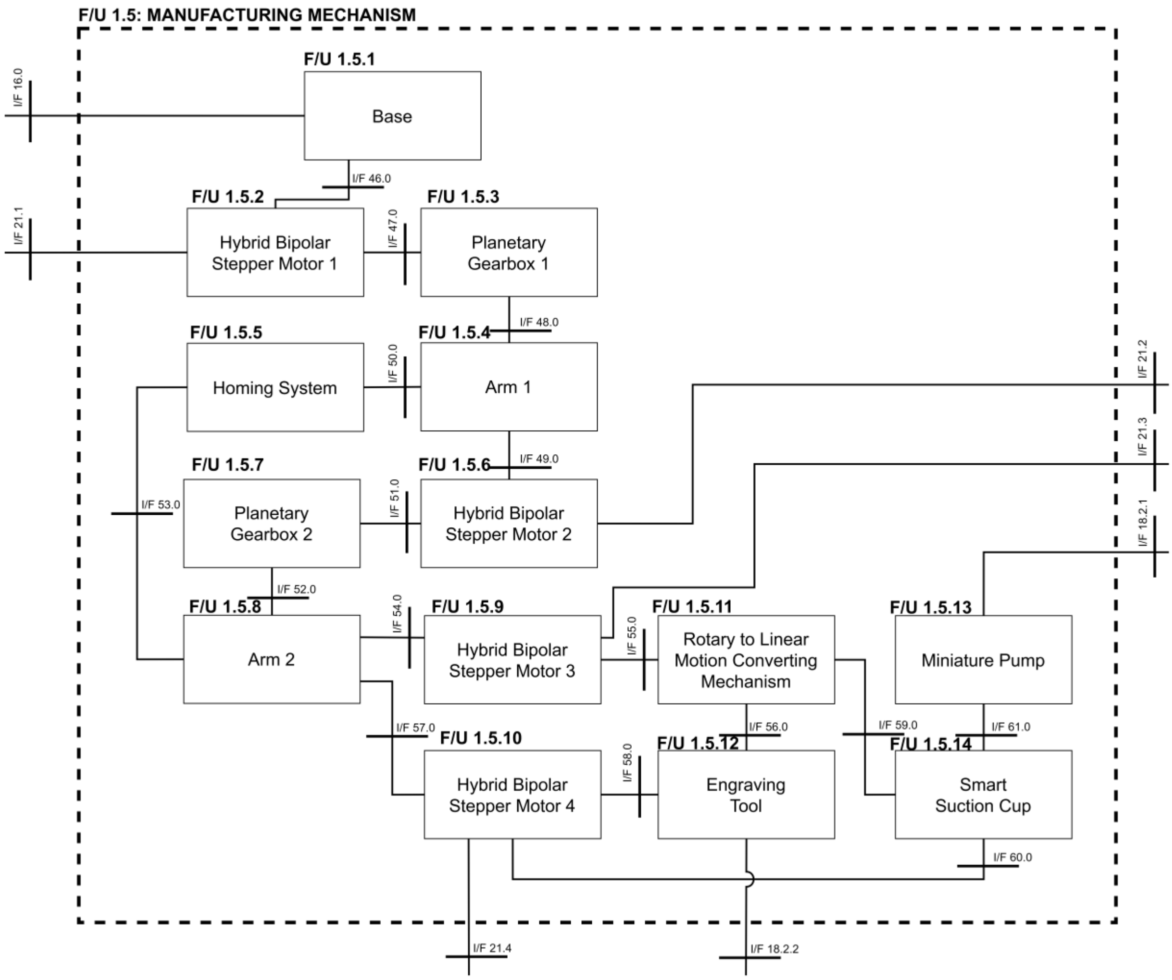


Figure 82: Architectural Design Level 2 Functional Unit 1.5

3.2.4.4 Level 3 (Detailed Architectural Drawing)

Now that we know which compound functional units are necessary and how they are interfaced to a satisfactory degree, these units can be decomposed to their purchasable parts as mentioned in the previous sections of available technologies.

This led to at least 111 functional units (excluding resistors, diodes, veroboard, wires, washers, nuts, bolts, etc.), which are heavily interfaced as can be studied in Figure 83. The descriptions of the interfaces are available in Appendix C: Interfaces.

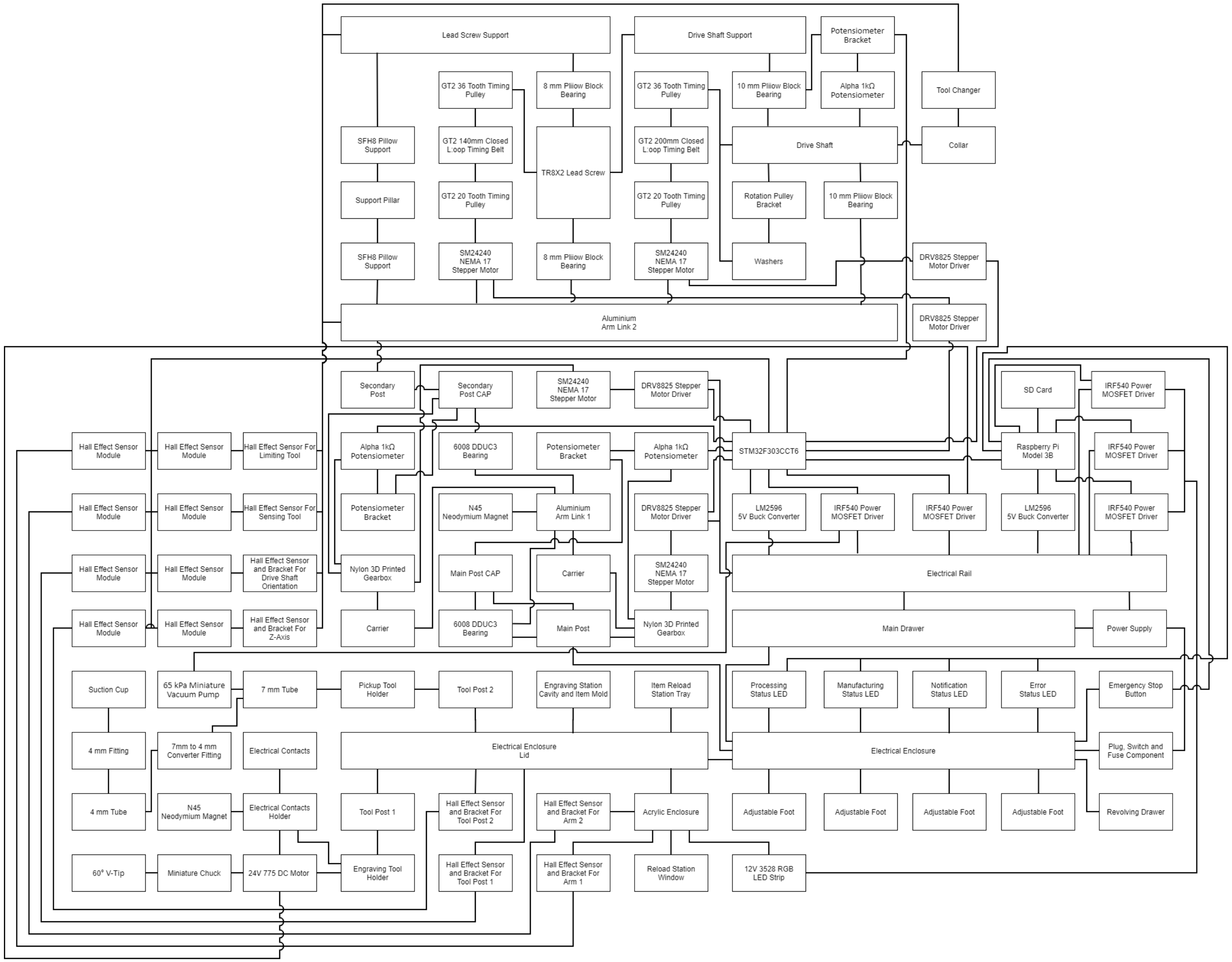


Figure 83: Detailed Architectural Design

3.3 CAD Design of Physical System

There are a few mechanisms, components and stations that also need to be designed physically. This will ensure that these components will have an acceptable shape, size etc. so that it can be evaluated if the project makes physical sense in accordance with the requirements.

3.3.1 PCB Design

The first of the lot is the most important part of the system, at least from a computer and electronic design perspective, the PCB. Since the system will require eight Hall-Effect sensors, their analogue to digital modules should be featured on the PCB. These modules are the blocks marked HSx, where x represents the number of the sensor module. The system also requires four stepper motors and, therefore, the stepper motor drivers (DRV8825) also need to be featured. These drivers are marked with labels SMx, where x represents the number of the stepper motor. The system also needs to change the duty cycle of the two DC motors (the engraver and the miniature vacuum pump). This can be accomplished by providing the system with power MOSFETs setup as switch modes. They are both labelled as “ENGRAVER” and “PUT” (Pickup Tool) respectively. Then there are three additional power MOSFET drivers which could be used for an LED strip if the project allows for such expenses to give the demonstration platform a more appealing look. Finally, the MCU is placed at the centre of all the electronic devices to make the PCB layout easily compatible. See Figure 84 for further details.

This PCB is too compact and hosts too many components to be designed as a single-layer PCB. Therefore, the PCB should be a two-layered one with 32 vias. The terminals are placed strategically to accommodate the layout of the other components in the main drawer as will be seen in a moment.

It should be noted that the large terminals can handle 15 A and the smaller ones, 6 A.

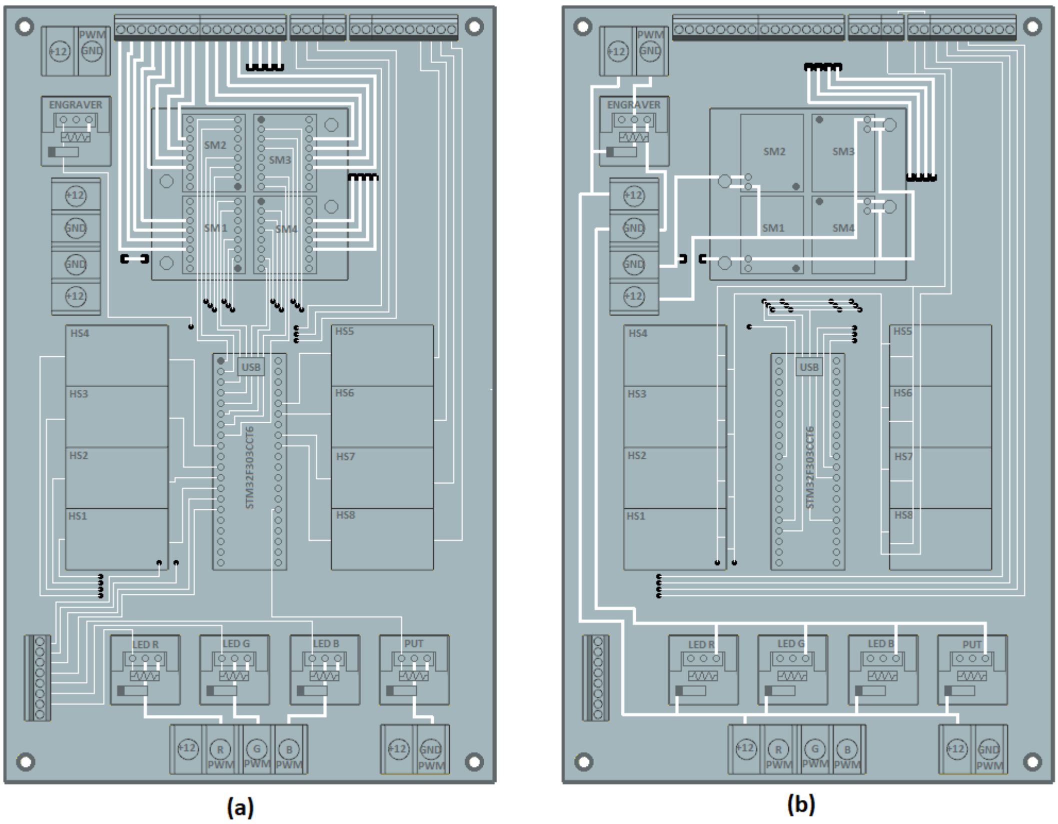


Figure 84: Schematic Diagram of the Two-Layer PCB Layout; (a) the Top and (b) the Bottom

3.3.2 The Main Drawer

The main drawer is where all the electronic components and static actuators are kept safe from outside interference and threats. The layout of this drawer is also optimised to ensure proper space for wires and easy interfacing to the other surrounding components to the PCB, such as the buck converters, Raspberry Pi, touchscreen, miniature vacuum pump and the power supply. An electric rail intercepts the wires from the power supply before reaching the PCB and buck converters to increase the current capacity in a smart way as will be seen later. This is because the power supply has three 12 V channels, each of which can provide 10 A. This is not enough in the case of the engraving motor suddenly stalling, which could lead to surges of up to 12.5 A. Furthermore, it makes the rest of the current division more equal. See Figure 85 for a better understanding of the layout.

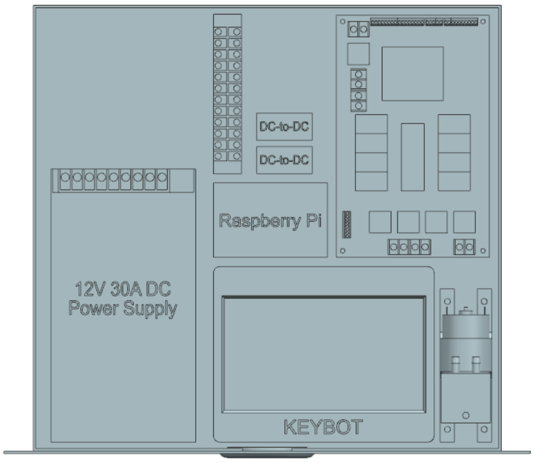


Figure 85: Main Drawer Layout

3.3.3 The Three Stations

As previously mentioned, the Keybot must be equipped with three stations for different operations. The first is the Reload Station for the reloading of items to be engraved and which acts as a source of items for the Keybot's SCARA mechanism during demonstrations. The second is the Engraving Station for fastening the items during the engraving process. This is somewhat elevated to promote the idea of a demonstration. Finally, the third, is the Dispensing Station for dispensing the post-engraved items to the user as a keepsake. The dimensions of all three stations were chosen while the requirements for the sizes of the items was kept in mind. See Figure 86 for further comprehension.

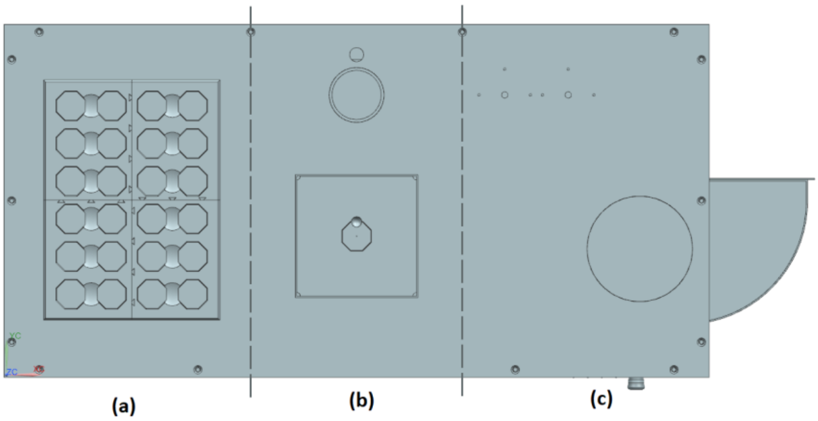


Figure 86: The Three Stations of Different Operation; (a) Reload Station, (b) Engraving Station and (c) Dispensing Station

3.3.4 SCARA Mechanism

The SCARA mechanism was designed with the purpose of minimum weight, minimum height, minimum cost and maximum range of movement. The combined length of the identical arms is 470 mm. This is enough to access all the items, as well as the centre of the Dispensing Station. This is, however, too long to easily move over to the other side of the system, as the enclosure will get in the way and cause a collision. There is, however, a way to avoid this, which is to fully extend the arms in either of the corners before allowing the second arm to switch sides. This will have to be incorporated in the software when planning the path of the mechanism.

The arm has four degrees of freedom (see Figure 87). The first is an angular movement around the post, the second is also an angular movement, however, around the joint between the two arms. These two alone already covers the entire XY plane. The third is the z-axis, which enables the engraving- and pickup tool to be elevated from or lowered to the item to interact with it appropriately. This covers the third dimension. Finally, the last degree of freedom is the angular movement around the drive shaft, which enables the SCARA mechanism to properly orientate the items when placing them in specifically shaped and oriented cavities at the Engraving Station. This extra degree of freedom is also what enables the SCARA mechanism to install and uninstall tools, which we will see more of later.

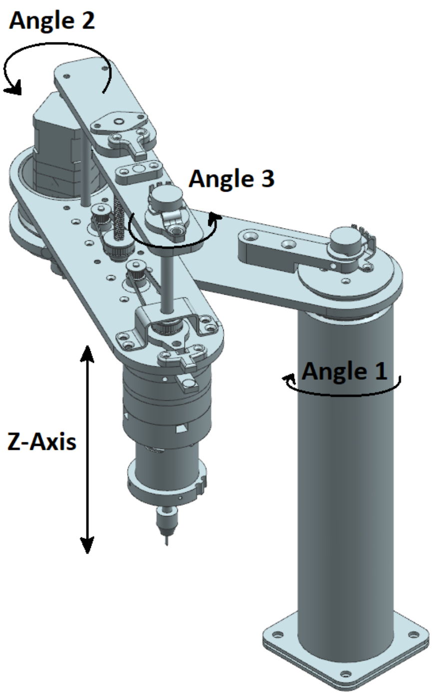


Figure 87: CAD Design of the SCARA Mechanism

3.3.5 Tool Changer Mechanism

Since the SCARA mechanism needs to be able to move an item around and engrave it, it needs to be able to use both tools. To incorporate both tools in a static manner on the arm was troublesome and a myriad of issues and problems kept coming forth when trying to implement such a design. Therefore, it was thought best to use a tool changing mechanism, which would be able to uninstall a tool and install the other while being able to connect electrically (engraver) and pneumatically (the vacuum pickup tool). This would lead to some smart mechanics to allow for such an ability, but it has advantages (less weight comes to mind).

Figure 88 shows the inside of the tool changer mechanism. It features five sections as indicated on the figure. Section A receives a collar lock, which makes it possible to fasten the tool changer to the drive shaft with three grubscrews. Section B hosts a neodymium magnet, spring and hall-effect sensor to push the contacts downward and sense when the tool is deep enough for lock and unlock during the tool changing process. Section C has a spigot that guides the disk with the two mounted hall sensors (one in section B and another in D), it also guides the electrical contacts (orange pillars seen in the disassembled view). Section D houses the electrical contacts, another Hall-Effect sensor and limits the tool from moving up too much into the changer. This second Hall-Effect sensor senses whether either of the tools are installed. Section E provides guide grooves for the pins coming out of the tool housing, which is used to lock the tool in place.

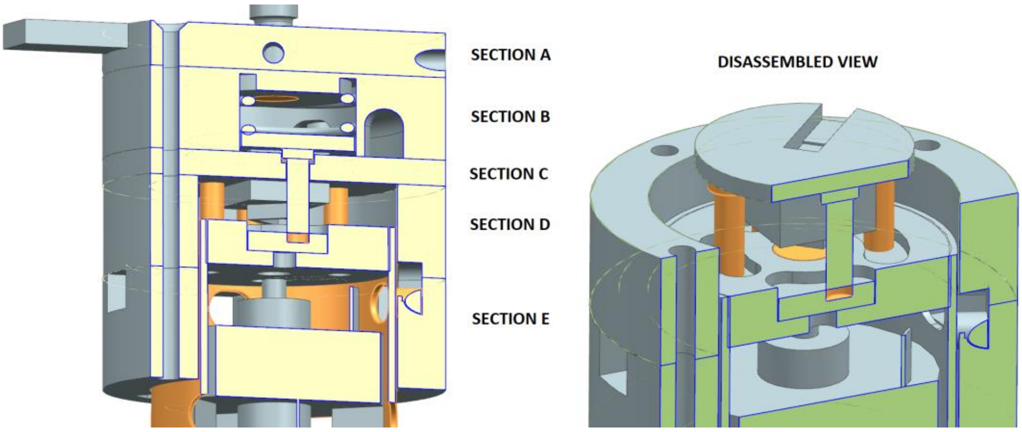


Figure 88: CAD Cross Sectional View of the Tool Changer Mechanism

The housing of the engraving tool also has four bean shaped electrical contact guides, two of which is used to provide power to the motor. The vacuum pickup tool has a tube coming from its side and is therefore always pneumatically connected. Both tools have neodymium magnets attached to the top to aid the Hall-Effect sensor in sensing the presence of a tool in the chamber.

3.3.6 Tool Post

The Tool Post is used to put away the inactive tools. These holders have their own key (see orange ring in Figure 89) to uniquely identify the post meant for which tool to avoid confusing the Keybot. They are also equipped with their own Hall-Effect sensors to enable the Keybot to sense if a tool is missing from the post after a power failure and possibly, when sensing an installed tool in the arm, would know which is installed so that it can act appropriately.

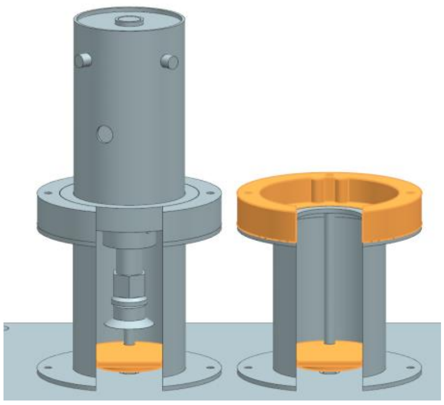


Figure 89: Tool Post

3.3.7 Final CAD Assembly Design

Below in Figure 90 is the finished CAD Assembly Design of the Keybot.

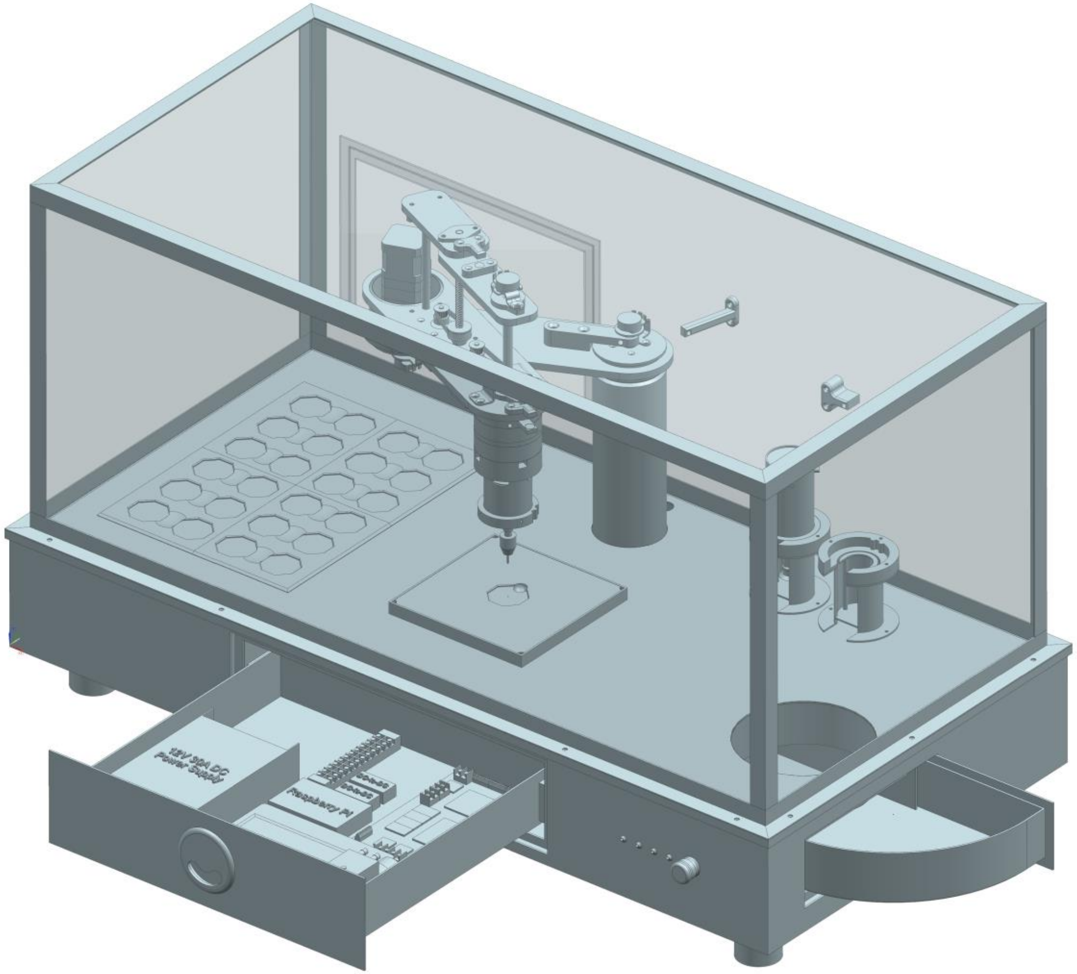


Figure 90: Final CAD Assembly Design

3.4 Software-Based Design

The software design of the system is crucial and will help understand the logical flow of the cycles of the system. This aided the hardware design in a parallel manner, as it made it clear which operations would need physical components and which physical parts needed special software.

3.4.1 System States

The system has its own finite state machine (FSM) defined in the System Requirements Document (Appendix A). We will therefore only briefly look at what is comprises of.

Figure 91 shows that there are mainly five states that the Keybot system could encounter itself in. The first is the initial state, which is the Powered-Down State. From this state, it should be able to enter the Active State once powered on and fall back when turned off. In the Active State, the user can command the system to enter the Reload State, Emergency Stop State or the Manufacturing State from the main menu. During the Reload State, the actuators will not move and allow a safe zone for a human to insert items into the Reload Station. During the Emergency Stop State (which could be entered from almost any other state), the system disrupts any kinetic process to allow a safe space for humans to handle the emergency. During the Manufacturing State, the SCARA mechanism will demonstrate a full cycle of picking up an item and transferring it to the Engraving Station where Engraving will commence and upon completion, will then transfer the item once more, but to the Dispensing Station, where the prospective student can collect their memento of the demonstration.

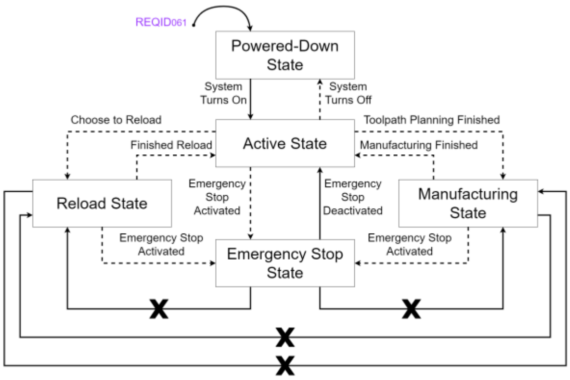


Figure 91: System State Diagram

3.4.2 System Modes

Each state has their own modes in which the Keybot may operate differently. In the Active State, the Keybot will be able to perform self-tests, initialise itself, idle, shut itself down, create a design or plan the toolpath for the design (see Figure 92 for reference of requirements found in Appendix A).

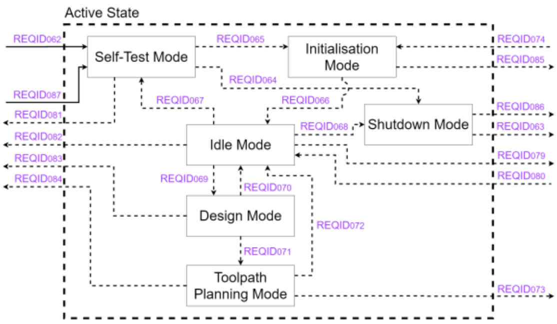


Figure 92: System Mode Diagram of the Active State

The Manufacturing State can be divided into an ATC mode (Automatic Tool Changing mode), Pick-and-Place mode or Item Engraving Mode. The Reload State is pure and only has a reload mode and the same goes for the Emergency Stop State. See Figure 93 for requirement references.

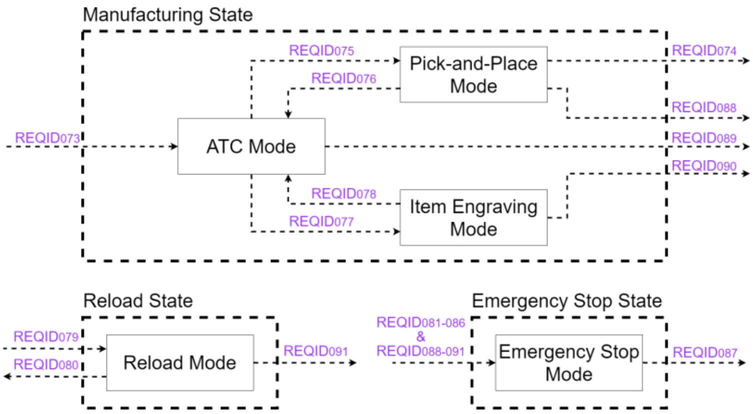


Figure 93: System Mode Diagrams of the Manufacturing State, Reload State and Emergency Stop State

3.4.3 GUI Mock-Ups

The GUI mock-ups are used to plan the logical interfacing flow with the operator and spectators. It is therefore important to keep it user friendly to enhance UX.

Figure 94 shows that during the self-test mode, the Keybot could communicate which processes were completed, which are being checked and which are still to be checked.

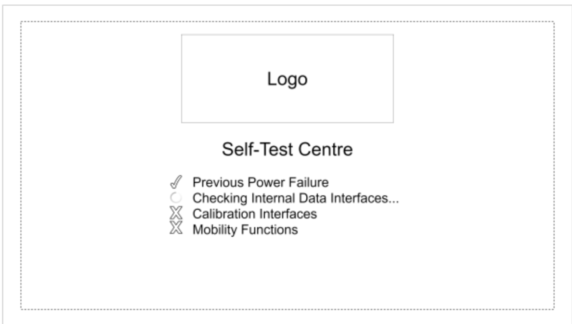


Figure 94: GUI Screenshot of the Executing Self-Test Centre

Figure 95 shows that when a self-test occurred in a failure, the user should be able to see contact information for assistance and have the option to turn the system off until maintenance can begin.

Figure 95: GUI Screenshot of the Self-Test Centre after a Failure Occurred

Figure 96 shows that the Keybot could communicate to the user which processes are yet to be completed before completion of the shutdown process.

Figure 96: GUI Screenshot of the Shutting Down Centre after Power Down is Commanded

Figure 97 shows the same as Figure 96, but for the initialisation process.

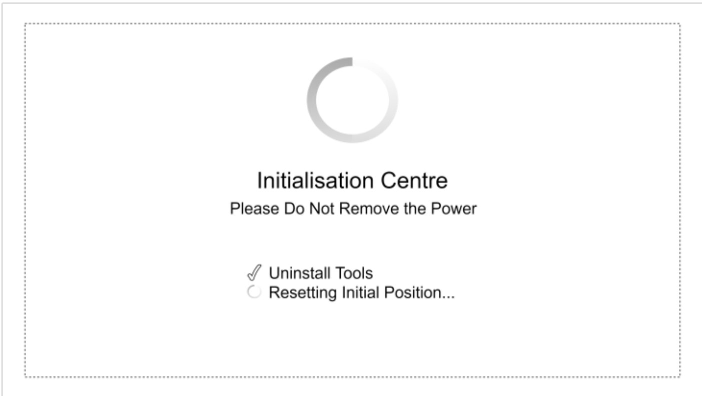


Figure 97: GUI Screenshot of the Executing Initialisation Centre after Successful Self-Test

Figure 98 shows the options for navigating the system from its command centre. The user can choose to create an item, reload items, run a self-test or shutdown.

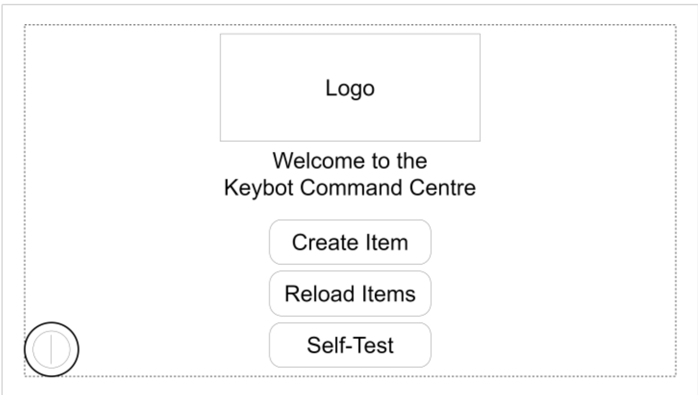


Figure 98: GUI Screenshot of the Command Centre after Successful Initialisation

Figure 99 shows the options that the user has upon entering the Reload Centre. The user can choose to reload the palette with items, create a new type of palette (for a new type of item) or delete a palette. It also shows which slots are still occupied according to the system and where the centre of mass of the item is located relative to a circumscribed circle bounding the item.

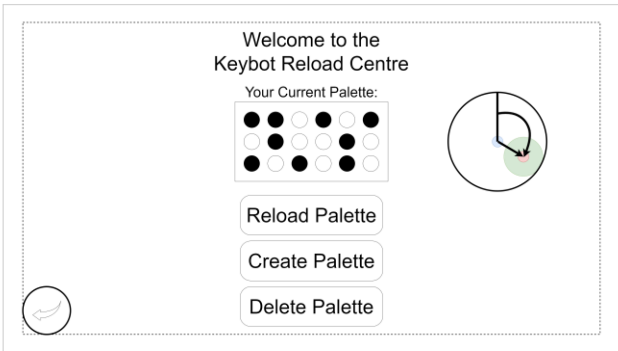


Figure 99: GUI Screenshot of the Reload Centre after the User Chose to "Reload Items" from the Command Centre

Figure 99 shows a table of existing palettes created by the operator, which is stored in the database of the system. It allows the user to choose a palette to load, specify which slots are occupied or to download the dimensions of the plan for the palette for constructing the palette for compatibility.

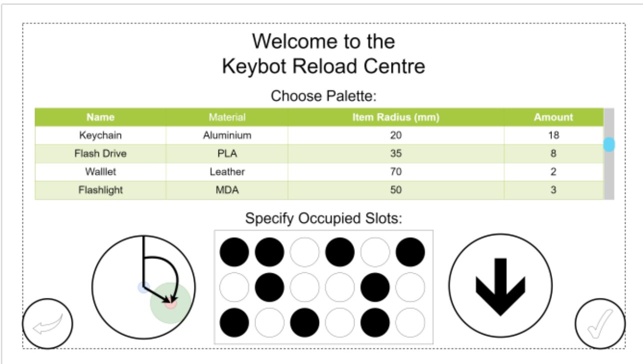


Figure 100: GUI Screenshot of the Reload Centre after the User Chose to "Reload Palette" from the Reload Centre

Figure 101 shows the form to create a new palette. This includes a name, item material specification, size and number of items. The latter will be limited respective to the chosen size.

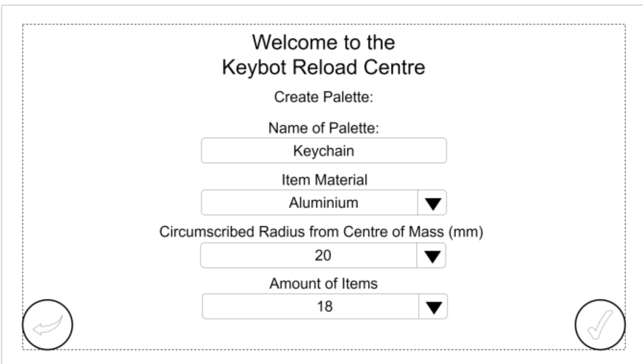


Figure 101: GUI Screenshot of the Reload Centre after the User Chose to "Create Palette" from the Reload Centre

Figure 102 shows the second part of the form that needs to be completed to create a new palette. This relates to the centre of mass and its position with relation to the body of the item. This will help the Keybot balance the item when picking it up.

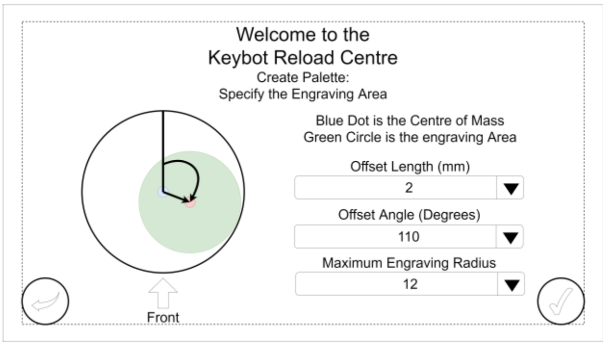


Figure 102: GUI Screenshot of the Reload Centre after the User Chose to Continue from the First Part of the Form

Figure 103 shows the resulting generated palette once a valid form was submitted. The user can choose to accept the design or download the dimensions.

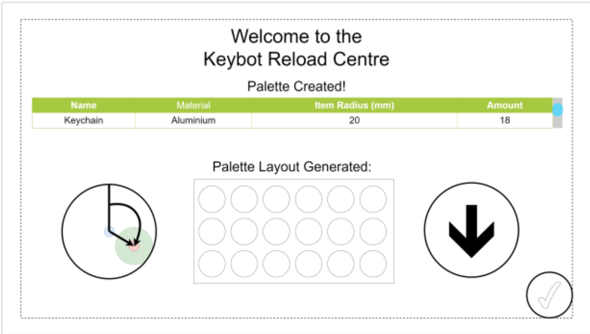


Figure 103: GUI Screenshot of the Reload Centre after the User Completed the Form and a Valid Palette Plan was Generated.

Figure 104 shows that the user will be able to see where the downloaded dimensions plan can be located after a successful download.

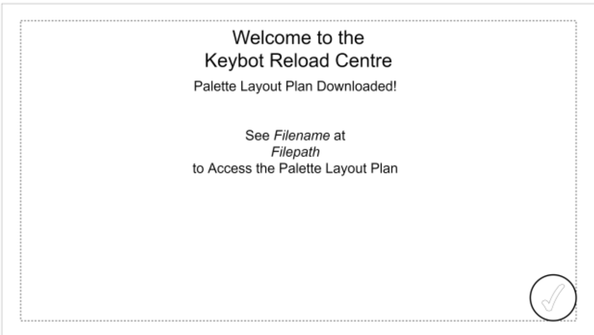


Figure 104: GUI Screenshot of the Reload Centre after the User Chose to Download the Dimensions of the Generated Palette Layout

There could arise instances where a user wants to delete a palette plan from the database. Figure 105 shows the screen used exactly for this purpose. A list of all the palettes is shown in list format and the user can mark which once need to be deleted and specify whether to continue deleting the selected plans or cancel the request.

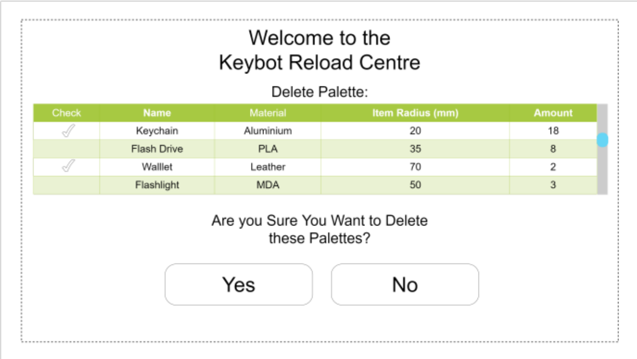


Figure 105: GUI Screenshot of the Reload Centre after the User Chose to "Delete Palette" from the Reload Centre

Figure 106 shows the list the user will see to notify the successful deletion of the specified plans.

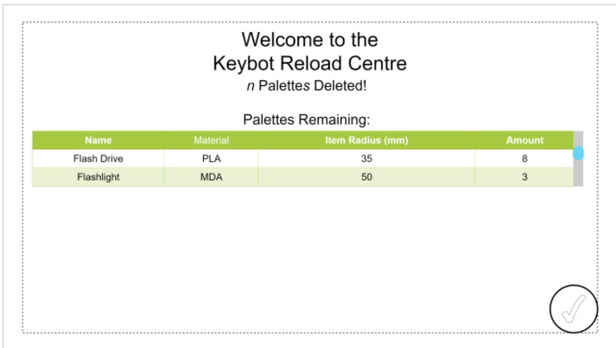


Figure 106: GUI Screenshot of the Reload Centre after the User Chose to Continue Deleting the Selected Plans

Figure 107 shows the options that the operator will have once selecting to create an item from the command centre. This includes editing the design, choosing an item or starting the process.

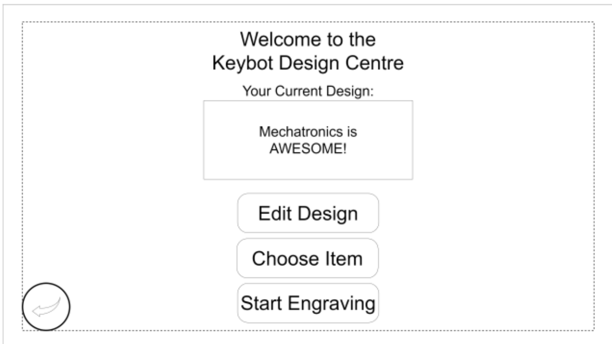


Figure 107: GUI Screenshot of the Design Centre after the User Chose to "Create Item" from the Command Centre

Figure 108 shows on on-screen keyboard to which the user will have access to when specifying the letters to be engraved on the item. The user enters this screen when selecting to edit the design.

Figure 108: GUI Screenshot of the Design Centre after the User Chose to "Edit Design" from the Design Centre

Figure 109 shows the palette last specified by the operator to be active at the time. The occupied slots will be highlighted to indicate that they can be chosen. The user can touch an item to choose which slot to retrieve the item to be engraved from.

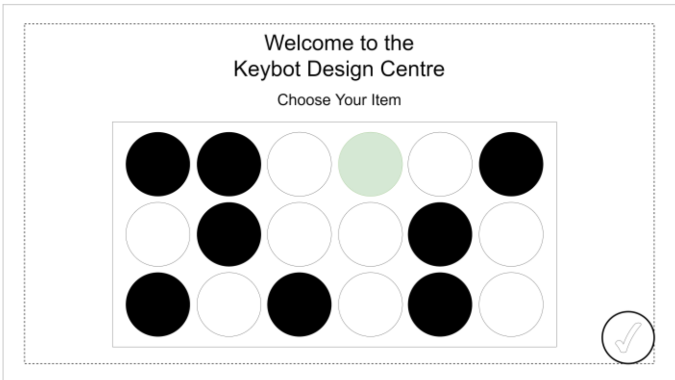


Figure 109: GUI Screenshot of the Design Centre after the User Chose to "Choose Item" from the Design Centre

Figure 110 shows that the system could communicate how far along the toolpath planning process is before the demonstration process can commence.

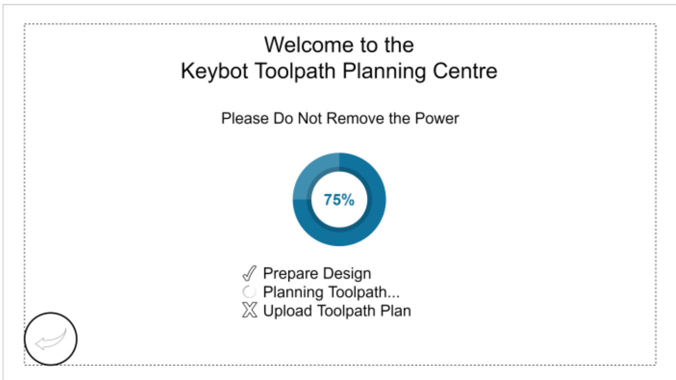


Figure 110: GUI Screenshot of the Toolpath Planning Centre after the User Chose to "Start Engraving" from the Design Centre

Figure 111 shows that the system could communicate the processes that have been completed, which are in process and which are yet to begin. This can also help the demonstrators keep track of their explanation of the system during demonstration.

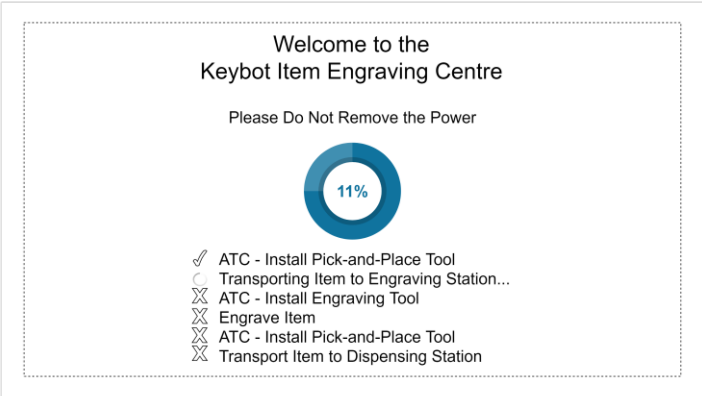


Figure 111: GUI Screenshot of the Engraving Centre after the System has Completed the Toolpath Planning Process from the Toolpath Planning Centre

3.4.4 ERD's

The system will require a database to store all the designs of the palettes. To implement a database, an entity relationship diagram (ERD) is best used to understand how the database should be set up.

Figure 112 is such a model and has three entities with relations. The first is the palettes table, which stores all the general information of the layout and dimensions of the palette. The second is the items table, which stores the name, material type and size of the item. The last table is the materials table, which is used to store parameters of the duty cycle of the different methods of engraving if the system is to expand to other engraving alternatives. Since a palette may only host one type of item and an item may be loaded into different size palettes, this relationship is a one-to-many. Also, since the items are allowed to only exist of one type of material and a type of material may take the form of different items, this is also a one-to-many relationship.

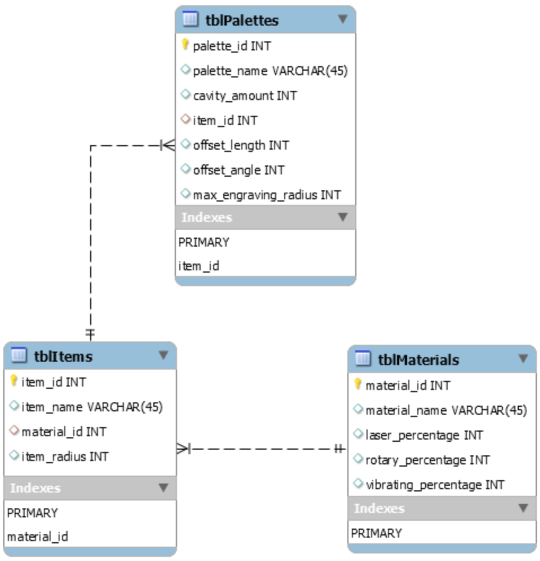


Figure 112: ERD of the Keybot System for Storing Palette Layout Models

3.5 Resource Allocation Matrix

Since the System is too complex to easily communicate the entire resource allocation matrix together with all the codes of the functional blocks and functionals units, Table 25 is only an essential version thereof. I.e., only the most important functions are grouped and listed for evaluating resources. Since all the functions have at least one resource assigned to it, all the functions have been provided for with the above detailed system architecture.

Table 25: Keybot System Essential Resource Allocation Matrix

	Adjustable Feet	Aluminium Enclosure	Emergency Stop Button	7-inch Capacitive Touchscreen	Eight Hall-Effect Sensors	STM32F303CCT6	Raspberry Pi 3 Model B	Two Buck Converters	Power MOSFET Drivers	12V 30A Power Supply	Miniature Vacuum Pickup Tool	Mechanical Rotary Engraver	Four DRV8825 Stepper Motor Drivers	Four SM24240 Stepper Motors	Tool Changer	Tool Post	Reload Station	Engraving Station	Dispensing Station	Nylon 3D Printed Gearboxes (1:16)	Three Potentiometers
Provide Power								•		•											
Receive Commands from User			•	•			•														
Communicate Results with User				•			•														
Design Path				•			•														
Toolpath Planning							•														
G-Code Interpreter						•															
Generate Actuator Controlling Signals						•															
Control Stepper Motor Direction						•							•								
Control Stepper Motor Steps						•							•								
Control Engraver RPM						•			•			•									
Control Vacuum Intensity						•			•		•										
Move Arm 1													•	•						•	
Move Arm 2													•	•						•	
Move Z-Axis Drive Shaft													•	•						•	
Move Orientation Drive Shaft													•	•						•	
Initialise Steps					•	•							•	•						•	•

3.6 Conclusion

The systems engineering design process was executed and documented in this chapter.

A functional flow diagram was extracted from the system requirements document and an accommodating physical architectural design was designed. A lot of alternatives between technologies were compared to one another and the most appropriate and compatible technologies were chosen.

It was concluded that the Keyboy will comprise of the following parts:

- Adjustable Feet
- Aluminium Enclosure
- Emergency Stop Button
- 7-inch Capacitive Touchscreen
- Eight Hall-Effect Sensors
- STM32F303CCT6
- Raspberry Pi 3 Model B
- Two Buck Converters
- Power MOSFET Drivers
- 12V 30A Power Supply
- Miniature Vacuum Pickup Tool
- Mechanical Rotary Engraver
- Four DRV8825 Stepper Motor Drivers
- Four SM24240 Stepper Motors
- Tool Changer
- Tool Post
- Reload Station
- Engraving Station
- Dispensing Station
- Nylon 3D Printed Gearboxes (1:16)
- Three Potentiometers

The software's structure will be an FSM with five states:

- Shutdown State
- Active State
- Reload State
- Emergency Stop State
- Manufacturing State

The Active State will have six modes:

- Self-Test Mode
- Initialisation Mode
- Idle Mode
- Shutdown Mode
- Design Mode
- Toolpath Planning Mode

The Manufacturing State will have three modes:

- ATC Mode
- Pick-And-Place Mode
- Item Engraving Mode

The Reload and Emergency Stop States are Pure and does not have multiple modes.

The mock-up GUIS were designed for optimal UX and is well-suited for addressing the functional requirements of the system.

An ERD diagram was designed which will aid the system in recalling all the saved palette layout designs.

4 Implementation

After a few months of COVID-19, the lockdown was lifted to level1 and the citizens of South Africa could buy products once more from non-essential businesses. This has put my project under a lot of time pressure and the project could not be fully implemented in time. I did, however, suffice to implement a substantial part thereof and I am hoping to be able to demonstrate a functional project before the deadline thereof. However, my hands were tied and there was little I could do to finish such a large project intime, especially given the circumstances.

I did, however, have more than enough time to search for components on the internet to find the best prices for the day we could buy products without restrictions. The total cost of the project was around R13 000. The electronic components cost about R8 900 and the mechanical parts, the rest.

I should also note that a mechatronics project such as this one is not ideal for demonstrating computer and electronic engineering. Although these aspects are included in the scope, the mechanical part has also taken a huge toll on my available time and the mechanical issues, which we will address later, have obstructed my progress and ability to demonstrate working parts (mostly software development for controlling the motors given a serial command from the Raspberry Pi to the STM32F303CCT6). The arm did, however, move around, but with great difficulty. This prevented the system to engrave the items and is therefore not featured in this report.

4.1 Hardware

The hardware implementation of the system was completed to the best of my ability given the circumstances described above. The CAD designs of the system can also be found in Appendix B: System CAD Design Pack. There remains, however, mechanical issues with the SCARA mechanism, which will be addressed in the next chapter.

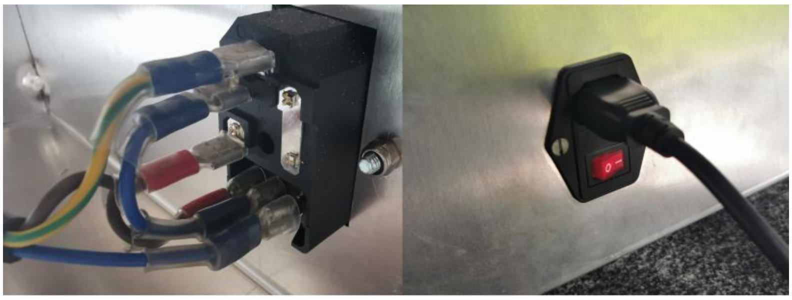
4.1.1 3D Printed Nylon Gearbox

The planetary gearbox designed in NX in chapter 3 was converted to STL files and as seen in Figure 1, 3D printed by me (relatively a beginner of a few months at the compilation of this report). Take note that Nylon is one of the most difficult filaments to print with MDF printers, however, the gears fit snugly into each other and there is a noticeable increase in torque and decrease in speed on the output shaft of the stepper motor and gearbox system. I therefore accepted this part as sufficient.


(a) (b)

Figure 113: 3D Printed Nylon Planetary Gearbox (a) Cross Sectional View (b) Stacked Gearbox

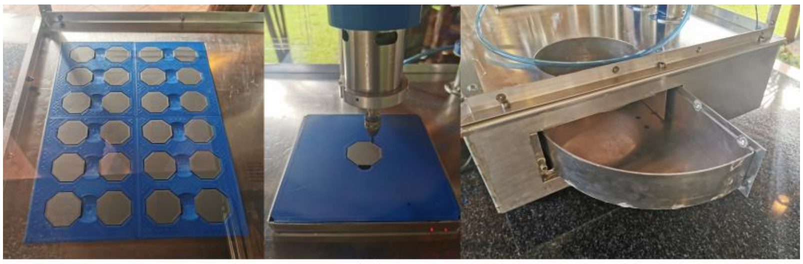
There was strangely no datasheet for wiring the main power supply three-in-one plug, fuse and switch. I did, however, manage to figure it out and it works as expected (see Figure 114).



(a) (b)

Figure 114: Main Power Supply Plug, Fuse and Switch (a) Installation (b) Result

Figure 115 shows the three stations of different operation in its realised form. The palette in (a) and the cavity in (b) can easily be swoped with others to accommodate different types of items. The Dispensing station has its own push to open mechanism for collecting the item.



(a) (b) (c)

Figure 115: The Three Stations of Different Operation Realised; (a) Reload Station, (b) Engraving Station and (c) Dispensing Station

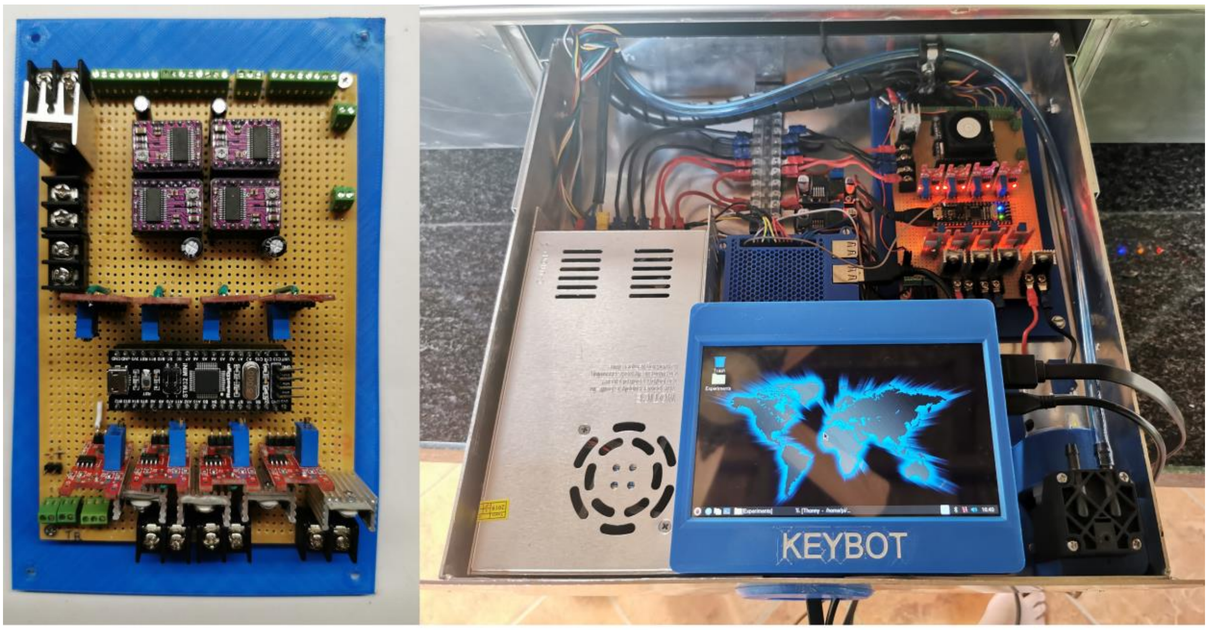
The SCARA mechanism also has some of its own tolerance to precision but performs well. See Figure 116 for the realised mechanism.

(a) (b)

Figure 116: SCARA Mechanism Realised (a) Full View (Closeup)

During the lockdown period, I did not know when or if it would be safe to order a PCB from a PCB manufacturer. I therefore took an alternative root by implementing a veroboard (seen in

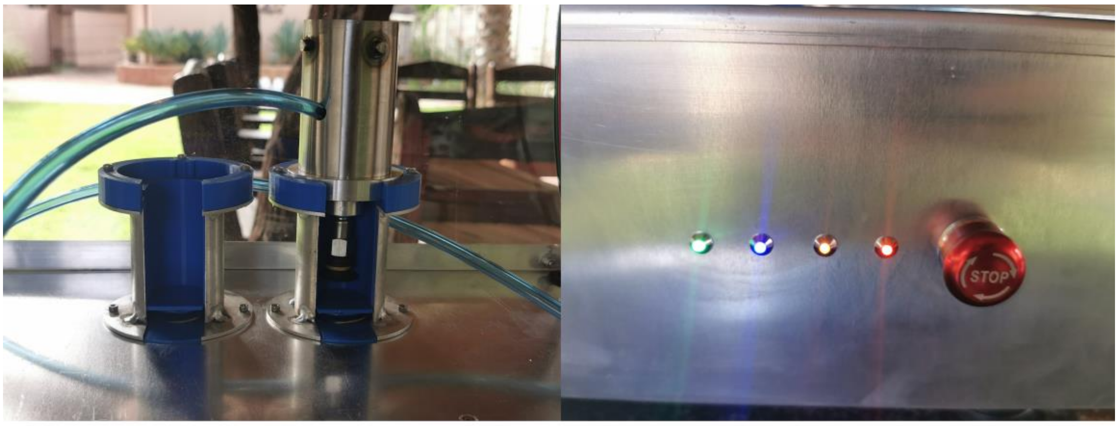
Figure 117 (a)). The bottom of this board has a bunch of wires and is therefore isolated from the conductive drawer by means of an ABS printed film. As can be seen in Figure 117 (b), all the electronics and actuators fit into the drawer and the touchscreen also works fine.



(a) (b)

Figure 117: Realised Electrically Wired System (a) Veroboard Implementation (b) Main Drawer Displayed

As seen in Figure 118 (a), the tool post is also implemented. I also decided to implement a secondary interface which is used to indicate what state the Raspberry Pi finds itself in. The green light is meant for indicating processing, the blue is used for indicating manufacturing, the yellow is for indicating the presence of notifications to the user and the red one is for indicating that the emergency stop state is active.



(a) (b)

Figure 118: Realised (a) Tool Post and (b) Secondary Interface

Figure 119 shows a closable grommet designed and printed by me for sealing and opening the front of the main drawer to accommodate for the cables of the touchscreen. Now the drawer does not have to be opened to access the touchscreen and the electronics are better protected.

(a) (b)

Figure 119: Closable Grommet for Cables (a) Closed (b) Opened

Figure 120 is a picture of the finished Keybot system at its fully extended volume.

Figure 120: Built Keybot System

4.2 Software

Given the time consumed by the mechanical issues and delay of parts, the software could not be fully implemented at a GUI and database level, but could maybe be implemented before demonstration, as this is not a vital part of the functionality of the system. The only parts vital to the functionality of the system is the reception of a design, conversion to g-code, serial transmission of the g-code to the STM32, interpretation of the code (with some sort of handshake to the Raspberry Pi) and the generation and reception of signals to actuators and their modules, and from sensors.

We will thus divide this subsection into two parts: the software of the STM32 and that of the Raspberry Pi.

4.2.1 STM32F303CCT6 - Configuration

This MPU has an M4 32-bit Arm Cortex CPU with a max clock frequency of 72 MHz. It has an operating voltage of 2.0 V to 3.6 V, 256 Kbytes of flash memory and 40 Kbytes of SRAM. It has a 12-channel direct media access controller (DMA), 4 ADCs of up to 39 channels, 13 timers with different numbers of PWM channels and up to 5 UARTS.

For the Keybot to operate, the following is required: two PWM pins for the DC motors, eight digital input pins for the Hall-Effect sensors, three ADC pins for the potentiometers, one UART and another eleven digital output pins for controlling the stepper motor drivers.

The layout of the PCB, the interfacing with other electronics in the drawer, and the availability of peripherals on each pin were all kept in mind when the pin configurations were considered. I managed to configure the MPU to incorporate all the previously mentioned peripherals in a way as to spare the most valuable pins for future use while using the least number of timers and CPU computational overhead (see Table 26 for the mapping of the peripherals to their pins and the external devices).

Table 26: Map of External Devices to Pins and Peripherals using Macros

External Device	Type of Peripheral	Macro	Pin
Power MOSFET Driver for Engraver DC Motor	PWM (TIM2 CH1)	MTR_E	PA15
Power MOSFET Driver for Vacuum Pump	PWM (TIM2 CH2)	MTR_V	PA1
Hall-Sensor 1 (Engraver Tool Post)	GPIO_Input	HS_1	PB5
Hall-Sensor 2 (Pickup Tool Post)	GPIO_Input	HS_2	PB4
Hall-Sensor 3 (Limit Sensor Z-Axis)	GPIO_Input	HS_3	PB3
Hall-Sensor 4 (Init. Sensor Orientation)	GPIO_Input	HS_4	PA12
Hall-Sensor 5 (Limit Sensor ATC)	GPIO_Input	HS_5	PB11
Hall-Sensor 6 (Tool Presence Sensor)	GPIO_Input	HS_6	PB10
Hall-Sensor 7 (Init. Sensor Arm1)	GPIO_Input	HS_7	PB0
Hall-Sensor 8 (Init. Sensor Arm2)	GPIO_Input	HS_8	PA7
Potentiometer 1 (Arm 1)	ADC2_IN3	POT_1	PA6
Potentiometer 2 (Arm 2)	ADC2_IN2	POT_2	PA5
Potentiometer 3 (Orientation)	ADC2_IN1	POT_3	PA4
UART TX	UART1_TX	TX	PB6
UART RX	UART1_RX	RX	PB7
Microstepping Setting (Register)	GPIO_Output	(M_2,1,0)	PB8,9,PA0
Stepper Motor Step_x, x = {1,2,3,4}	GPIO_Output	SMx_S	PB15,13, PA11,9
Stepper Motor Direction_x, x = {1,2,3,4}	GPIO_Output	SMx_D	PB14,12, PA10,8

After confirming that all the peripherals are configurable in a sparingly way while keeping the PCB design (minimal cross overs), and the location of the other external devices in the drawer in mind, the map in Table 26 was implemented in the STM32CubeIDE Package (see Figure 121).

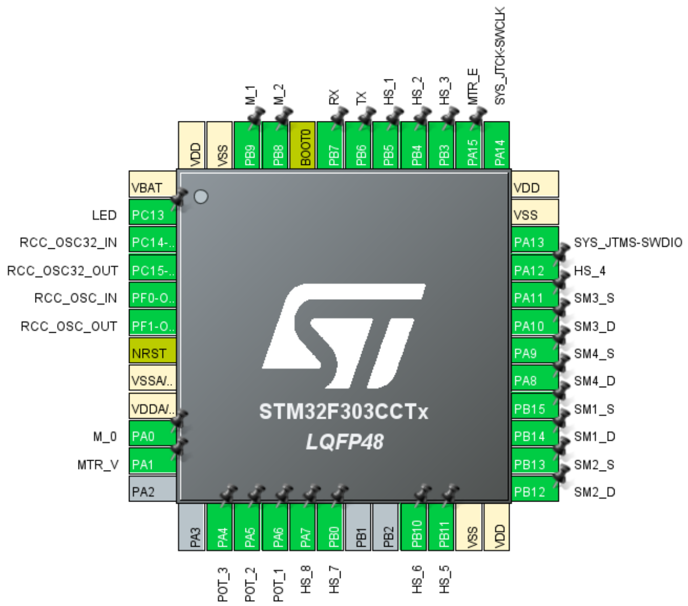


Figure 121: Pin Configuration of the STM32F303CCT6 in the STM32CubeIDE Package

This left PA2, PA3, PB1, PB2 and PC13 as unused pins. However, PB2 is not usable since it is the reset line of the MPU, and I implemented PC13 as a debugging tool (onboard LED). The other three pins are all left configurable as ADCs, DACs, COMP, OPAMP, PWM, GPIO or external interrupts with PA2 and PA3 having an additional option as UART2.

The concepts that made this optimised configuration possible is the extensive use of the DMA. The DMA is used to allocate memory addresses to peripherals so that the values from the peripherals are continuously stored in memory without bothering the CPU. This means that we can allow sufficient memory to a peripheral so that multiple instances of the same peripheral can be implemented in an exchanging way. Therefore, we are essentially multiplexing the three channels of ADC2 with DMA2's channel 1 to essentially act as three different ADCs. DMA1's channels 5 and four were also set up to extend the 8-bit receiving buffer of the UART to any programable array size.

Timers 1 to 3 were also configured to aid with the operations of the MPU. Timer 1 was implemented with a pre-scaler of 72 (71 in the register) and maxed ARR to incorporate a polling function for debugging purposes at a microsecond scale since the HAL_Delay() function works on the millisecond scale. Timer 2 is used as the source for the PWMs controlling the DC motors and is set at a pre-scaler of 360 (359 in the register) and period of 100 (ARR of 99) to result in 2kHz PWM signals. I will explain the implementation of Timer 3 at a later stage.

4.2.2 STM32F303CCT6 – FSM

Since the STM32 PMU is essentially a slave to the Raspberry Pi, it makes sense that it should also have its own finite state machine. These states include Idle, Change_PWM, Update_Target_Position, Emergency_Stop, Acknowledge, Initialisation, Change_Tool, SET_Angles and Increment.

The Idle state waits for the HAL_UART_RxCpltCallback function to be called as soon as enough data is received, which stores the data in the DMA in a variable called rx_message. This process also raises a flag that indicates when the STM32 has unprocessed messages. The Raspberry Pi then waits for an ACK for up to 60 seconds before resending the data. Therefore, no messages will be written over unprocessed ones.

The instructions sent by the RPi are not traditional g-code instructions, but rather a new variant that always sends the same length of data, i.e., 10 bytes to trigger the DMA's call-back function. The instructions range as explained in Table 27.

Table 27: Summary of Available Instructions to Callout to the STM32

Instruction Format	Description	x MASK Range
TOOL1_xxxx	Changes the PWM Percentage of Tool 1 Accordingly.	0000 - 0100
TOOL2_xxxx	Changes the PWM Percentage of Tool 2 Accordingly.	0000 - 0100
ANG1_xxxxx	Changes the Target Steps Variable for SM1.	00000 - 12800
ANG2_xxxxx	Changes the Target Steps Variable for SM2.	00000 - 22755
ANG3_xxxxx	Changes the Target Steps Variable for SM4.	00000 - 00800
ZPOS_xxxxx	Changes the Target Steps Variable for SM3.	00000 - 14400
SETANG_xxx	Changes the Step Level of the SMs to Targets.	N/A
ACK_xxxxxx	Sends an ACK back to the RPi.	N/A
INST_xxxxx	Installs Tool 1 or 2.	00001 - 00002
ESTOP_xxxx	Enables the Emergency Stop State	N/A
INIT_xxxxx	Initialises the System	N/A
PARK_xxxxx	Parks the System	N/A
SM1_xxxxxx	Increments/Decrements the Step Level Accordingly	-99999 – 999999
SM2_xxxxxx	Increments/Decrements the Step Level Accordingly	-99999 – 999999
SM3_xxxxxx	Increments/Decrements the Step Level Accordingly	-99999 – 999999
SM4_xxxxxx	Increments/Decrements the Step Level Accordingly	-99999 – 999999

These messages are then separated in two parts, the *instruction_type* and the *instruction_parameter_int* variables. A switch is called upon the first of the two, which, if identified as valid, will enter the respective state, where the *instruction_parameter_int* variable is further used for processing.

There exist two interesting functions, the Sample_ADC() and Set_SM_Steps() functions.

The sample ADC function multiplexes the three potentiometer's channels and samples the ADC level for each, a total of 100 times into the DMA. It then takes the average thereof to improve the precision of the ADC.

The set stepper motor steps function checks all four stepper motors' levels and compares it to the target thereof. It then determines which motors should turn and determines which motor will take the longest to achieve its position. The function then paces the other stepper motors to finish at the same time as that stepper motor, resulting in a straight-line movement (shortest travel distance from A to B).

After completion of the task set aside in the respective state, an ACK is sent to the RPi and the idle state is entered once more. This process then repeats itself until the system is shut down.

4.2.3 Raspberry Pi – Logic Flow

Since the FSM for the Raspberry Pi has been explained extensively throughout the System Requirements Document (Appendix A) and previously in this report, I will not cover that part again. I will rather look at the implementation of the toolpath finding algorithm.

Python has a very powerful image processing library called OpenCV. Here, one of the edge detection functions, called the Canny function, can be used to convert images to edge detection images. Since the requirements are only for engraving text, this will improve the functionality of this function even more. This is improved by the fact that when converting text to an image, there already exists little noise and the edges will appear much more prominent. One can then analyse the pixels by implementing a type of regression calculation along this path to be able to predict the next best direction to step and stay on the path. This path can then be recorded, and islands can be identified as single letters. This will, however, not provide the path for the inside of the pockets as well, but for a prototype version, this will suffice. See the example in Figure 122 below, where the letters “NWU” is converted to an image with a white background and black text (a) and after the Canny function is implemented on the original image, the result is represented by (b).

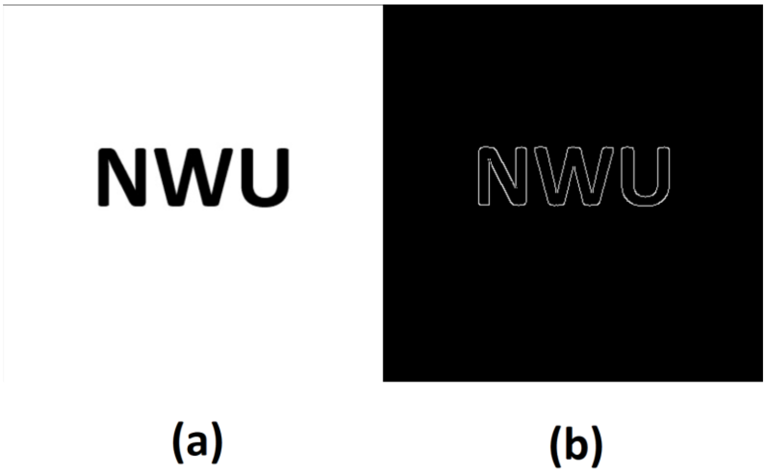


Figure 122: Edge Detection Software Results on the Text “NWU” (a) Before Detection (b) After Detection

This recording of the coordinates of the adjacent pixels is then stored in a linked list, which can be mapped to the area of the Engraving Station in millimetres, which can then undergo the following equations to transpose the pixel positions in millimetres to angles. There will always be only two answers to this mapping of pixels, as the SCARA mechanism can access the same point from the left or right side. Therefore, if we choose the direction of the arm to always be in a specified direction while engraving, there will always be only one set of angles that will match the coordinate of the pixel.

If we study the variables represented in Figure 123, equations (19) to (21) can easily be followed to arrive at equations (22) and (23), the transfer function from a cartesian plane to a SCARA plane.

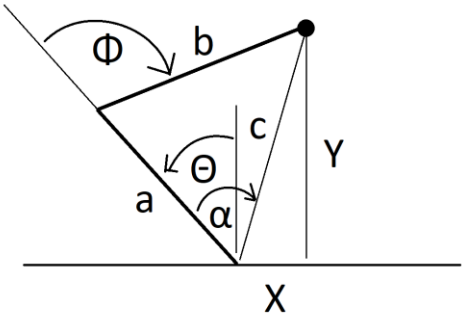


Figure 123: Diagram of the Common Position of a SCARA Mechanism and the Annotated Variables

From Figure 123, using the Pythagorean Theorem, we get

$$c = \sqrt{X^2 + Y^2}\,. \tag{19}$$

Using the Law of Cosine, we get

$$\alpha = cos^{-1}\left(\frac{b^2 - a^2 + c^2}{2bc}\right). \tag{20}$$

Now, if $a = b$, we get

$$\alpha = \pm cos^{-1}\left(\frac{c}{2a}\right). \tag{21}$$

Which means that

$$\Phi = 2\alpha \tag{22}$$

and

$$\Theta = \alpha + tan^{-1}\left(\frac{Y}{X}\right) - 90°. \tag{23}$$

4.3 Conclusion

The hardware and software were implemented to the best of the student's abilities given the mechanical issues and the time lost during the COVID-19 lockdown period in South Africa and around the world. The setup together with the programming seem to show promise of a working prototype system soon.

5 Testing and Evaluation

The system had some verification requirements it had to adhere to in the System Requirements Document (Appendix A) section 5. We will now consider whether these requirements have been met and to what a degree they have been met.

During testing of the UART communication between an FTDI232 controller and the STM32F303CCT6 MPU, I could send instructions to the MPU from my computer and could manually control the arm. The one gearbox did, however, start to cause problems by preventing the system to turn counter clockwise from the first stepper motor. There was no issue with the programming since I could still control everything else. The time has run out unfortunately and I could therefore not take the time to disassemble the whole project to solve this issue. It did, however work for a good while and the gearbox connected on the second arm is still working perfectly. I can therefore not test the latest version of my code to supply a photo of an engraved item.

I did, however, test all the commands related to turning the stepper motors and turning on the vacuum and pickup tool. The stepper motors did achieve the top speeds by timer and the positioning of the stepper motors without gearboxes are perfect. This led me to believe that the gearboxes hold this whole project back with its imprecision and friction that lowers its efficiency. I have no reason to believe that a more precise metal gearbox will have the system working close to perfectly. I even had to increase the gear ratio from a 1:16 ratio (which was already three times stronger than what is mathematically required) to a 1:64 ratio. The arm did not move much with the 1:16 ratio but moves much better with the new ratio. This, however, introduces an even slower system and introduces even more imprecision.

5.1 Orientation Accuracy

The Keybot System will be able to orientate an item with some resolution, at some angular velocity and with some inaccuracy.

Since the stepper motor has a full step size of 1.8°, and the pulley system reduces that with a factor of 36/20, together with the microstepping of ¼, the resolution of the system is 0.25°. Therefore, the resolution of the orientation accuracy requirement falls in the 75% to 100% range.

The Top Speed of the stepper motors is 1.62 rev/s. The pulley system slows it down by a ratio of 36/20. Therefore, the maximum speed of the orientation accuracy is 54 rev/minute.

The pulley and belt configuration around the orientation point is yet to slip and according to the datasheet, the inaccuracy of the stepper motor is not cumulative, but will always be out by at most two micro steps at any given moment. This means that the inaccuracy of the orientation movement will never exceed 2 slips/rev.

Parameter	0% - 25%	25%-50%	50%-75%	75%-100%	Grade
Resolution (°)	(1.8, ∞)	(1.4, 1.8]	(1.0, 1.4]	(0.0, 1.0]	75% - 100%
Angular Velocity (rev/minute)	[0.0, 2.0)	[2.0, 4.0)	[4.0, 6.0)	[6.0, ∞)	75% - 100%
Inaccuracy (Slips/rev)	(9.0, ∞)	(6.0, 9.0]	(3.0, 6.0]	(0.0, 3.0]	75% - 100%
		Average			75% - 100%

5.2 Positioning Accuracy

The Keybot System will be able to position the Manufacturing Mechanism with some resolution at the furthest point of reach, at some displacement velocity and with some inaccuracy.

The resolution of the SCARA arm at extended length can easily be evaluated by first determining the resolution in degrees, which is 0.014° when taking the microstepping of 2 and the gearbox ratio of 64 into account. This can then be used together with the arc equation at an arm length of 470 mm to arrive at 0.115 mm resolution.

The max displacement velocity can be calculated when both stepper motors 1 and 2 are turning at the same time. Since the second motor is at half the length than the first motor, its speed is twice as slow as the first motor's speed. Therefore, we can say that if the first stepper motor can reach two thirds of the top speed of the system, the system would have reached this speed. Therefore, because the top speed of the motor is 1.62 rev/s and the gearbox reduces this speed by a factor of 64, we arrive at an angular velocity of 9.1125°/s. Again, using the arc formula, this correlate to around 74.75mm/s. Multiplying this by the 3/2 factor (since the second motor adds 50% speed), this adds to about 112 mm/s.

As of this moment, the friction in the gearboxes is too much for the arm to move without slipping while under load. Therefore, I would forfeit this part, although there seems to be no issues with no load present.

Parameter	0% - 25%	25%-50%	50%-75%	75%-100%	Grade
Resolution (mm diameter)	(5.0, ∞)	(3.0, 5.0]	(1.5, 3.0]	(0.0, 1.5]	75%-100%
Displacement Velocity (mm/s)	[0, 25)	[25, 50)	[50, 75)	[75, ∞)	75%-100%
Inaccuracy (Resolution Slips/m)	(5.0, ∞)	(3.0, 5.0]	(2.0, 3.0]	(0.0, 2.0]	0% - 25%
		Average			50%-75%

5.3 Engraving Feed Rate

The Keybot System will be able to engrave an item with some fineness at a certain feed rate for MDF.

Since the stepper motor controlling the position of the z-axis has a resolution of 5.55 um, the fineness can virtually be set to any mm diameter.

The feed rate is also easily achievable up to the speeds of around 50mm/s at the centre of the engraving station.

Parameter	0% - 25%	25%-50%	50%-75%	75%-100%	Grade
Fineness (mm diameter)	(7.0, ∞)	(5.0, 7.0]	(3.0, 5.0]	(0.0, 3.0]	75%-100%
Feed Rate (mm/s)	[0.0, 2.0)	[2.0, 5.0)	[5.0, 8.0)	[8.0, ∞)	75%-100%
		Average			75%-100%

5.4 Weight Transportation

The Keybot System will be able to transport an item with a maximum weight at its maximum speed without dropping the item.

I have tested the capability of the pickup tool separately from the SCARA arm and found that at 50% PWM, the suction cup could lift around 750 g, i.e., around 7 N. So 2 N should be no problem for the system.

Parameter	0% - 25%	25%-50%	50%-75%	75%-100%	Grade
Weight (N)	[0.0, 0.5)	[0.5, 1.0)	[1.0, 2.0)	[2.0, ∞)	75%-100%

5.5 Other General Requirements

There were also some more general types of requirements to have been met.

5.5.1 Mass Limit

The system had a mass limit requirement of 30 kg so that two people can relatively easily transport the system without obtaining an injury. The system weighs 27 kg in total.

5.5.2 Box Volume Limit

The build volume should not have exceeded 1100x600x600 mm and the system (when in its compact form) measures 1000x500x600 mm, which is well within its limits. When the drawers are extended, however, the box volume increases to 1150x865x615 mm.

5.5.3 Handleable Item Size

The handleable item volume should have been at least in the range from 20 to 70 mm, and is 12 to 70 mm. The height should have been between 3 and 50 mm, however, the handleable height is 2 to 40 mm.

5.6 Homing System

I tested the homing system and discovered that the Hall-Effect sensors does not always sense the magnets at the same distance and that the output from the module were almost of an analogue type. I then proceeded with connecting the output of the modules to an oscilloscope and wrote a small program to drive PC13 high when the MPU registered the signal as a high. I then also connected this pin to the oscilloscope and saw that the sensor triggers prematurely and almost randomly at certain distances (see Figure 124 (a)). I then implemented a filter function that test the polarity of the reading over 500 samples (500us) and programmed the MPU to only register the signal as a high when it was high for more than 75 % of the time while in the toggle area (see Figure 124 (b)). This decreased the random firing of the sensor module to about over 0.1 mm, which was a great improvement.

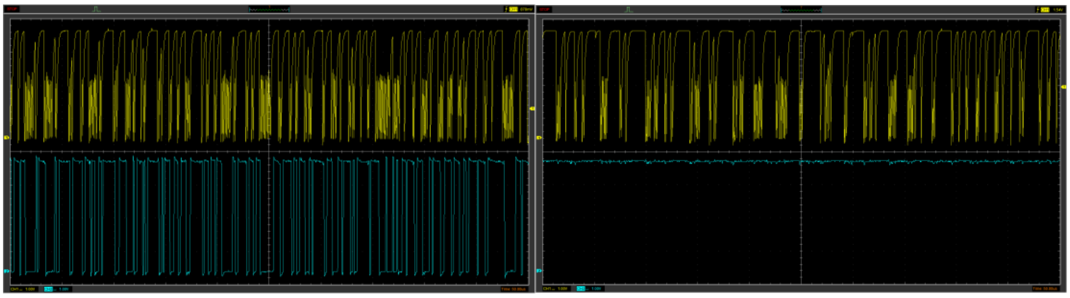


Figure 124: Homing System Hall Effect Sensor Module Output (a) Unfiltered vs (b) Filtered

6 Conclusion and Recommendations

The system has a lot of room for improvements. The most important change I would make to the system in the future is to get proper metal gearboxes instead of the 3D printed Nylon Gearboxes. The 3D printed gearbox concept could maybe still work if a more experienced 3D printer operator manufactured the gearbox, however, that is not me now.

I would say, despite that, the rest of the system seems to work quite well. All the other stepper motors achieve top speeds close to their theoretical rated speeds, the resolution and precision of those stepper motors are also impressive.

It does, however, seem that there still exists some type of feedback in the system due to inductive loads, especially whilst the vacuum pickup tool is set to a PWM above 30%. This is not a huge issue for now, since 2 N can easily be pickup up by the vacuum pickup tool at percentages of even lower than 15%.

I would still want to see the vacuum pickup tool improved by adding an inline air filter to the tube and maybe even a solenoid valve for quicker release in negative pressure when letting go of the item.

I would still recommend that the Keybot get a blue laser diode of at least 4 Watts with protection windows blocking wavelengths around 450 nm with an OD rating of 4 or higher.

I would also like to see the GUI and database become more extended and could even see the system connected to the internet for remote design and manufacturing.

I would not recommend getting larger stepper motors, since that would mean a whole change in the physical design and larger stepper motor drivers.

There are three extra pins and tool post space available for the addition of other engraving tools if needs be. The laser diode would work better since there would be no resistance to the movement while engraving.

I would also try to include idle line detection together with the DMA at the STM32's side of the serial communication so that it would not be necessary to send so many meaningless bits just to trigger the DMA on its own.

I believe that the system would work well for one of its price range as soon as the mechanical issues are left to an expert in that field. The timers, PWM channels, DMA, ADC, hall-effect sensors, stepper motor drivers, engraving tool, pickup tool and even the emergency stop button works well. The software is also written in such a way that adding new states could easily be done in less than five changes to different lines of the code.

I am positive that this prototype can only improve from here on out and noticed that many companies show great interest in the product when I talk about it. I believe that this system could become a symbol of the NWU at open days and that it has the potential to inspire a lot of young and brilliant minds to strongly consider studying Mechatronics as a career path.

Above all else, this project had a lot of ups and downs and I have learned quite a lot about robotics this year and am looking forward to implementing my newly found knowledge and skills in physics, mechanics, electronics, actuators and CNC machines.

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Appendix A:
System Requirements Document

SYSTEM REQUIREMENTS SPECIFICATION

Keybot System

Mr Pieter Marx
29703662

DOCUMENT IDENTIFICATION

Project Title:	2020004 - Keybot System
Document Number:	SyRS-KS_V1.0
System / Sub-System:	Keybot System
Document Issue Date:	2020-04-27
Client:	Dr Henri Marais – NWU
Client Reference:	SyRS - Keybot System

ORIGINATION AND APPROVAL

Checked by Party	Individual Name	Signature	Date
Author:	Mr Pieter Marx		
Quantity Assurance:			
Technical Approval:	Dr Henri Marais		
Project Manager:	Prof Leenta Grobler		

ACCEPTANCE

Checked by	Individual Name	Signature	Date
Approved by:	Dr Henri Marais		

DISTRIBUTION LIST

Company	Individual Name	Date
NWU (Limited)	Prof Leenta Grobler	
NWU (Limited)	Dr Henri Marais	

SECURITY LEVELS AND RESTRICTIONS

Level	Description	Applicable Level
1	Strictly Confidential – not to be distributed	
2	Company Confidential – distributed inside company	
3	Client Confidential – distributed to limited clients and contractors	X
4	Public Domain – distributed freely	

CONTACT INFORMATION

Contact Person	Mr Pieter Marx
Company	NWU (Limited) – EERI474 2020
Street Address	18 Calderbank Ave, Potchefstroom, 2520, South Africa
Telephone Number	0732457508
Email address	pietermarx.pm@gmail.com
Web site	None

DOCUMENT REVISION HISTORY

Date	Responsible person	Description	Revision No.
2020-04-27	Mr Pieter Marx	Document creation	1.0

Table of Contents

1 Introduction and scope

1.1 Identification

This system specification pertains to the Keybot System being developed by the North West University (NWU).

1.2 Intended use

Mechatronic engineering is a commonly confused field of study. Many people confuse it with electromechanics, which is the union of both mechanical and electrical engineering. This however is understandable, since mechatronic engineering is the union of mechanical and electronic engineering, but with the addition of computer systems and control/information systems. This is not always easily conceptualised and should be clarified for prospective students and their parents.

The Keybot System is intended to be used as a mechatronics demonstration platform at live events, such as open days at the university. It will demonstrate a few key elements of mechatronics, such as material handling, Computer Numerical Control (CNC), automated subtractive manufacturing processes (i.e. mechanical- or laser engraving), digital signal processing (DSP) and control theory. The user will provide the Keybot with a small item, such as a keychain, and use the Human-Machine Interface (HMI) to provide the Keybot with a design for engraving. The demonstration commences and entails personalising the small item in a while-you-wait fashion, thereafter, dispensing the item as a keepsake to the user.

1.3 Document Overview and Use

This SyRS is intended to be used by the client and their appointed contractors to develop the Keybot System. Unless explicitly stated herein all contents of this SyRS is to be treated as client confidential by any contractors. At the discretion of the client this SyRS may be distributed to any party deemed to have a stake in the development of this system or the management of the system development.

2 Applicable and other referenced documents

2.1 Applicable documents

Unless explicitly states any requirement in this specification that is found to conflict with the referenced standards shall be subservient to said standard.

DOCUMENT IDENTIFIER	DOCUMENT DESCRIPTION
BASIC CONDITIONS OF EMPLOYMENT ACT, NO 75 OF 1997 REGULATLONS ON HAZARDOUS WORK BY CHILDREN IN SOUTH AFRICA	Indicates the safety precautions that needs to be taken in the case that a child (under 18 years) performs physical labour.
GUIDE FOR THE USE OF THE INTERNATIONAL SYSTEM OF UNITS (SI): NIST SPECIAL PUBLICATION 811 (2008)	Document describing the use and meaning of SI units.
REQUIREMENTS FOR THE SAFE USE OF CLASS 3B AND CLASS 4 LASERS OR LASER SYSTEMS: V2.0 (2004)	Indicates the type of safety measures that need to be taken in case of utilizing a laser in systems.

2.2 2.2 Other referenced documents

(None)

3 Meanings, Acronyms, and Abbreviations

3.1 Meanings

Unless otherwise explicitly states here all words and terms shall be interpreted as per the latest edition of the United Kingdom variant of the Oxford English dictionary.

TERM	DEFINITION
BOX VOLUME	A 3-dimentional space in the form of a right rectangular prism.
CENTRE OF MASS	The 1-dimentional point contained within a box volume enclosing an item, representing the origin of the weight vector of the item.
CONTROLLING MECHANISM	The subordinate part of the Keybot System that is responsible for generating toolpaths and sending the appropriate signals to the driver circuitry to control the Manufacturing Mechanism.
FEED RATE	The velocity at which the engraving tool advances in reference to the item being engraved.
INTERFACE MECHANISM	The subordinate part of the Keybot System that is responsible for the communication means between the Keybot System and an external party.
KEYBOT SYSTEM	A demonstration platform capable of demonstrating the concept of mechatronic engineering through the execution of some key elements thereof, simultaneously personalising an item as a keepsake for the user.
MANUFACTURING MECHANISM	The subordinate part of the Keybot System that is responsible for executing the physical operations of the Keybot System.
MATERIAL HANDLING	The act of displacing and positioning some type of material.
MAY	Expresses permissive guidance.
MODE	The mode of a system refers to the state of doing of a system. Typically, modes are encapsulated within states.
NORMAL VECTOR	The imaginary vector passing perpendicularly through an infinitesimal part of a larger surface.
PALETTE	A moulded tray, with slots, for laying down the items separately during the reload of the Keybot System.
RELATIVE HUMIDITY	The percentage of water vapour needed to saturate the air at a given temperature.
SHALL	Expresses a characteristic which must be present in the item of specification, thus a binding requirement.
SHOULD	Expresses a goal or target to be pursued but not necessarily achieved.

STATE	The state of a system refers to a state of being of the system.
WHILE-YOU-WAIT	A way a person waits during the execution of some action.
WILL	Expresses a declaration of intent on the part of a party.
XY-PLANE	The 2-dimentional range stretching horizontally in a 3-dimentional space.

3.2 Acronyms

ACRONYM	DEFINITION
ATC	Automatic Tool Change
CNC	Computer Numerical Control
DSP	Digital Signal Processing
HMI	Human-Machine Interface
IP	Ingress Protection
MTQ	Manufacturing Task Queue
NWU	North West University
OCI	Operator Control Interface
OVI	Operator Visual Interface
PLP	Palette Layout Plan
SYRS	System Requirements Specification
TBD	To Be Defined

3.3 Abbreviations

ABBREVIATION	EXPLANTATION
E.G.	For example
I.E.	That is
REQID	Requirement Identifier

4 Requirements

4.1 Identification of External Interfaces

The Keybot System shall have the following external interfaces

4.1.1 Power Supply Interface REQID001

This interface shall provide electrical power to the system, from a 220 - 240 V AC @ 50 Hz power outlet.

4.1.2 Operator Visual Interface (OVI) REQID002

This interface shall provide visual communication from the system to the operator.

4.1.3 Operator Control Interface (OCI) REQID003

This interface shall provide control of the system to the operator.

4.1.4 Item Loading Interface REQID004

This interface shall provide the possibility to supply the system with items, which are meant for engraving.

4.1.5 Pickup Tool Interface REQID005

This interface shall provide the possibility to pick up the item, which is meant for engraving.

4.1.6 Item Engraving Interface REQID006

This interface shall be used to physically engrave the item, which is meant for engraving.

4.1.7 Item Fasten Interface REQID007

This interface shall be used to fasten the item, meant for engraving, before engraving commences.

4.1.8 Item Dispensing Interface REQID008

This interface shall dispense the engraved item to the user for collection.

4.1.9 Visual Demonstration Interface REQID009

This interface shall provide the opportunity for the crowd to study the demonstration of mechatronics.

4.1.10 Levelling Interface REQID010

This interface shall be used to level the system on a supporting surface.

4.1.11 Transport Fasten Interface REQID011

This interface shall be used to fasten the system during transportation.

4.2 Identification of States and Modes

The system shall have the following states and modes.

4.2.1 States

With the definition of “state” in mind from section 3.1, the states of the system are as follows. Also, see Figure 1 for clarification.

4.2.1.1 *Powered-Down State* REQID012

In the Powered-Down State, the system shall not be operational, and could be transported or stored away.

4.2.1.2 *Active State* REQID013

In the Active State, the system shall either perform self-tests, initialise the system, idle, accept designs from users, perform toolpath planning related tasks or perform a shutdown procedure.

4.2.1.3 *Manufacturing State* REQID014

In the Manufacturing State, the system shall perform automatic tool changing (ATC)-, material handling- and engraving related tasks.

4.2.1.4 *Reload State* REQID015

In the Reload State, the system shall provide the opportunity to the operator to reload the system with more items for engraving and other reload related tasks.

4.2.1.5 *Emergency Stop State* REQID016

In the Emergency Stop State, the system shall perform an emergency stop routine, disabling, and removing power to, the majority of the Keybot System.

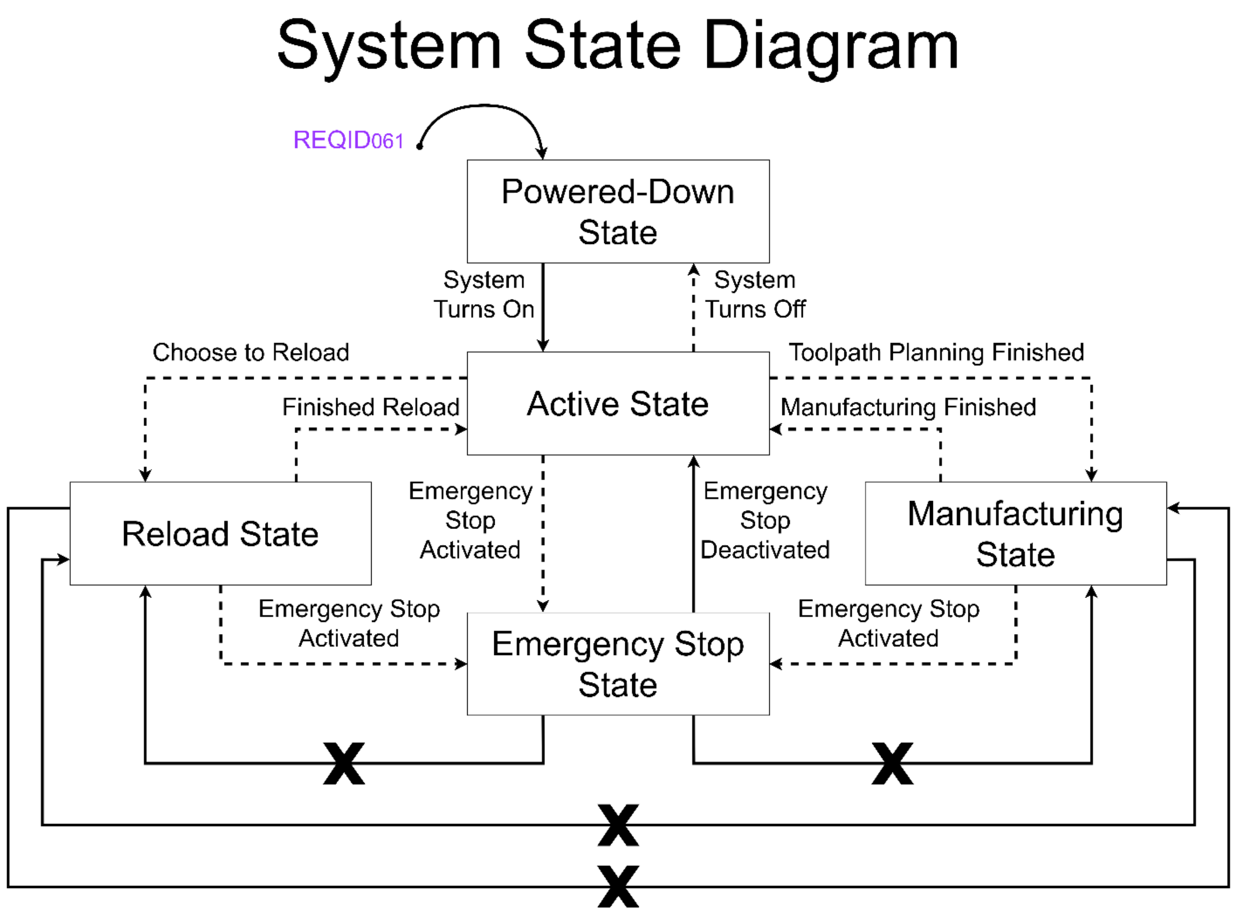


Figure 1: System State Diagram

4.2.2 Modes

With the definition of “mode” in mind from section 3.1, the modes of the system are as follows. Also, see Figure 2 for clarification.

4.2.2.1 *Self-Test Mode* REQID017

During the Self-Test Mode, the system shall perform tests to determine the functionality and the general condition of the system. This includes testing internal data interfaces, calibration interfaces, mobility functions and if the system is at risk, due to a previous power failure.

4.2.2.2 *Initialisation Mode* REQID018

During the Initialisation Mode, the system will initialise the Manufacturing Mechanism by uninstalling the installed tool and resetting to the initial position.

4.2.2.3 *Idle Mode* REQID019

During the Idle Mode, the system shall not perform any material handling or engraving related tasks and shall monitor any input commands from the operator/user.

4.2.2.4 *Design Mode* REQID020

During the Design Mode, the system shall provide an interface for the user to communicate the desired, engraving design to the system and specify which item to engrave by using the Interface Mechanism.

4.2.2.5 *Toolpath Planning Mode* REQID021

During the Toolpath Planning Mode, the Controlling Mechanism shall determine which path it will follow to perform all the necessary ATC, material handling- and engraving related tasks.

4.2.2.6 *ATC Mode* REQID022

During the ATC Mode, the system shall automatically uninstall any installed tool from the previous task and/or install another tool, which will be fit for the next task in the manufacturing task queue (MTQ).

4.2.2.7 *Pick-and-Place Mode* REQID023

During the Pick-and-Place Mode, the system shall pick up, transport the item to the desired location and place down the item for or after engraving.

4.2.2.8 *Item Engraving Mode* REQID024

During the Item Engraving Mode, the system shall perform mobility tasks while operating the engraving tool to engrave the item as instructed by the generated toolpath.

4.2.2.9 *Reload Mode* REQID025

During the Reload Mode, the system shall provide the opportunity for the operator to load more items into the system for future engraving, to create new palette layouts for different item shapes and amounts and to delete existing palette layouts.

4.2.2.10 *Emergency Stop Mode* REQID026

During the Emergency Stop Mode, the system shall disable most parts of the system and remove the power to all actuators and tools to cease any physical processes, in the case of an emergency.

4.2.2.11 *Shutdown Mode* REQID027

During the Shutdown Mode, the system shall ensure that the Manufacturing Mechanism is initialised before powering itself down; to ensure a safe position for transport and safe storage.

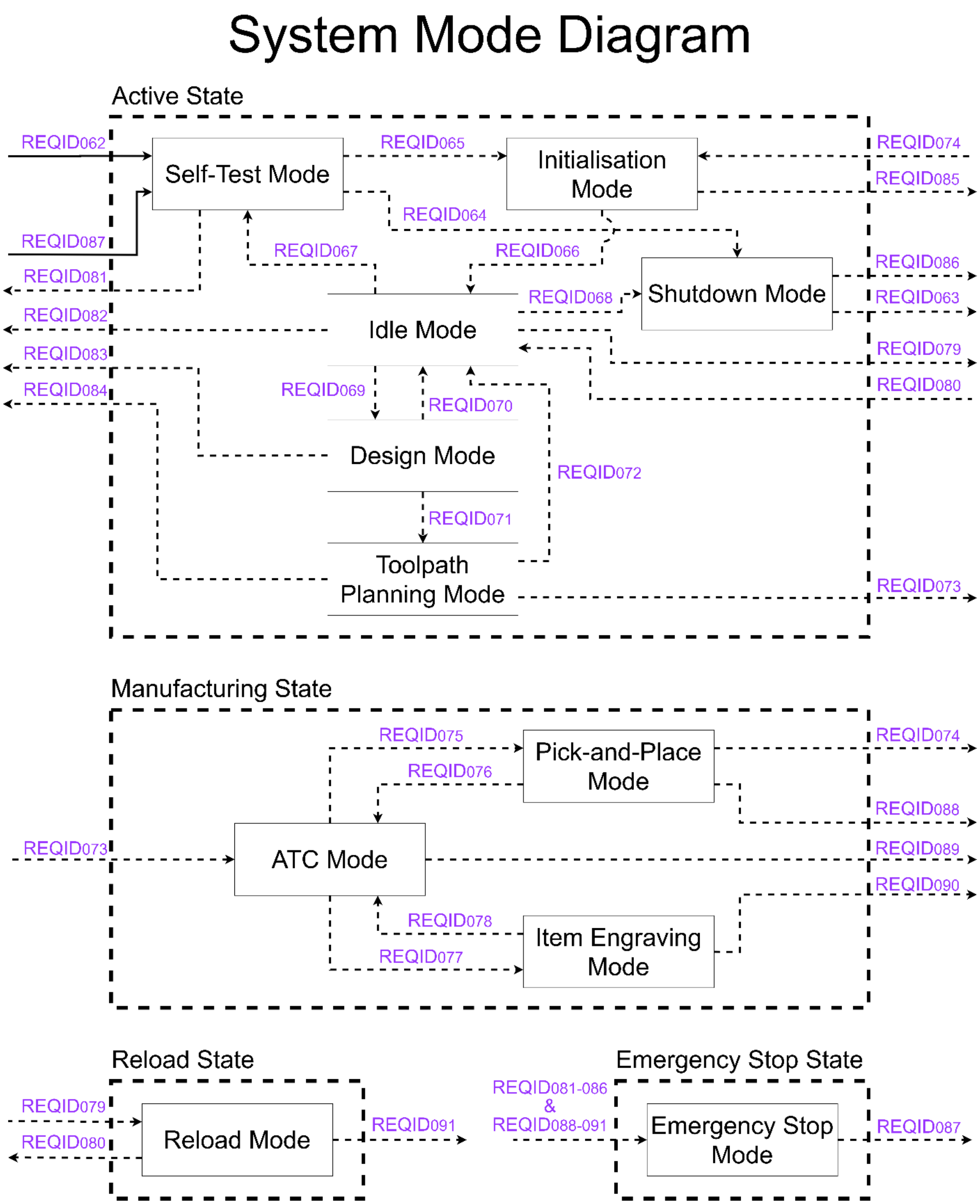


Figure 2: System Mode Diagram

4.3 System Function and Performance Requirements

4.3.1 Self-Test Function

The Keybot System shall start the Self-Test Function, within 1 second, after fully transitioning into the Self-Test Mode. REQID028

The Self-Test Function shall notify the operator of the condition of the system by performing tests to determine the status of the following characteristics

a) Internal data interfaces
b) Calibration interfaces
c) Mobility functions
d) Previous power failures

completing the tests within 3 minutes from the start of the function. REQID029

4.3.2 Initialisation Function

The Keybot System shall start the Initialisation Function, within 1 second, after fully transitioning into the Initialisation Mode. REQID030

The Initialisation Function shall initialise the Manufacturing Mechanism by performing the following tasks

a) Uninstalling the installed tool by calling the Automatic Tool Removal Function
b) Resetting the mechanism to its initial position

within 1 minute from the start of the function. REQID031

4.3.3 Design Function

The Keybot System shall start the Design Function, within 1 second, after fully transitioning into the Design Mode and the user chooses to edit the design. REQID032

The Design Function shall allow the system to at least accept personalised strings of data from the user as a pure text-based design, with a maximum buffer length of no less than 255 characters. REQID033

4.3.4 Item Choosing Function

The Keybot System shall start the Item Choosing Function, within 1 second, after fully transitioning into the Design Mode and the user chooses to specify a certain item to be engraved. REQID034

The Item Choosing Function shall allow the user to choose an item, which the user desires to be engraved with the user's design within 1 second upon submission of the choice. REQID035

4.3.5 Toolpath Planning Function

The Keybot System shall start the Toolpath Planning Function, within 1 second, after fully transitioning into the Toolpath Planning Mode. REQID036

The Toolpath Planning Function shall implement an execution-time-minimisation algorithm that shall at least generate a toolpath for pure text-based designs with a speed of no less than 255 characters per minute upon the start of the function. REQID037

4.3.6 Automatic Tool Installation Function

The Keybot System shall start the Automatic Tool Installation Function, within 1 second, after fully transitioning into the ATC Mode when a tool must be installed. REQID038

The Automatic Tool Installation Function shall at least be able to install a pickup tool and an engraving tool at different instances within 20 seconds from the start of the function. REQID039

4.3.7 Automatic Tool Removal Function

The Keybot System shall start the Automatic Tool Removal Function, within 1 second, after fully transitioning into the ATC Mode and a tool must be uninstalled. REQID040

The Automatic Tool Removal Function shall be able to uninstall at least a pickup tool and an engraving tool at different instances within 20 seconds from the start of the function. REQID041

4.3.8 Pick-and-Place Function

The Keybot System shall start the Pick-and-Place Function, within 1 second, after fully transitioning into the Pick-and-Place Mode. REQID042

The Pick-and-Place Function shall perform the full motion of picking up or placing down the item, within 15 seconds upon the start of the respective motion type. REQID043

The Pick-and-Place Function shall enable the system to pick up items with at least a flat, filled top surface, where the normal vector of said surface is parallel to the pick-and-place direction. REQID044

The Pick-and-Place Function shall enable the system to pick up items containable within a cylindrical volume with a ranging radius from the vertically projected centre of mass, at least between 20 mm and 70 mm and height parallel to the pick-and-place direction, at least between 3 mm and 50 mm. REQID045

The Pick-and-Place Function shall enable the Keybot System to pick up items with a maximum weight of at least 2 N with a vector in line with the vertically projected centre of mass of which the initial position is within reach of the Manufacturing Mechanism and not closer than 20 mm to any edge of the top surface of the item. REQID046

The Pick-and-Place Function shall enable the Keybot System to transfer the item with a maximum speed of no less than 50 mm/s with a placing inaccuracy of no more than a 5 mm diameter and angular orientation inaccuracy of no more than 1.8 degrees. REQID047

4.3.9 Item Engraving Function

The Keybot System shall start the Item Engraving Function, within 1 second, after fully transitioning into the Item Engraving Mode. REQID048

The Item Engraving Function shall enable the Keybot System to engrave items, which are at least made from ABS plastic or MDF wood. REQID049

The Item Engraving Function shall enable the Keybot System to engrave items made from said materials at a maximum feed rate of no less than 8 mm/s. REQID050

4.3.10 Reload Function

The Keybot System shall start the Reload Function, within 1 second, after fully transitioning into the Reload Mode and the operator chooses to reload items into the Keybot System. REQID051

The Reload Function shall enable the Keybot System to receive a new palette and/or new items for engraving and receive information from the operator as to the existing palette layout loaded and which slots of the palette are occupied. REQID052

4.3.11 Create Palette Function

The Keybot System shall start the Create Palette Function, within 1 second, after fully transitioning into the Reload Mode and the operator chooses to create a new palette layout plan. REQID053

The Create Palette Function shall enable the Keybot System to save information regarding the palette layout plan (PLP) to generate a PLP for the operator to utilise later, within 1 second upon submission of the information. REQID054

4.3.12 Delete Palette Function

The Keybot System shall start the Delete Palette Function, within 1 second, after fully transitioning into the Reload Mode and the operator chooses to delete an existing palette layout plan. REQID055

The Delete Palette Function shall enable the Keybot System to delete a PLP, within 1 second upon choosing to delete the PLP. REQID056

4.3.13 Emergency Stop Function

The Keybot System shall start the Emergency Stop Function, within 100 ms, after fully transitioning into the Emergency Stop Mode. REQID057

The Emergency Stop Function shall disable the other functions of the Keybot System and remove the power to all actuators and tools within 400 ms upon the start of the Emergency Stop Function. REQID058

4.3.14 Shutdown Function

The Keybot System shall start the Shutdown Function, within 1 second, after fully transitioning into the Shutdown Mode. REQID059

The Shutdown Function shall enable the system to initialise itself for safe storage, if able, and to keep a log of the condition of the system, within 30 seconds from the start of the function. REQID060

4.4 Relationships between States and Modes

4.4.1 Powered-Down State

The system shall start in the Powered-Down State. REQID061

4.4.2 Powered-Down State ↔ Active State

The system shall transition from the Powered-Down State to the Self-Test Mode of the Active State within 2 minutes, when an external source of electrical power is applied to the Keybot System. REQID062

The system shall transition from the Active State to the Powered-Down State within 3 seconds, after successful execution of the Shutdown Function during the Shutdown Mode. REQID063

4.4.3 Active State Modes

During the Active State, the Keybot System shall transition from the Self-Test Mode to the Shutdown Mode within 3 seconds, when the operator commands the system to do so after the Self-Test Function returns a failure. REQID064

During the Active State, the Keybot System shall transition from the Self-Test Mode to the Initialisation Mode within 3 seconds, when the Self-Test Function returns a success. REQID065

During the Active State, the Keybot System shall transition from the Initialisation Mode to the Idle Mode within 3 seconds, when the Initialisation Function has been fully executed. REQID066

During the Active State, the Keybot System shall transition from the Idle Mode to the Self-Test Mode within 3 seconds, when the operator commands the system to do so. REQID067

During the Active State, the Keybot System shall transition from the Idle Mode to the Shutdown Mode within 3 seconds, when the operator commands the system to do so. REQID068

During the Active State, the Keybot System shall transition from the Idle Mode to the Design Mode within 3 seconds, when the operator commands the system to do so. REQID069

During the Active State, the Keybot System shall transition from the Design Mode to the Idle Mode within 3 seconds, when the user commands the system to exit the design mode. REQID070

During the Active State, the Keybot System shall transition from the Design Mode to the Toolpath Planning Mode within 3 seconds, when the user submits the desired engraving design to the system. REQID071

During the Active State, the Keybot System shall transition from the Toolpath Planning Mode to the Idle Mode within 5 seconds, when the user commands the system to abandon the Toolpath Planning Mode. REQID072

4.4.4 Active State ↔ Manufacturing State

The system shall transition from the Toolpath Planning Mode of the Active State to the ATC Mode of the Manufacturing State within 3 seconds, when the system has finished planning the toolpath of the desired design for engraving the item. REQID073

The system shall transition from the Pick-and-Place Mode of the Manufacturing State to the Initialisation Mode of the Active State within 3 seconds, when the system has finished a successful engraving cycle by dispensing the item to the user. REQID074

4.4.5 Manufacturing State Modes

During the Manufacturing State, the Keybot System shall transition from the ATC Mode to the Pick-and-Place Mode within 3 seconds, when the Manufacturing Mechanism has finished installing the pickup tool. REQID075

During the Manufacturing State, the Keybot System shall transition from the Pick-and-Place Mode to the ATC Mode within 3 seconds, when the pickup tool must be exchanged with the engraving tool if the next task in the MTQ is related to engraving. REQID076

During the Manufacturing State, the Keybot System shall transition from the ATC Mode to the Item Engraving Mode within 3 seconds, when the Manufacturing Mechanism has finished installing the engraving tool. REQID077

During the Manufacturing State, the Keybot System shall transition from the Item Engraving Mode to the ATC Mode within 3 seconds, when the engraving tool must be exchanged with the pickup tool if the next task in the MTQ is related to pick-and-place. REQID078

4.4.6 Active State ↔ Reload State

The system shall transition from the Idle Mode of the Active State to the Reload Mode of the Reload State within 3 seconds, when the operator commands the system to do so. REQID079

The system shall transition from the Reload Mode of the Reload State to the Idle Mode of the Active State within 3 seconds, when the operator commands the system to do so. REQID080

4.4.7 Active State ↔ Emergency Stop State

The system shall transition from the Self-Test Mode of the Active State to the Emergency Stop Mode of the Emergency Stop State within 0.5 seconds, when the operator commands the system to do so. REQID081

The system shall transition from the Idle Mode of the Active State to the Emergency Stop Mode of the Emergency Stop State within 0.5 seconds, when the operator commands the system to do so. REQID082

The system shall transition from the Design Mode of the Active State to the Emergency Stop Mode of the Emergency Stop State within 0.5 seconds, when the operator commands the system to do so. REQID083

The system shall transition from the Toolpath Planning Mode of the Active State to the Emergency Stop Mode of the Emergency Stop State within 0.5 seconds, when the operator commands the system to do so. REQID084

The system shall transition from the Initialisation Mode of the Active State to the Emergency Stop Mode of the Emergency Stop State within 0.5 seconds, when the operator commands the system to do so. REQID085

The system shall transition from the Shutdown Mode of the Active State to the within 0.5 seconds, when the operator commands the system to do so. REQID086

The system shall transition from the Emergency Stop Mode of the Emergency Stop State to the Self-Test Mode of the Active State within 0.5 seconds, when the operator commands the system to do so. REQID087

4.4.8 Manufacturing State → Emergency Stop State

The system shall transition from the Pick-and-Place Mode of the Manufacturing State to the Emergency Stop Mode of the Emergency Stop State within 0.5 seconds, when the operator commands the system to do so. REQID088

The system shall transition from the ATC Mode of the Manufacturing State to the Emergency Stop Mode of the Emergency Stop State within 0.5 seconds, when the operator commands the system to do so. REQID089

The system shall transition from the Item Engraving Mode of the Manufacturing State to the Emergency Stop Mode of the Emergency Stop State within 0.5 seconds, when the operator commands the system to do so. REQID090

4.4.9 Reload State → Emergency Stop State

The system shall transition from the Reload Mode of the Reload State to the Emergency Stop Mode of the Emergency Stop State within 0.5 seconds, when the operator commands the system to do so. REQID091

4.5 System External Interface Requirements

4.5.1 Power Supply Interface

The Power Supply Interface shall provide the operator with a means to connect the Keybot System to an M type 220 - 240 V AC @ 50 Hz electrical power outlet capable of handling at least 250 V AC @ 10 A AC. REQID092

4.5.2 Operator Visual Interface (OVI)

The OVI shall inform the operator of the self-test status, regarding the internal data interfaces, calibration interfaces, mobility functions and whether a previous power failure occurred, during the Self-Test Mode. REQID093

The OVI shall inform the operator of the self-test results and the contact information of the custodian of the Keybot System when the Self-Test Function returns a failure during the Self-Test Mode. REQID094

The OVI shall inform the operator of the shutdown preparation status of the Keybot System, during the Shutdown Mode. REQID095

The OVI shall inform the operator when the Keybot System has successfully entered the Emergency Stop Mode, after the operator commands the system to enter the mode, and how to go about to abort the Emergency Stop Mode. REQID096

The OVI shall inform the operator of the execution status, regarding the initialisation tasks, during the Initialisation Mode. REQID097

The OVI shall pass the option to the operator for navigating the Keybot System from the Idle Mode to the Shutdown Mode. REQID098

The OVI shall pass the option to the operator for navigating the Keybot System from the Idle Mode to the Self-Test Mode. REQID099

The OVI shall pass the option to the operator for navigating the Keybot System from the Idle Mode to the Reload Mode. REQID100

The OVI shall pass the option to the operator for navigating the Keybot System from the Reload Mode back to the Idle Mode. REQID101

The OVI shall inform the operator of the current PLP, regarding the occupied slots and orientation of the items installed in these slots, during the Reload Mode. REQID102

The OVI shall pass the option to the operator for changing the PLP and/or reload the palette with new items, during the Reload Mode. REQID103

The OVI shall pass the list of available PLP's to the operator, during the Reload Mode. REQID104

During the Reload Mode, the OVI shall inform the operator of the option to download available PLP's, with the purpose of physically constructing the palettes accordingly, for later implementation thereof. REQID105

The OVI shall pass the option to the operator for deleting existing PLP's from a list, which is also provided to the operator through the OVI, during the Reload Mode. REQID106

The OVI shall pass the option to the operator for creating a new PLP, during the Reload Mode. REQID107

The OVI shall pass the list of preidentified engravable materials, when creating a new PLP during the Reload Mode. REQID108

The OVI shall pass the range of manageable radius lengths, from the centre of mass of the item to the circumscribed circle containing the item, when creating a new PLP, during the Reload Mode. REQID109

The OVI shall pass the range of the number of items allowed to fit onto the palette, given the radius length from the centre of mass of the items, when creating a new PLP, during the Reload Mode. REQID110

The OVI shall pass the range of allowed offset-distances from the item's centre of mass to the centre of the engraving area given the radius length of the item, when creating a new PLP during the Reload Mode. REQID111

The OVI shall pass the range of allowed offset-angles from the item's centre of mass to the centre of the engraving area, when creating a new PLP during the Reload Mode. REQID112

The OVI shall pass the range of allowed radius lengths of the engraving area, given the radius of the item from the centre of mass and the said offset parameters for the engraving area, when creating a new PLP during the Reload Mode. REQID113

The OVI shall pass a visualisation of the resulting generated layout plan depicting the amount, placement and orientation of the items to be loaded onto the palette, after creating a new PLP during the Reload Mode. REQID114

The OVI shall inform the operator of the filename and file path of the downloaded file containing the PLP, after the operator chooses to download the plan to a specific location during the Reload Mode. REQID115

The OVI shall pass the option to the user for navigating the Keybot System from the Idle Mode to the Design Mode. REQID116

The OVI shall pass the option to the user for navigating the Keybot System from the Design Mode back to the Idle Mode. REQID117

The OVI shall pass the current design for engraving the item to the user, during the Design Mode. REQID118

The OVI shall pass the option and platform to the user for editing the design during the Design Mode. REQID119

The OVI shall pass the option and platform to the user, for choosing a specific item from the palette, to be engraved with the design, during the Design Mode. REQID120

The OVI shall pass the option to the user for navigating the Keybot System from the Design Mode to the Toolpath Planning Mode. REQID121

The OVI shall pass the option to the user for navigating the Keybot System from the Toolpath Planning Mode back to the Idle Mode. REQID122

The OVI shall inform the user of the toolpath planning status of the Keybot System, during the Toolpath Planning Mode. REQID123

The OVI shall inform the user of the item engraving status of the Keybot System, during the Item Engraving Mode. REQID124

4.5.3 Operator Control Interface (OCI)

The OCI shall provide the operator with a means to command the Keybot System to execute the Shutdown Function after the Self-Test Function returned a failure, during the Self-Test Mode. REQID125

The OCI shall provide the operator with a means to command the Keybot System to enter the Emergency Stop Mode, during any of the modes. REQID126

The OCI shall provide the operator with a means to command the Keybot System to abort the Emergency Stop Mode, during the Emergency Stop State. REQID127

The OCI shall provide the operator with a means to command the Keybot System to execute the Shutdown Function, during the Idle Mode. REQID128

The OCI shall provide the user with a means to command the Keybot System to enter the Design Mode, during the Idle Mode. REQID129

The OCI shall provide the user with a way to command the Keybot System to receive/record the desired design from the user, during the Design Mode. REQID130

The OCI shall provide the user with a means to command the Keybot System to use a specific slot containing an item that is already loaded into the loading station, during the Design Mode. REQID131

The OCI shall provide the user with a way to command the Keybot System to abandon the Design Mode, thus returning to the Idle Mode. REQID132

The OCI shall provide the user with a way to command the Keybot System to start the engraving process during the Design Mode, thus entering the Toolpath Planning Mode. REQID133

The OCI shall provide the user with a way to command the Keybot System to abandon the Toolpath Planning Mode, thus returning to the Idle Mode. REQID134

4.5.4 Item Loading Interface

The Item Loading Interface shall enable the operator to at least load a palette, loaded with items for engraving, with a box volume of 200x200x60 in mm. REQID135

4.5.5 Pickup Tool Interface

The Pickup Tool Interface shall enable the Keybot System to exhibit a maximum lifting capacity of at least 2 N. REQID136

The Pickup Tool Interface shall enable the Keybot System to lift an item with at least 60 mm of height, from the item's resting position inside the palette. REQID137

The Pickup Tool Interface shall enable the Keybot System to at least lift an item with a flat top surface, with a normal vector parallel to the lifting direction. REQID138

The Pickup Tool Interface shall enable the Keybot System to lift an item with a top view surface area contained within a circumscribed circle with at least a maximum radius of 70 mm from the centre of mass of the item. REQID139

The Pickup Tool Interface shall enable the Keybot System to lift an item with a top view surface area containing an inscribed circle with at least a minimum radius of 20 mm from the centre of mass of the item. REQID140

4.5.6 Item Engraving Interface

The Item Engraving Interface shall enable the Keybot System to engrave at least items made of ABS plastic and MDF wood. REQID141

The Item Engraving interface shall enable the Keybot System to engrave said materials at a maximum feed rate of no less than 8 mm/s. REQID142

4.5.7 Item Fasten Interface

The Item Fasten Interface shall enable the Keybot System to fasten the items at least in the XY-plane, to prevent the item from moving more than 1 mm in any direction from the centre position, during the engraving process. REQID143

The Item Fasten Interface shall enable the Keybot System to fasten a range of item shapes adhering to the item volume requirements of REQID045, during the item engraving process. REQID144

4.5.8 Item Dispensing Interface

The Item Dispensing Interface shall enable the user to collect the item after undergoing the engraving-, and material handling processes. REQID145

4.5.9 Visual Demonstration Interface

The Visual Demonstration Interface shall enable at least three people to simultaneously view the material handling- and engraving processes, in a while-you-wait manner. REQID146

4.5.10 Levelling Interface

The Levelling Interface shall enable the operator to level the Keybot System for a steady position, during operations. REQID147

4.5.11 Transport Fasten Interface

The Transport Fasten Interface shall enable the operator to fasten the Keybot System at least in the rear car seats, given that the car has adjustable headrests, adjustable seat-angle and -position, safety belts and an available box volume space of at least 1100x600x600 in mm. REQID148

4.6 System Environmental Requirements

The Keybot System is a demonstration platform, which will be used at different live events at different geographical locations and different times of the year. Therefore, the environment that the system will be introduced to will vary, in terms of temperature, humidity, corrosion, rain, dust, scratches, vibrations, electromagnetic (EM)-waves, noise and static electricity, which means that the system can be affected in different ways. The system should be able to handle a variety of conditions if the system is to be used in said circumstances.

4.6.1 Classes of environment

The Keybot System will find itself in storage environments for at least weeks on end, transportation environments for hours on end and operational environments also for hours on end. Therefore, it is important to carefully specify the requirements of said environments, so that the Keybot system does not perish or obtain unintended damage in these environments. The general environment, in this SyRS, refers to the collection of said environments.

4.6.2 General environment

The Keybot System shall remain operational during and after exposure to ambient temperatures of at least -10 °C to 50 °C. REQID149

The Keybot System shall remain operational during and after exposure to a relative humidity of at least 45% to 80%. REQID150

The Keybot System shall not be susceptible to corrode when exposed to air, temporary water splashes or other splashes of liquids not dangerous to humans. REQID151

The Keybot System shall remain operational during and after exposure to dusty environments with nominally spherical dust particles (solid objects) with diameter over 1 mm. REQID152

The Keybot System shall remain operational during and after exposure to environments with water splashes from any angle, except for liquids that are present at the power outlet while operating. REQID153

The Keybot System should not be susceptible to scratches from the environment. REQID154

The Keybot System shall remain operational after exposure to g-forces of at least -0.5 g to +0.5 g. REQID155

The Keybot System should not be susceptible to EM-wave exposure. REQID156

The electronics of the Keybot System should not be susceptible to environmental static build-up. REQID157

4.7 External Resource Utilization Requirements

The Keybot System shall require an external power source capable of delivering 220-240 V AC @ 50 Hz, with a maximum current rating of at least 7 A AC. REQID158

The Keybot System shall consume no more than 1.25 kVA. REQID159

The Keybot System shall consume no more than 5 A AC. REQID160

The Keybot System shall require items to be engraved by the system, which shall be made from ABS plastic or MDA wood. (Additional material types are TBD, however, said materials are the minimum required materials) REQID161

The Keybot System shall require items to be engraved by the system, which shall fit within a cylindrical volume of radius between 20 and 70 mm (from the vertical axis through the centre of mass of the item) and vertical height ranging between 3 and 5 mm. (Additional sizes are TBD, however, said sizes are the minimum ranges required) REQID162

The Keybot System shall require items to be engraved by the system, which shall have a flat, filled, top surface with normal vector parallel to the vertical axis. (Additional uneven surfaces are TBD, however, said flat shape is the minimum top surface required) REQID163

The Keybot System shall require items to be engraved by the system, which shall have a maximum weight of 2 N. (Additional maximum weight loads are TBD, however, said weight is the minimum rating required) REQID164

The Keybot System shall require a free space with a box volume of no more than 1100x600x600 mm. REQID165

The Keybot System shall require designs from a type of human intelligence, in order to engrave the items. REQID166

The Keybot System shall require a new moulded tray (palette) for each creation and selection of a new PLP, of which the description of the physical layout shall be provided by the Keybot System. REQID167

The Keybot System shall require new components for upgrades or replacements, such as engraving bits, when advised so by the custodian. REQID168

The Keybot System shall utilise different frequency ranges of the EM-wave spectrum within a contained area, such as visible light and possibly radio waves. REQID169

The Keybot System shall utilise different frequency ranges of the Sound Spectrum within a contained area, such as the noise from a vacuum pump, noise from motors, noise from engraving etc. REQID170

4.8 System Physical Requirements

The Keybot System’s net weight shall not exceed the maximum lifting capacity of two average human beings, which should be at least 30 kg, according to the Basic Conditions of Employment Act. REQID171

The Keybot System shall not occupy more than the allowed box space volume of 1100x600x600 mm. REQID172

The Keybot System shall at least have an Ingress Protection (IP) rating of IP44. REQID173

4.9 Other System Qualities

The Keybot System shall be an ergonomic system to limit any discomfort for the operator, user, crowd or transporters. REQID174

The Keybot System’s software resources and -version control shall be maintained within an organised archive system. REQID175

4.10 Design and Construction Requirements

This section covers the requirements for design and construction that were not previously mentioned.

4.10.1 General Design and Construction Requirements

In the case that the Keybot System requires additive manufactured parts, it shall be optimised for the ease of development thereof. REQID176

The Keybot System shall be constructed in a manner that considers the least unintended damaging of any suitable transportation equipment. REQID177

The Keybot System shall be constructed in a manner that considers an ease of access to most components, for the custodian to perform efficient maintenance tasks. REQID178

4.10.2 Characteristics of sub-ordinate elements

The Keybot System shall consist of an enclosure apt for the environmental requirements previously defined. REQID179

The Keybot System shall consist of components capable of exceeding most of the previous mentioned performance- and utilisation requirements to limit the exhaustion of these components overtime. REQID180

The Keybot System shall minimise the likelihood of unavoidable safety or health risks presented by the system itself, such as mentioned in REQUIREMENTS FOR THE SAFE USE OF CLASS 3B AND CLASS 4 LASERS OR LASER SYSTEMS document. REQID181

4.11 Precedence of requirements

All requirements stated herein are subservient to requirements of safety. Should the satisfaction of a requirement lead to the safety requirement being violated the contractor is required to notify the stakeholder.

5 Verification requirements

5.1 Orientation Accuracy

The Keybot System will be able to orientate an item with some resolution, at some angular velocity and with some inaccuracy.

Parameter	0% - 25%	25% - 50%	50% - 75%	75% - 100%	Grade
Resolution (°)	(1.8, ∞)	(1.4, 1.8]	(1.0, 1.4]	(0.0, 1.0]	
Angular Velocity (rev/minute)	[0.0, 2.0)	[2.0, 4.0)	[4.0, 6.0)	[6.0, ∞)	
Inaccuracy (slips/rev)	(9.0, ∞)	(6.0, 9.0]	(3.0, 6.0]	(0.0, 3.0]	
Average					

5.2 Positioning Accuracy

The Keybot System will be able to position the Manufacturing Mechanism with some resolution at the furthest point of reach, at some displacement velocity and with some inaccuracy.

Parameter	0% - 25%	25% - 50%	50% - 75%	75% - 100%	Grade
Resolution (mm diameter)	(5.0, ∞)	(3.0, 5.0]	(1.5, 3.0]	(0.0, 1.5]	
Displacement Velocity (mm/s)	[0, 25)	[50, 25)	[50, 75)	[75, ∞)	
Inaccuracy (resolution slips/m)	(5.0, ∞)	(3.0, 5.0]	(2.0, 3.0]	(0.0, 2.0]	
Average					

5.3 Engraving Feed Rate

The Keybot System will be able to engrave an item with some fineness at a certain feed rate for MDF.

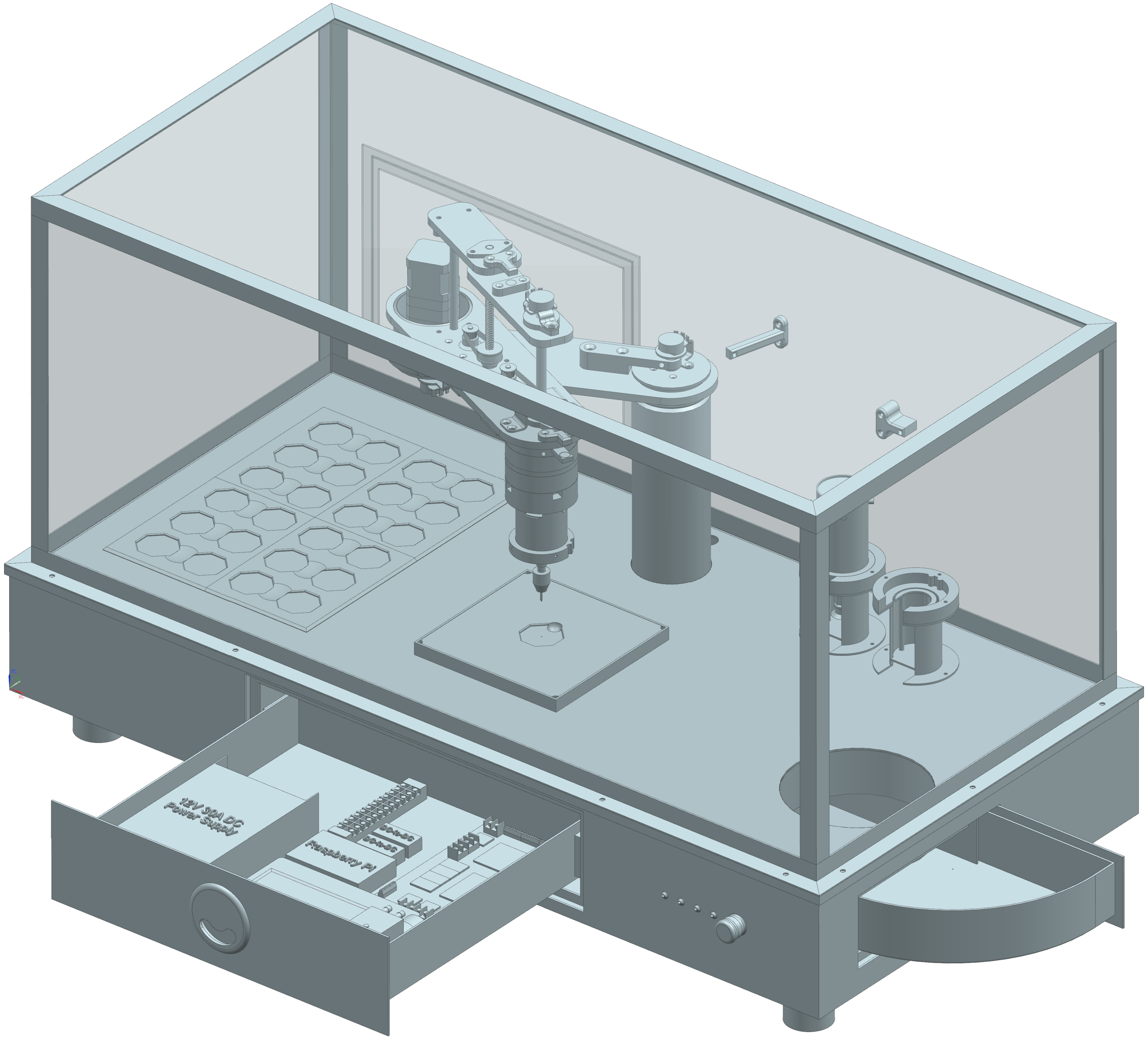
Parameter	0% - 25%	25% - 50%	50% - 75%	75% - 100%	Grade
Fineness (mm diameter)	(7.0, ∞)	(5.0, 7.0]	(3.0, 5.0]	(0.0, 3.0]	
Feed Rate (mm/s)	[0.0, 2.0)	[2.0, 5.0)	[5.0, 8.0)	[8.0, ∞)	
Average					

5.4 Weight Transportation

The Keybot System will be able to transport an item with a maximum weight at its maximum speed without dropping the item.

Parameter	0% - 25%	25% - 50%	50% - 75%	75% - 100%	Grade
Weight (N)	[0.0, 0.5)	[0.5, 1.0)	[1.0, 2.0)	[2.0, ∞)	

Appendix B:
System CAD Design Pack



FAKULTEIT INGENIEURSWESE	PROJECT REFERENCE	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	PROJECT 2020004 KEYBOT	PIETER MARX	29703662	MR

DOCUMENT DESCRIPTION	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	DOCUMENT LENGTH
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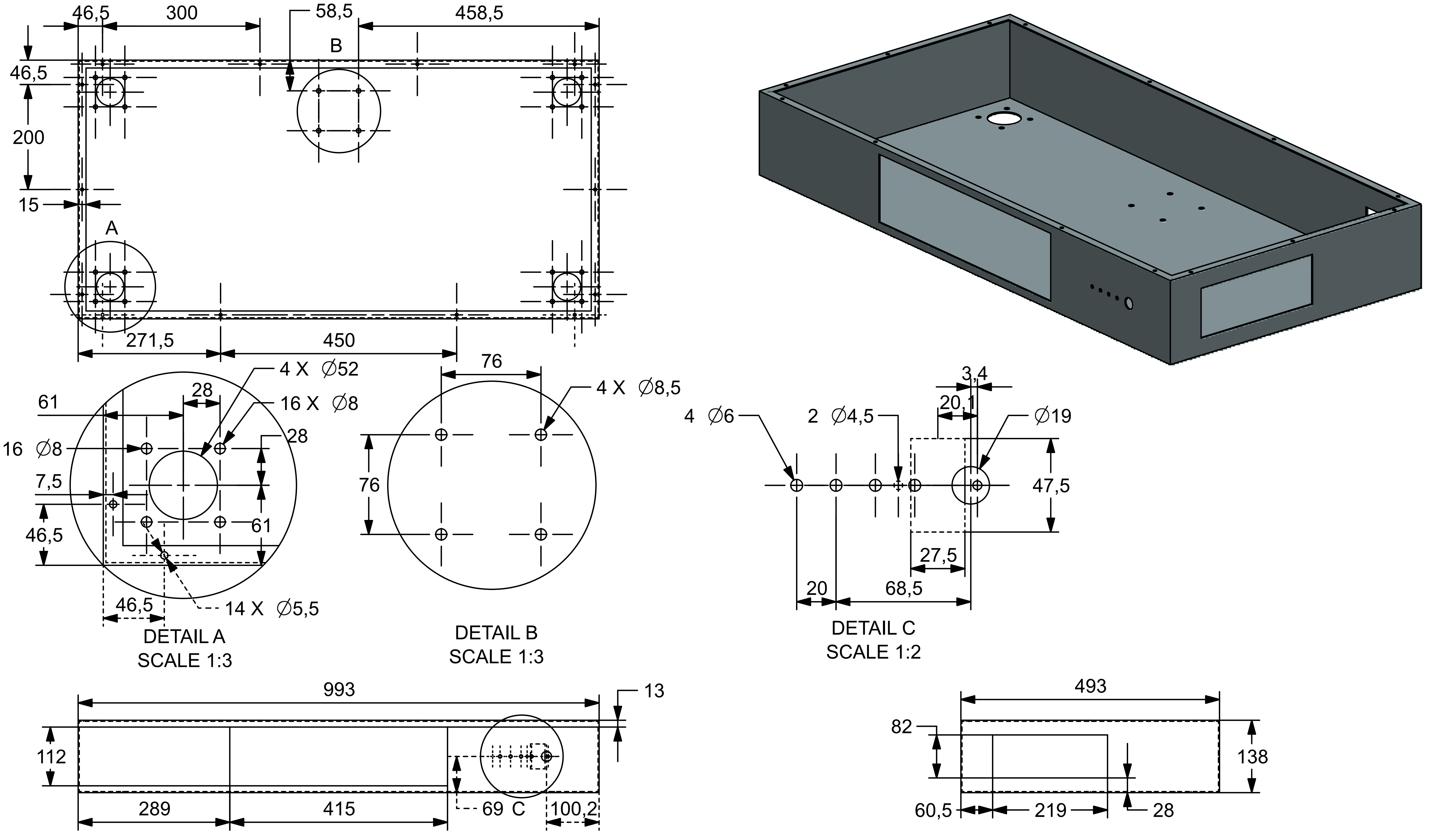
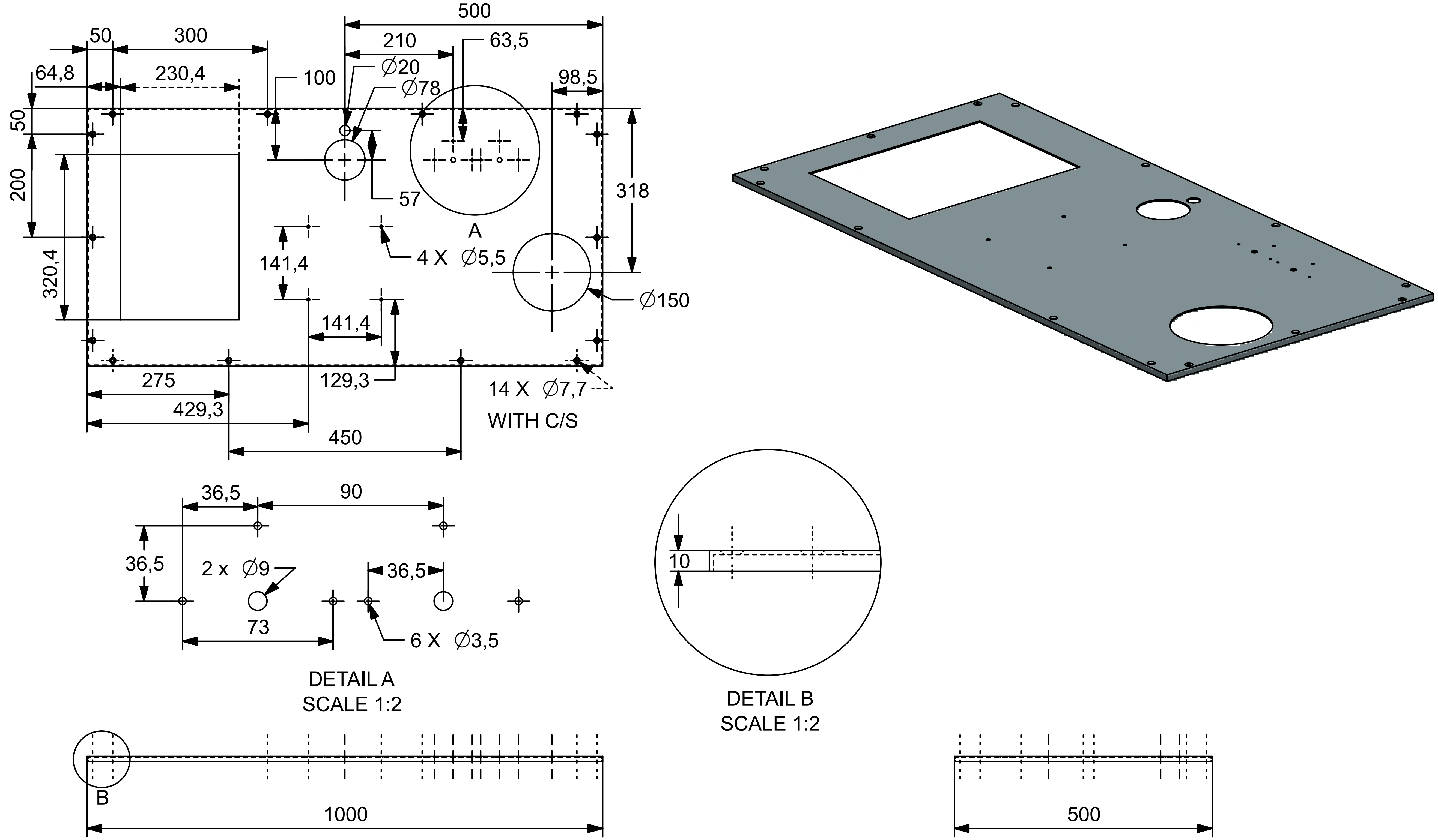
A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	2 MM ALUMINIUM SHEET	PIETER MARX	29703662	MR

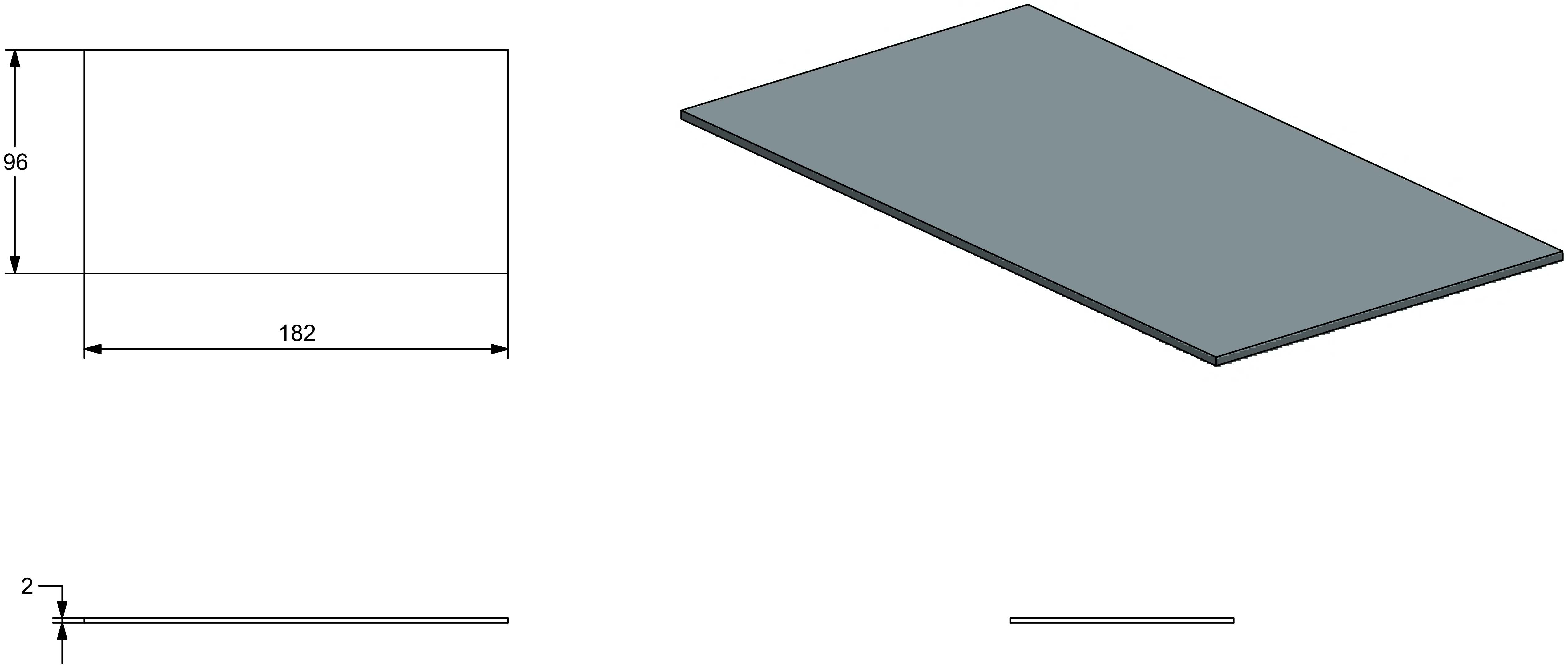
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	26/08/2020	SCALE 1:1	001-Electrical-Enclosure_V1	SHEET 1 OF 93

A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		**MATERIAAL/MATERIAL** 2 MM ALUMINIUM SHEET	**NAAM/ NAME** PIETER MARX		**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	**DATUM/DATE** 26/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 002-Electrical-Enclosure-Lid_V1	**BLADSY/ SHEET** SHEET 2 OF 93

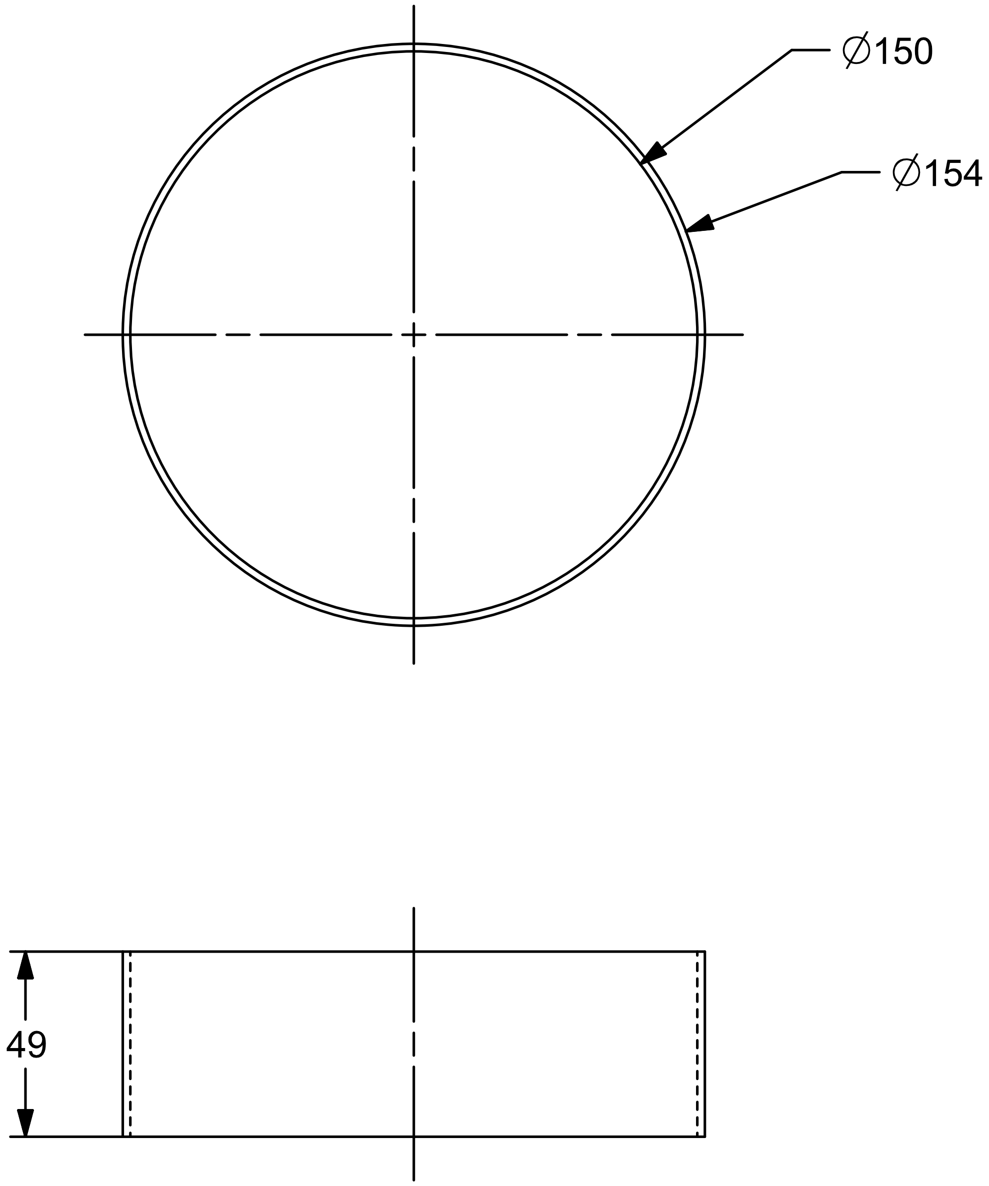
A3

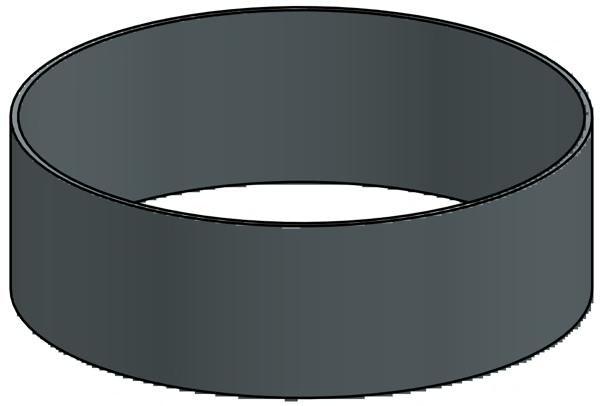


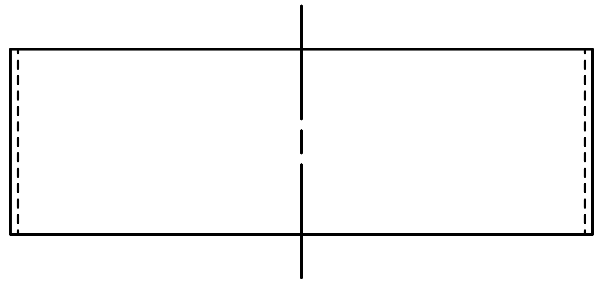
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 2 MM ALUMINIUM SHEET	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR

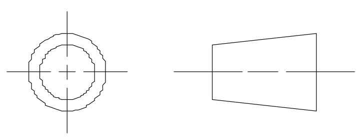
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
NONE	26/08/2020	SCALE 1:1	003-Revolving-Drawer-Stopper_V 1	SHEET 3 OF 93

A3



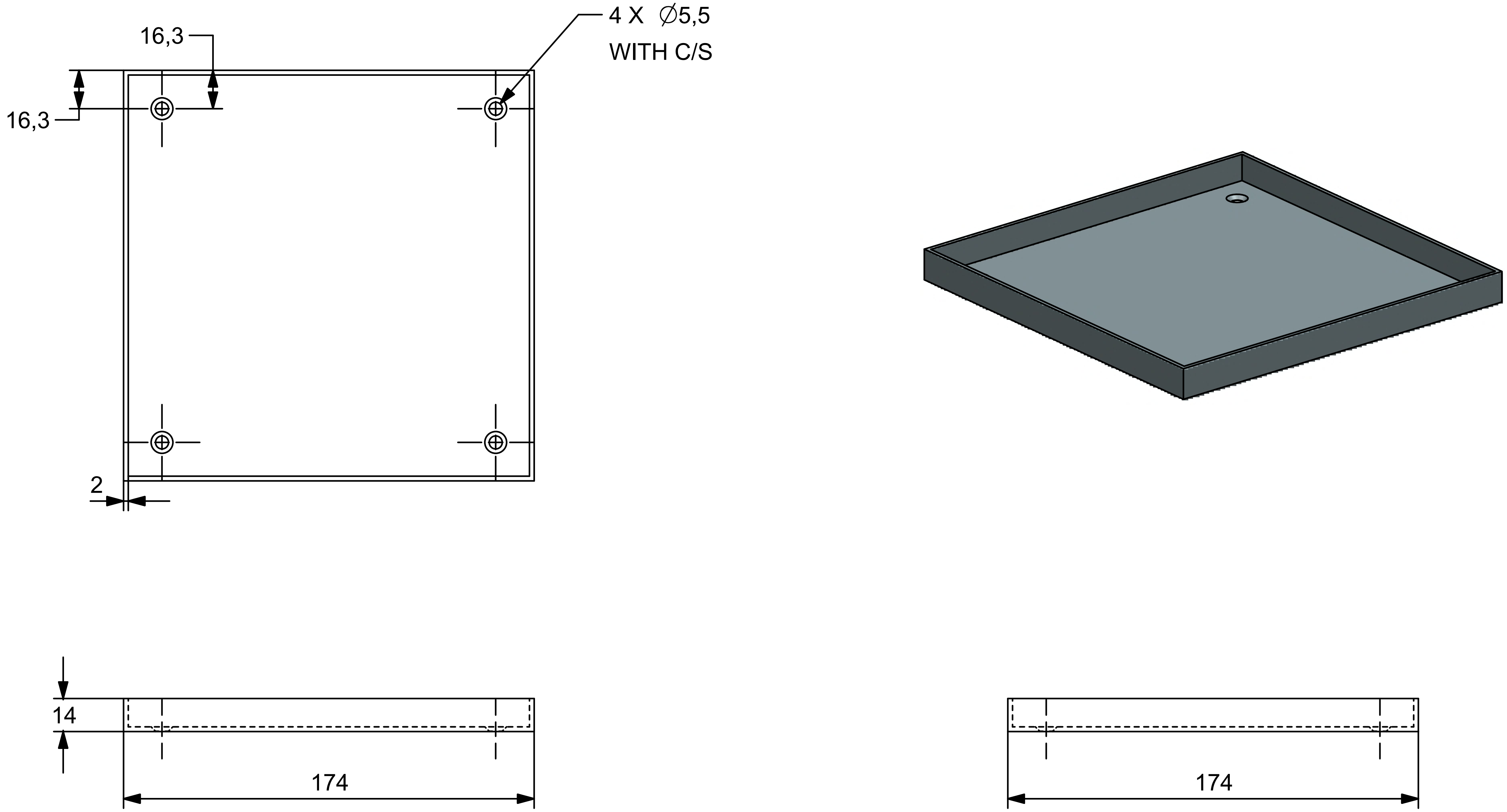






FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		**MATERIAAL/MATERIAL** 2 MM ALUMINIUM SHEET	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES ROLL AND WELD (ROLL AFTER WELDING)	**DATUM/DATE** 26/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 004-Revolving-Drawer-Shoot_V1
					BLADSY/ SHEET SHEET 4 OF 93

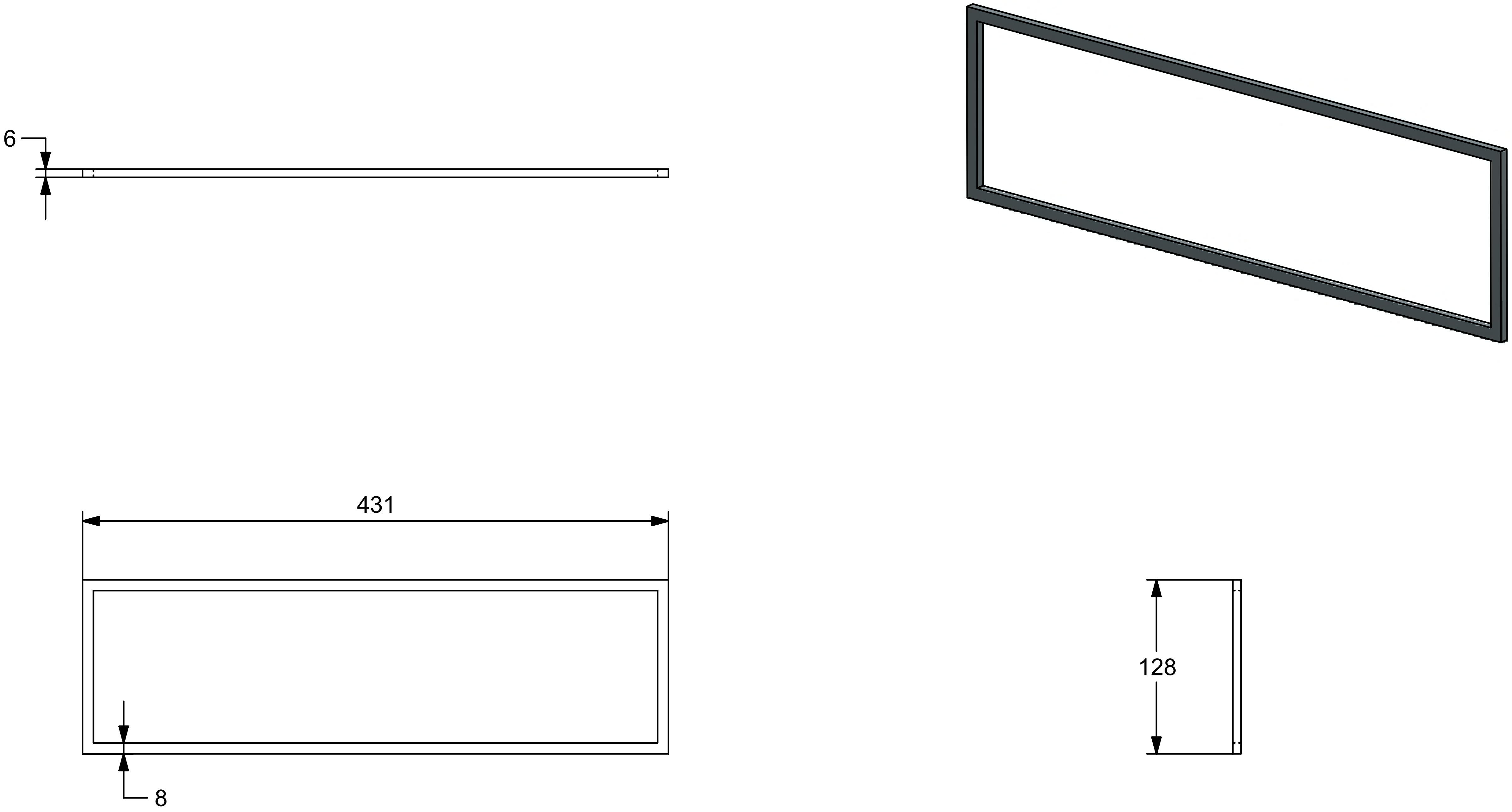
A3



MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL	
2 MM ALUMINIUM SHEET	PIETER MARX	29703662	MR	
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	26/08/2020	SCALE 1:1	005-Engraving-Station_V1	SHEET 5 OF 93

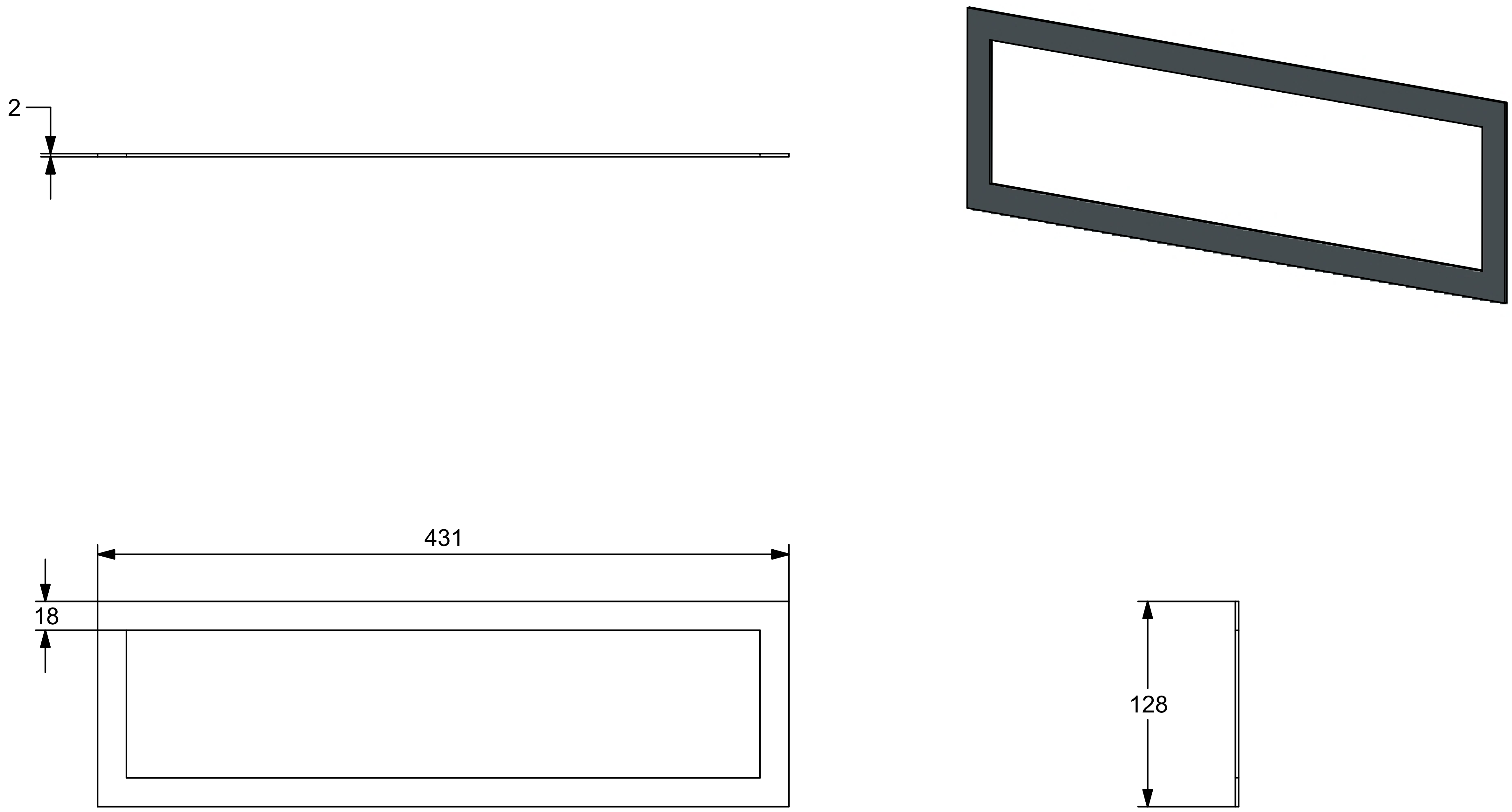
FAKULTEIT INGENIEURSWESE
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 8 MM ALUMINIUM PLATE	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR	
	ADDISIONELE NOTAS/ ADDITIONAL NOTES ONE OR FOUR PARTS	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 006-Main-Drawer-Frame_V1	BLADSY/ SHEET SHEET 6 OF 93

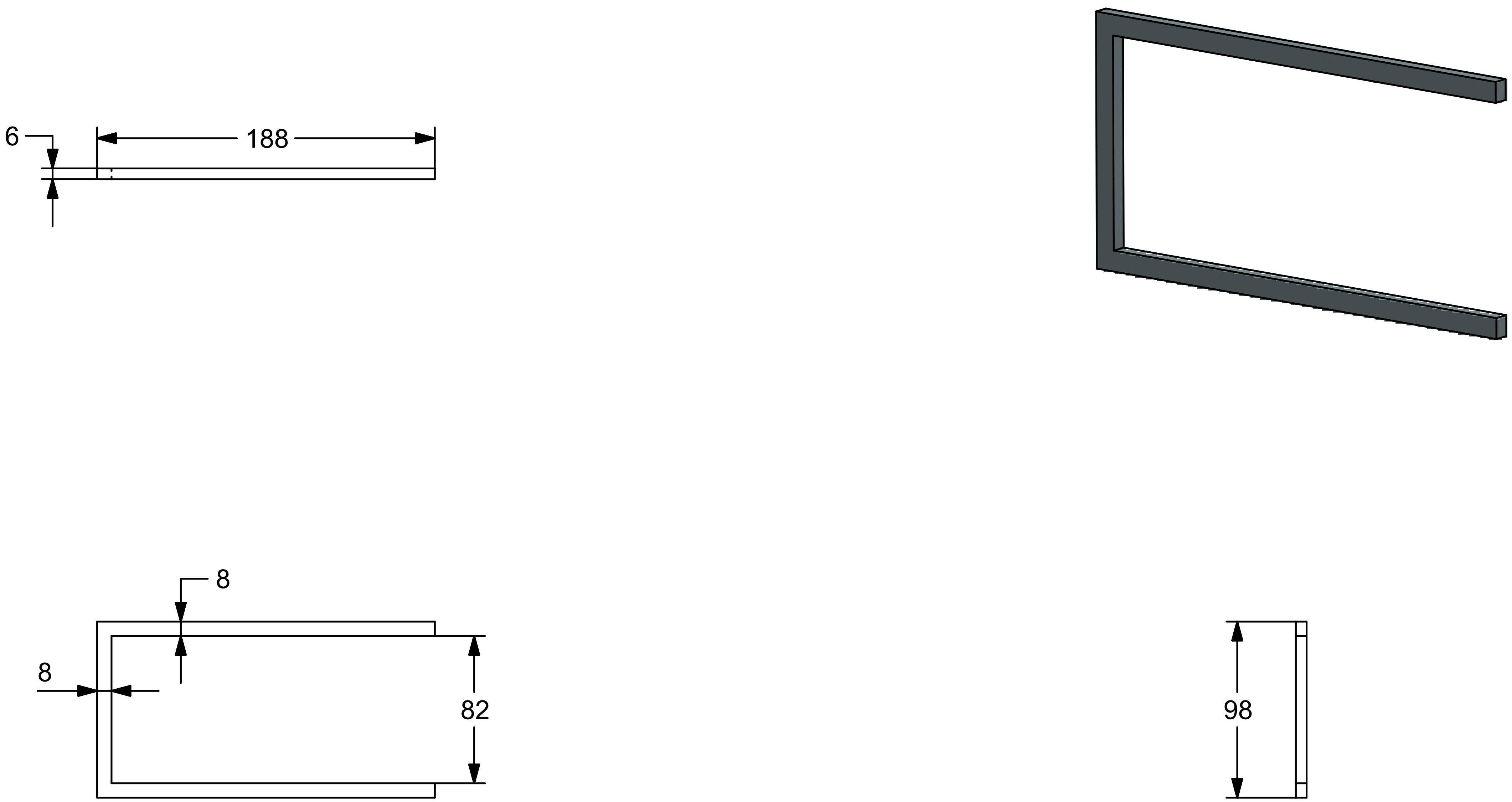
A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** 2 MM ALUMINIUM SHEET	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	**DATUM/DATE**	**SKAAL/SCALE**	**TEKENINGNOMMER/ DRAWING NUMBER**	**BLADSY/ SHEET**
ONE OR FOUR PARTS	26/08/2020	SCALE 1:1	007-Main-Drawer-Shoulder_V1	SHEET 7 OF 93

A3

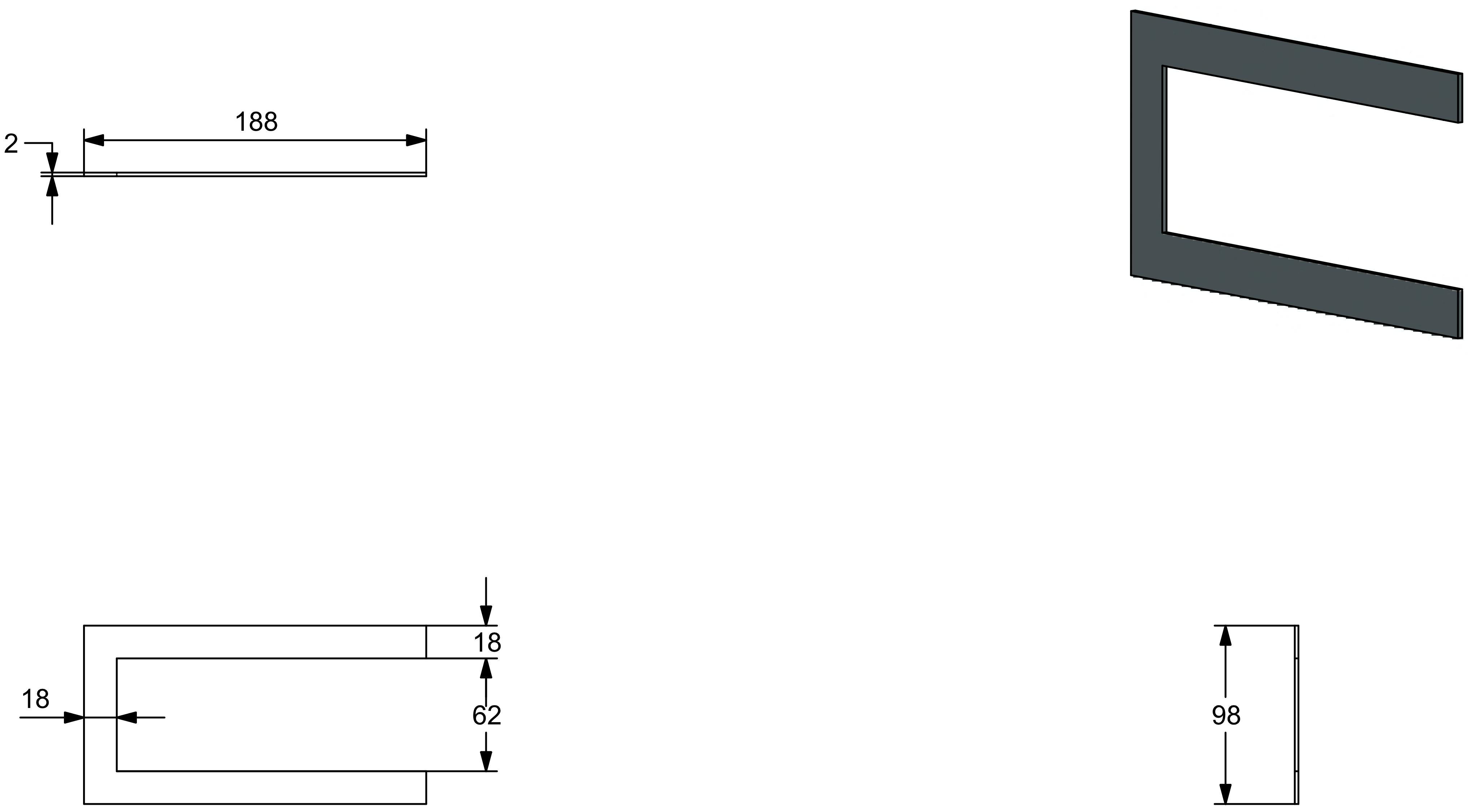


FAKULTEIT INGENIEURSWESE
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
8 MM ALUMINIUM PLATE	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
ONE OR THREE PARTS	26/08/2020	SCALE 1:1	008-Revolving-Drawer-Frame_V1	SHEET 8 OF 93

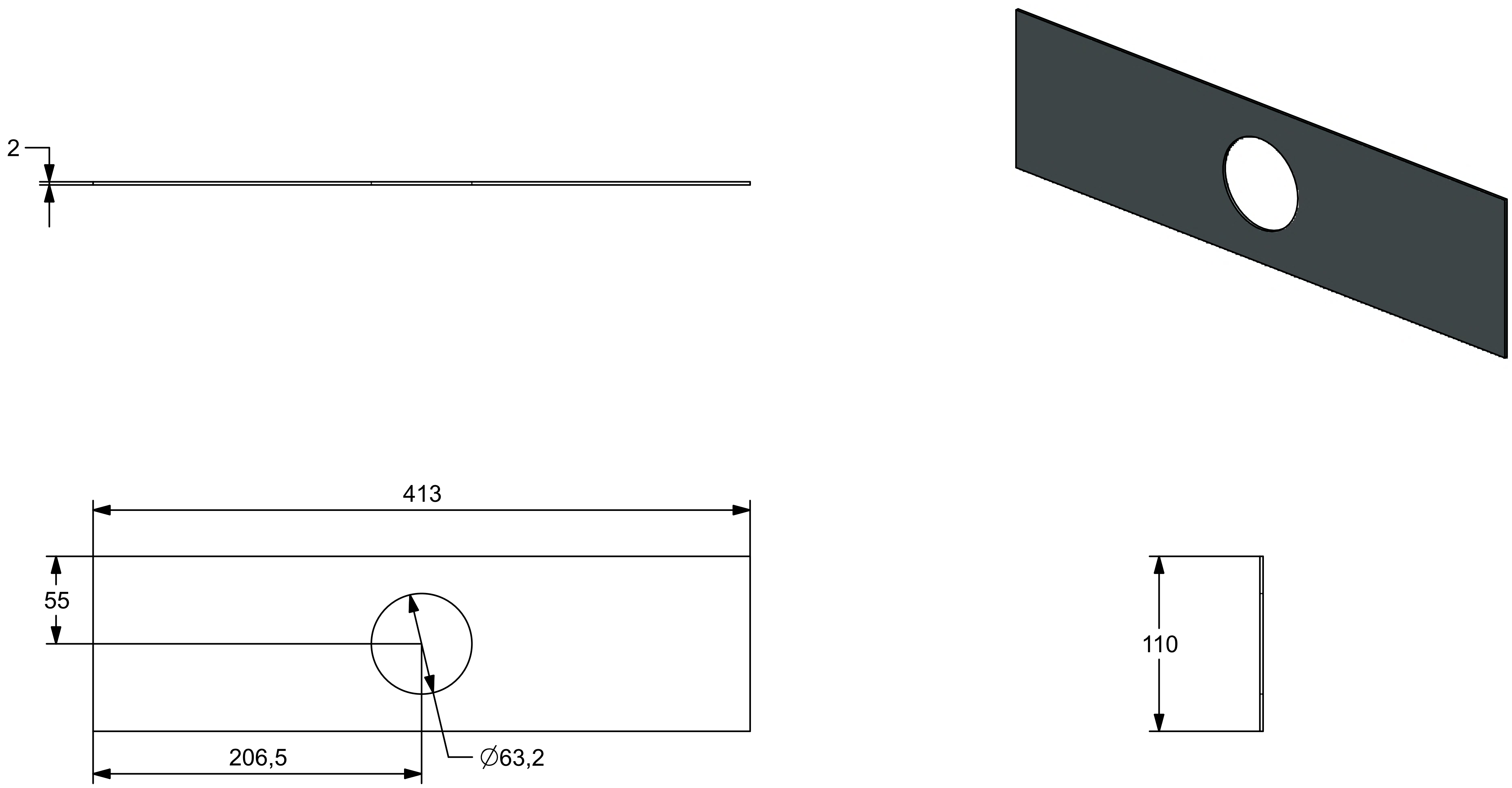
A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	2 MM ALUMINIUM SHEET	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
ONE OR THREE PARTS	26/08/2020	SCALE 1:1	009-Revolving-Drawer-Shoulder_ V1	SHEET 9 OF 93

A3



FAKULTEIT INGENIEURSWESE

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
2 MM ALUMINIUM SHEET	PIETER MARX	29703662	MR

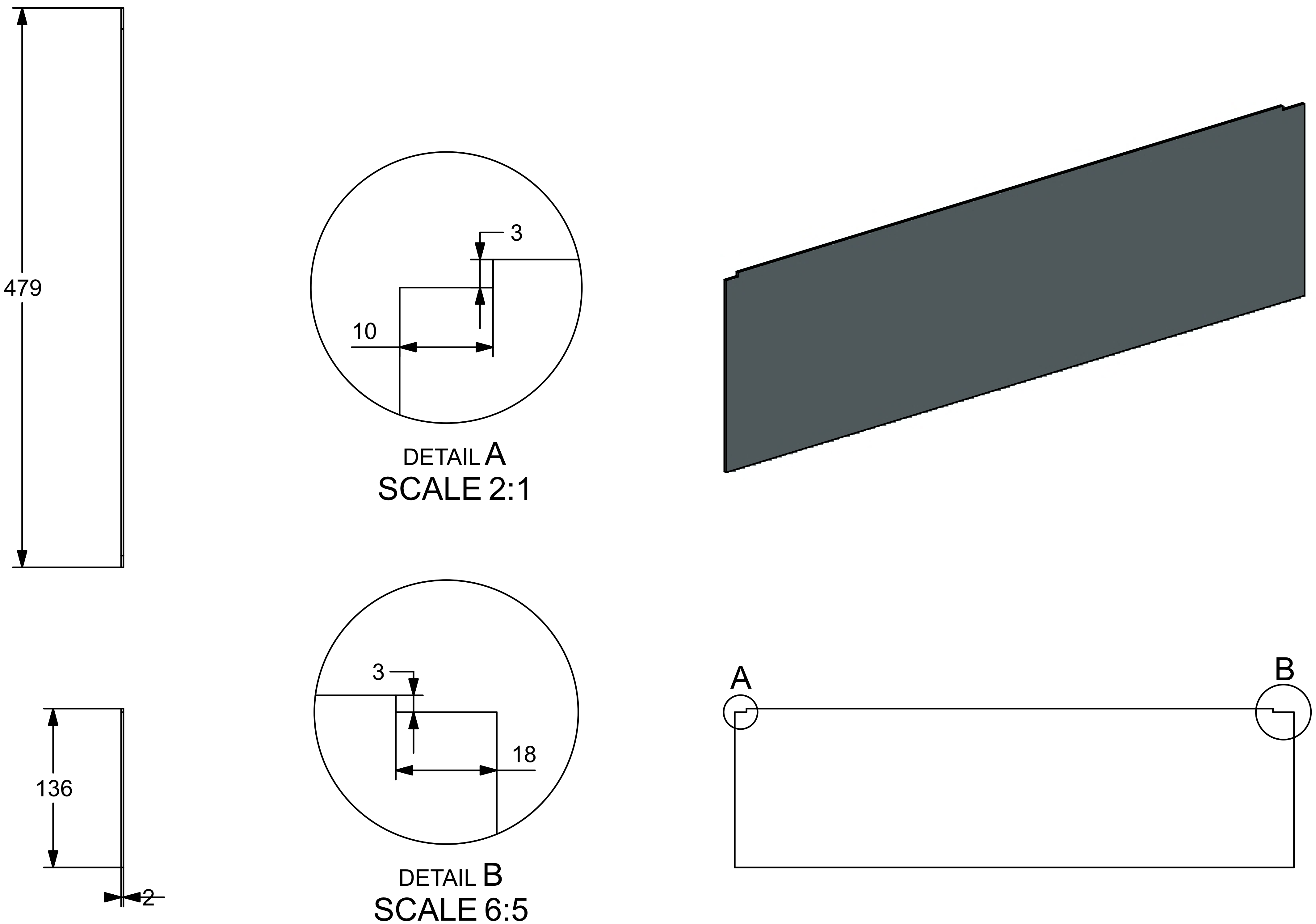
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
NONE	26/08/2020	SCALE 1:1	010-Main-Drawer-Lid_V1	SHEET 10 OF 93

A3

FAKULTEIT INGENIEURSWESE	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	2 MM ALUMINIUM SHEET	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
NONE	26/08/2020	SCALE 1:1	011-Revolving-Drawer-Lid_V1	SHEET 11 OF 93

A3



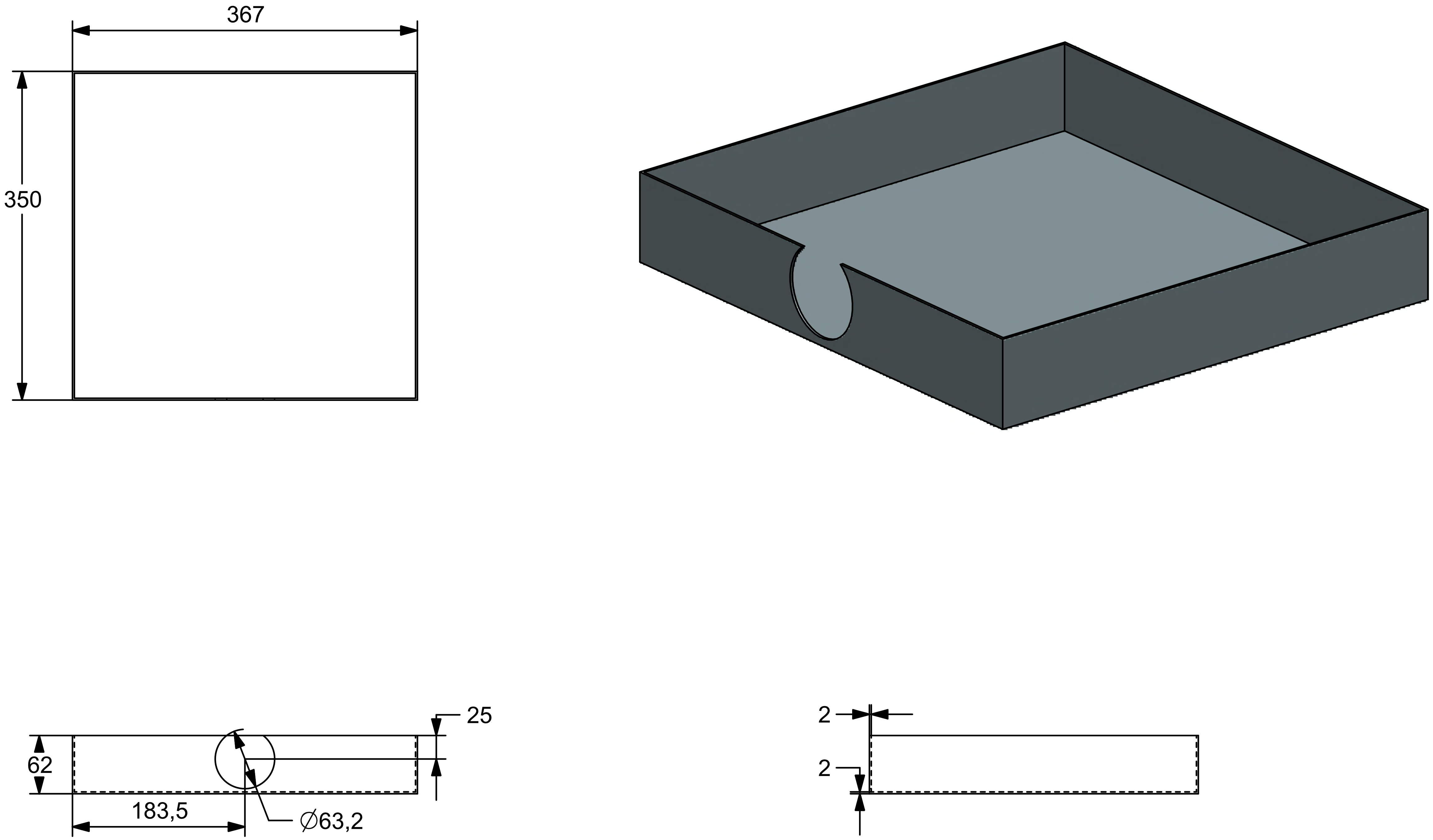
FAKULTEIT INGENIEURSWESE

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
2 MM ALUMINIUM SHEET 2 REQD	PIETER MARX	29703662	MR

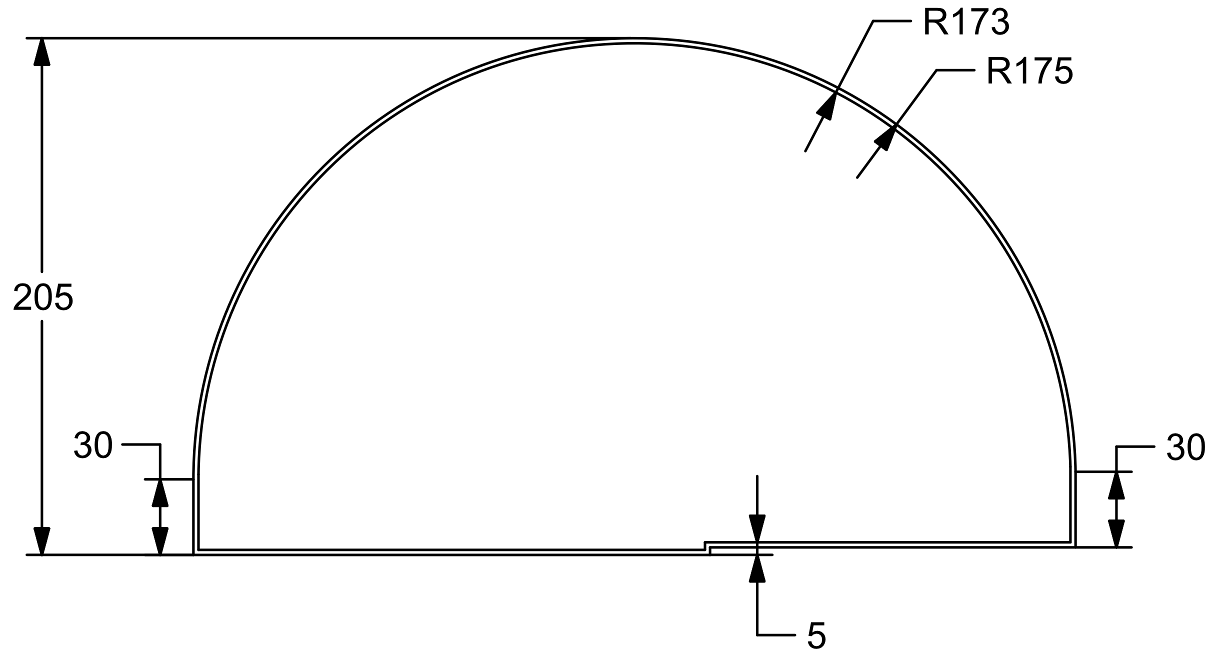
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
NONE	26/08/2020	SCALE 1:1	012-Main-Drawer-Rail-Structure-Support_V1	SHEET 12 OF 93

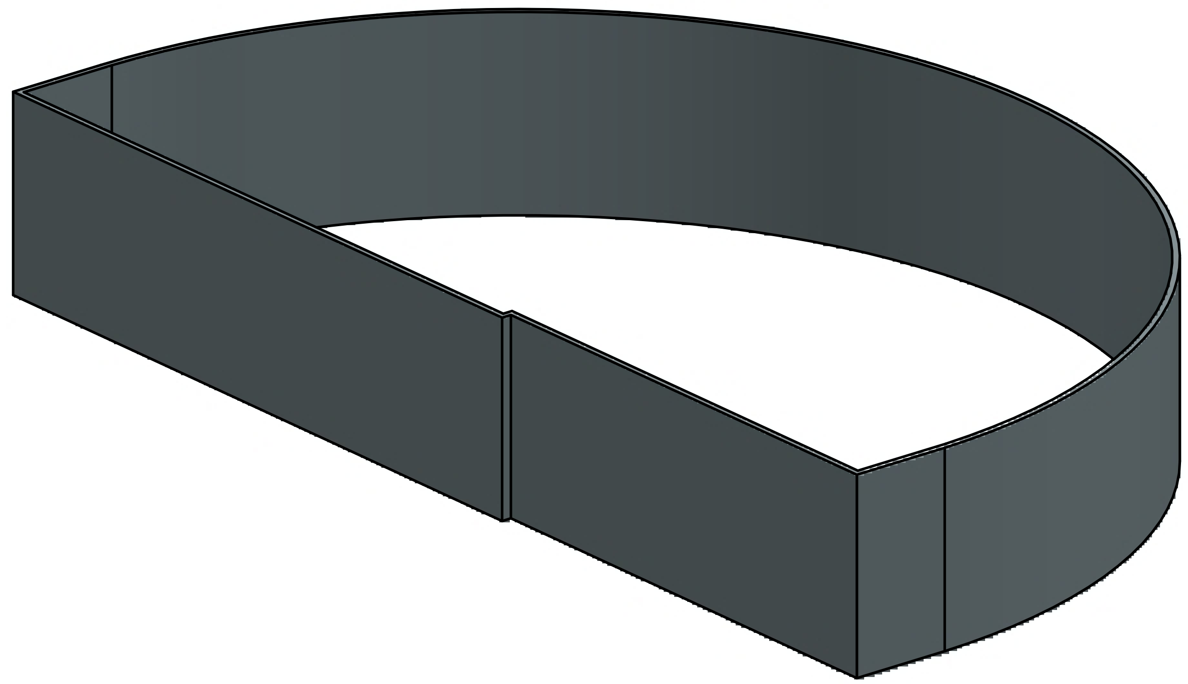
A3

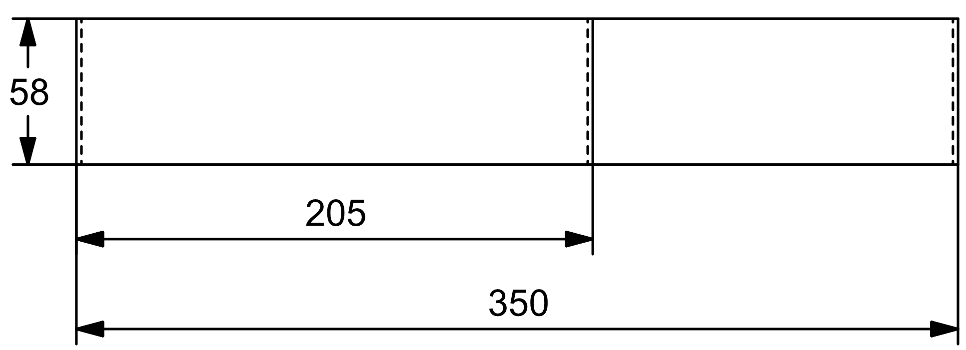


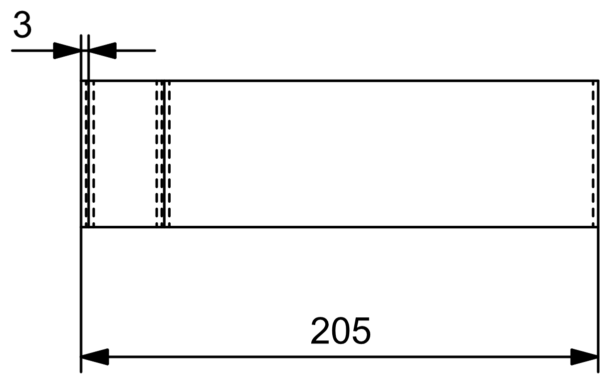
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 2 MM ALUMINIUM SHEET	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES NONE	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 013-Main-Drawer_V1	BLADSY/ SHEET SHEET 13 OF 93

A3



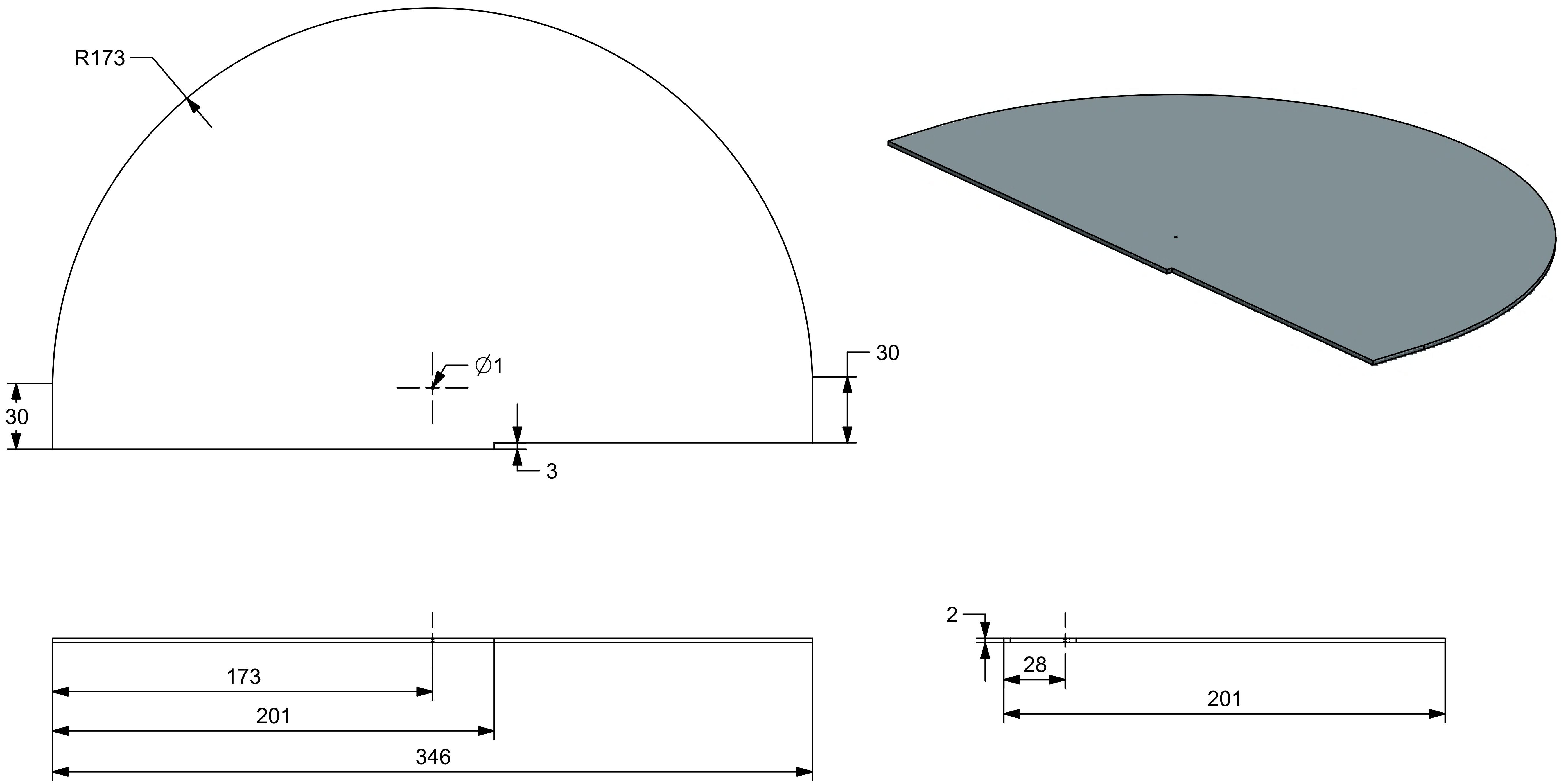






FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 2 MM ALUMINIUM SHEET	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662		TITEL/ TITEL MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES WHEN BENDING FRONT KINK, S-SHAPED BEND IS ACCEPTABLE, JUST KEEP FRONT 205 TRUE	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 014-Revolving-Drawer_V1		BLADSY/ SHEET SHEET 14 OF 93

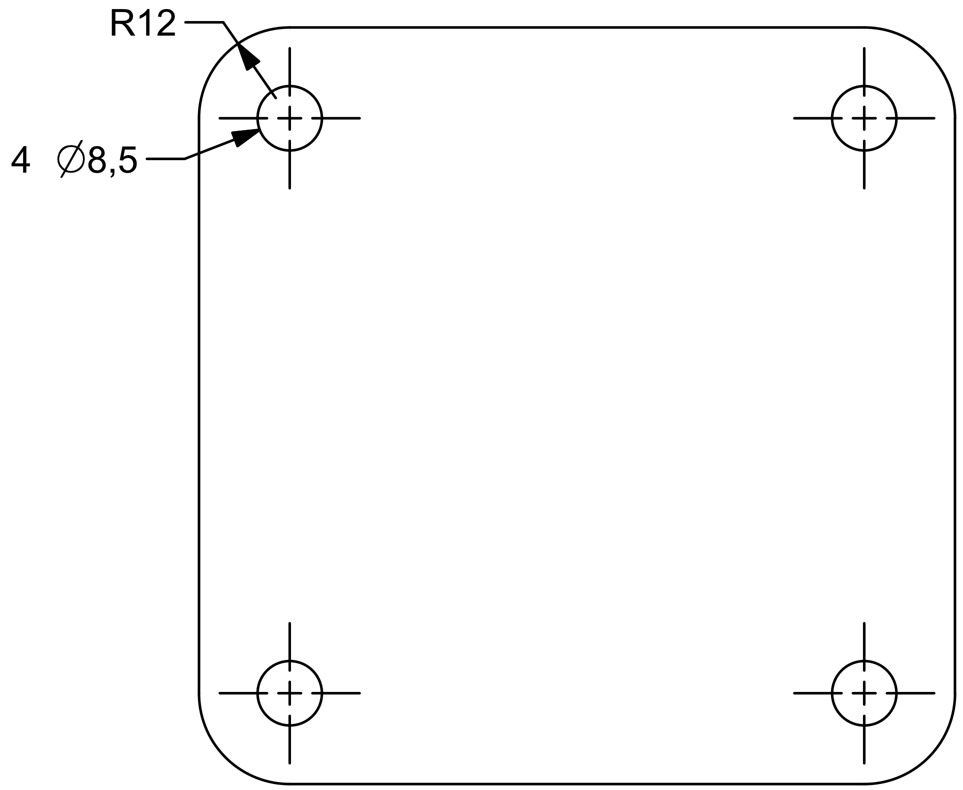
A3

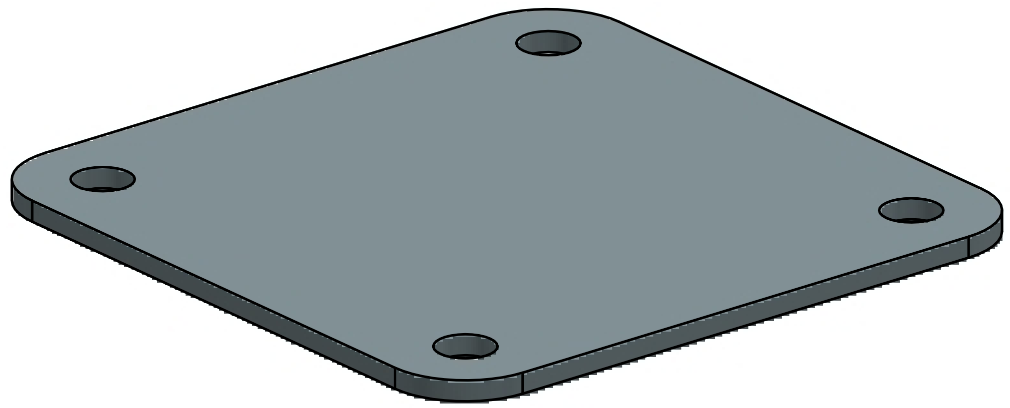


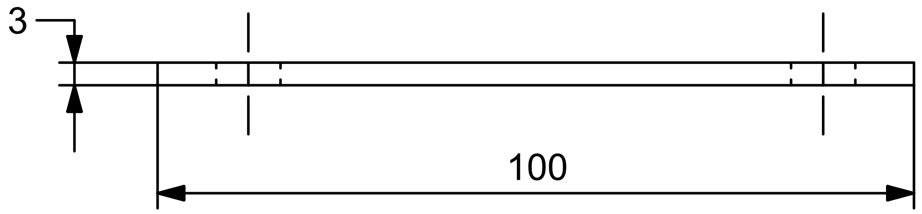
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	2 MM ALUMINIUM SHEET	PIETER MARX	29703662	MR

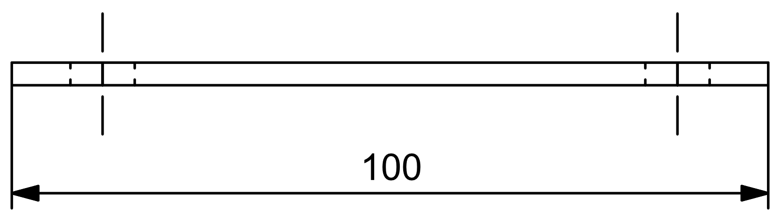
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	26/08/2020	SCALE 1:1	015-Revolving-Drawer-Bottom_V1	SHEET 15 OF 93

A3









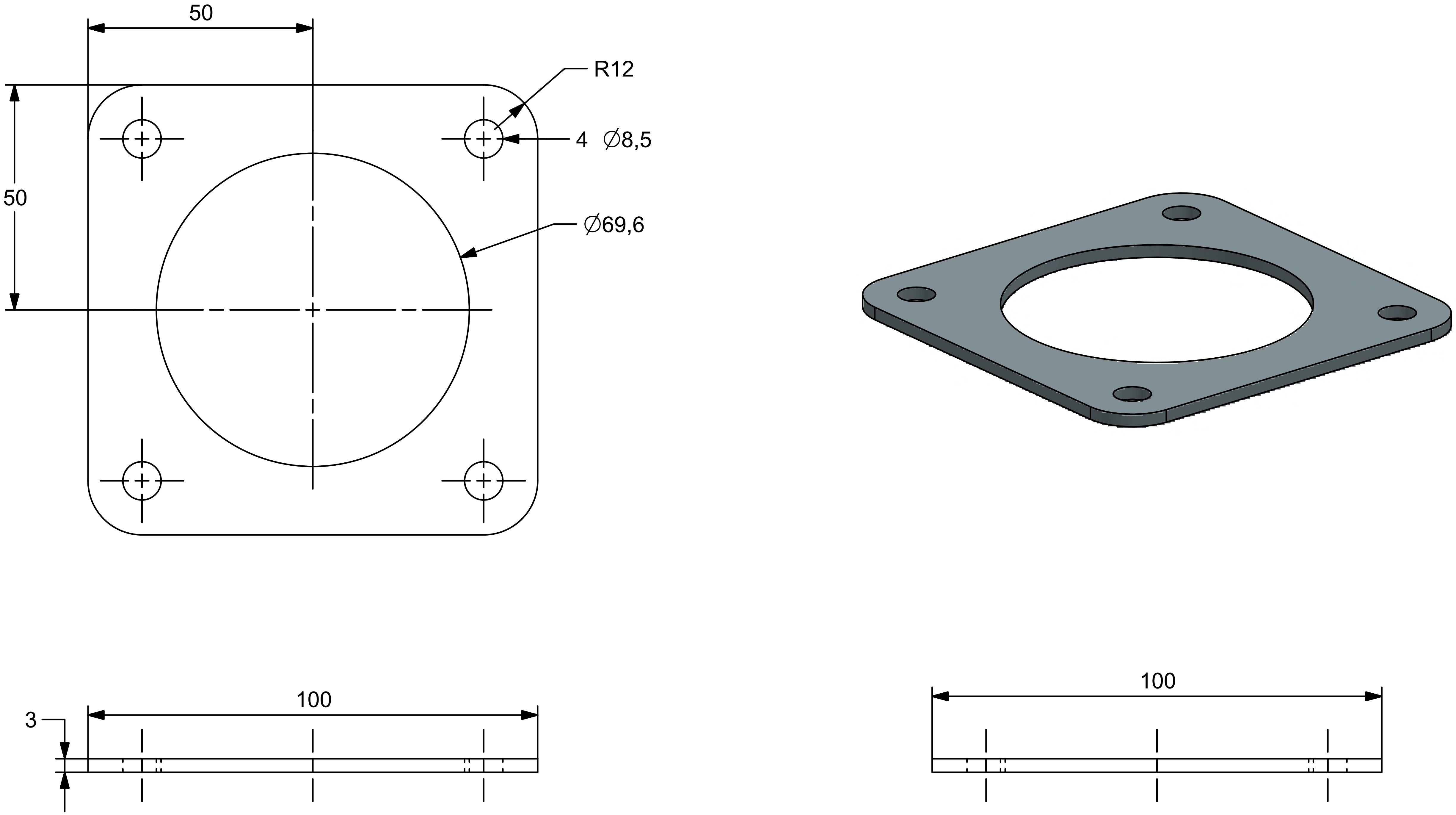
FAKULTEIT INGENIEURSWESE

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
3 MM ALUMINIUM SHEET	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	26/08/2020	SCALE 1:1	016-Post-Base-Support_V1	SHEET 16 OF 93

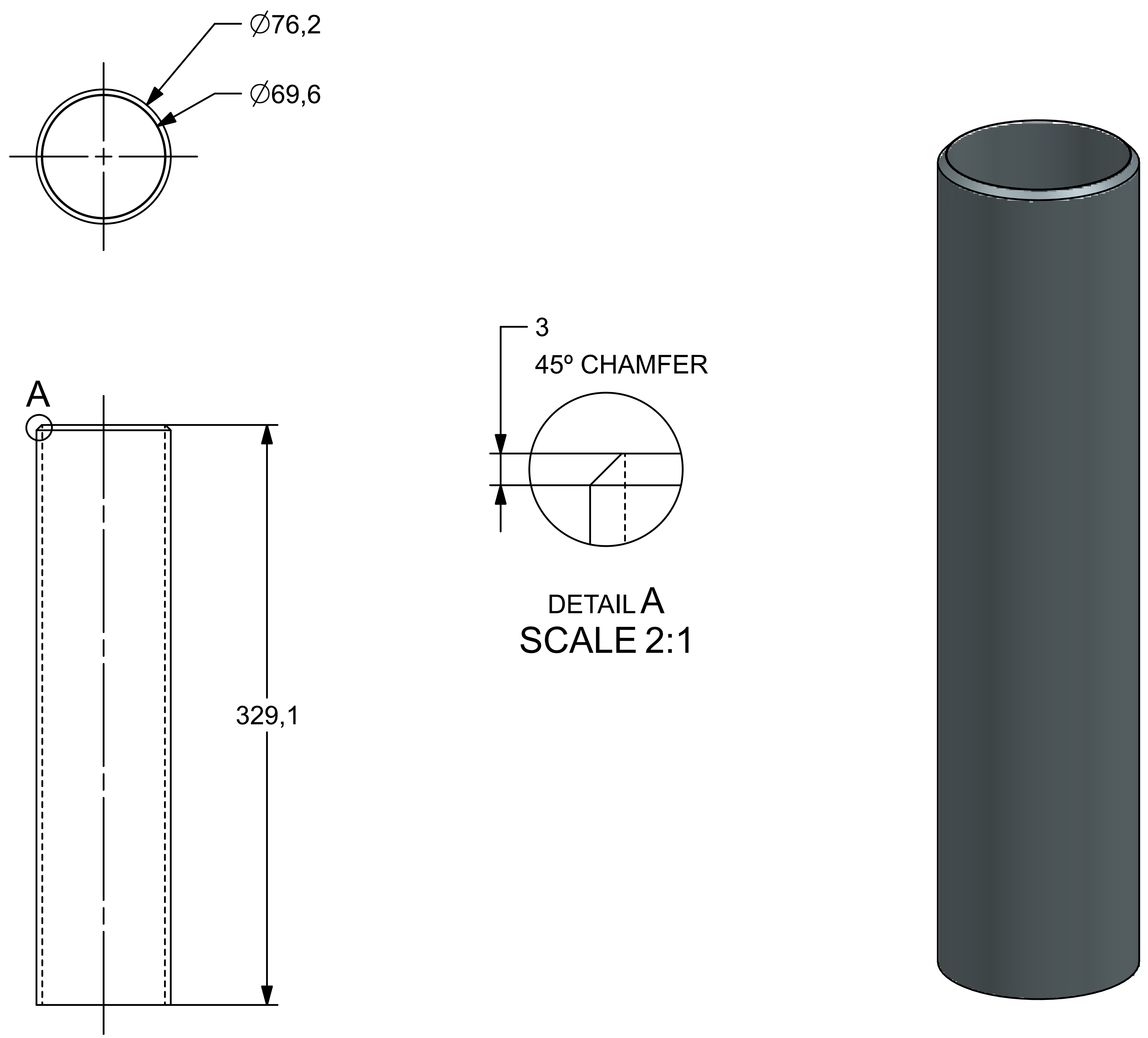
A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 3 MM ALUMINIUM SHEET	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR

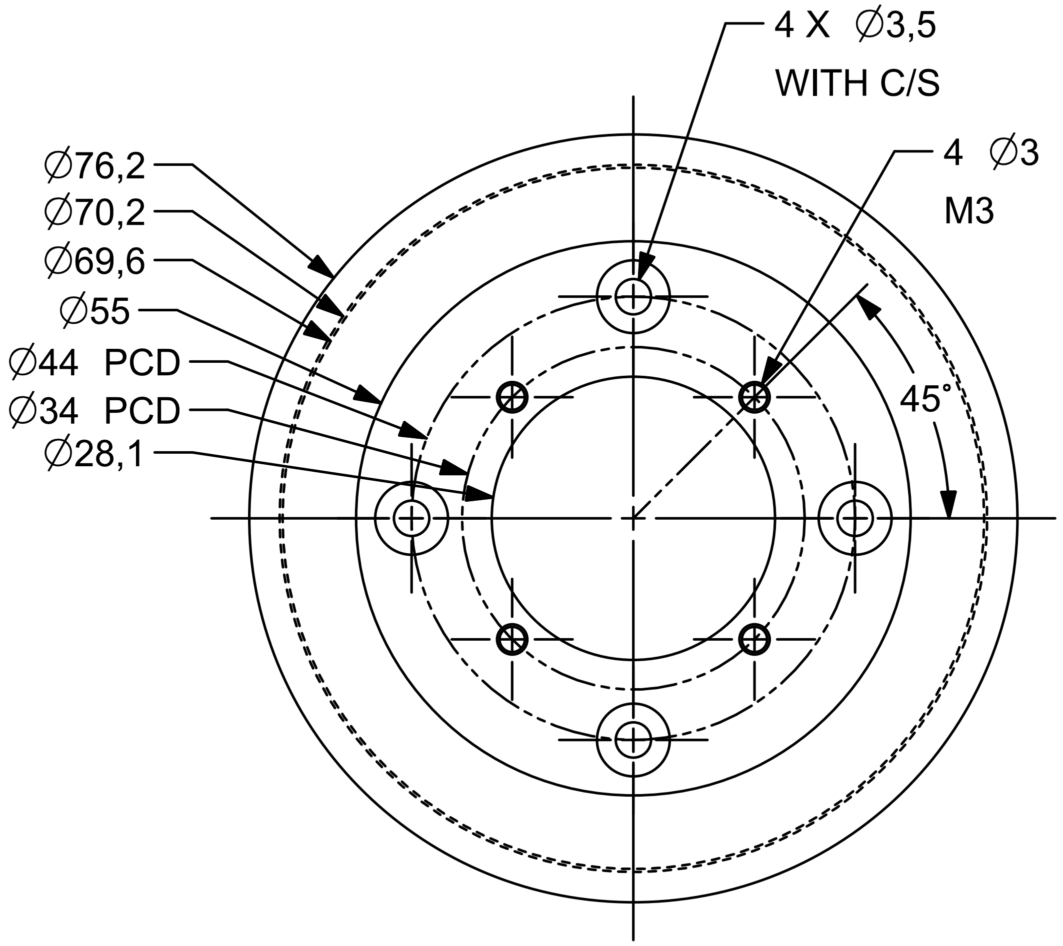
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	26/08/2020	SCALE 1:1	017-Post-Base_V1	SHEET 17 OF 93

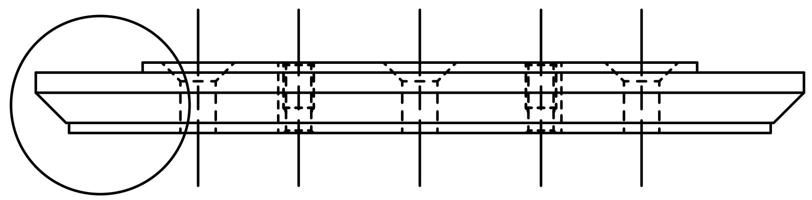
A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 3" ALUMINIUM ROUND TUBING	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR	
ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 018-Post_V1	BLADSY/ SHEET SHEET 18 OF 93	

A3





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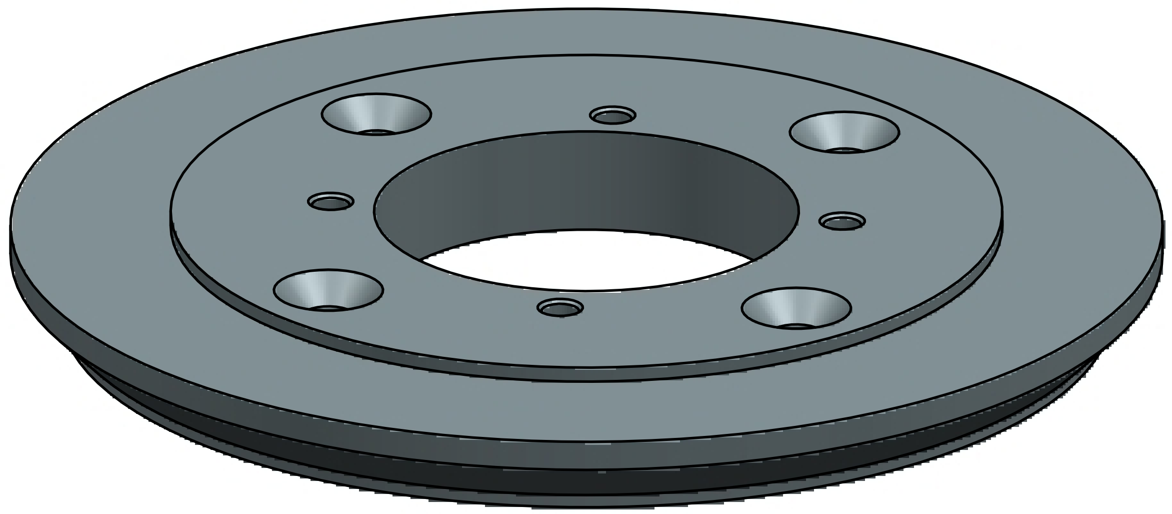
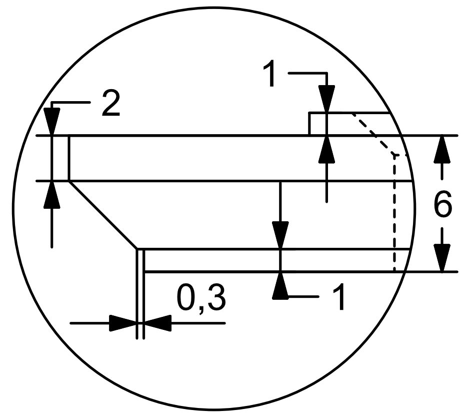


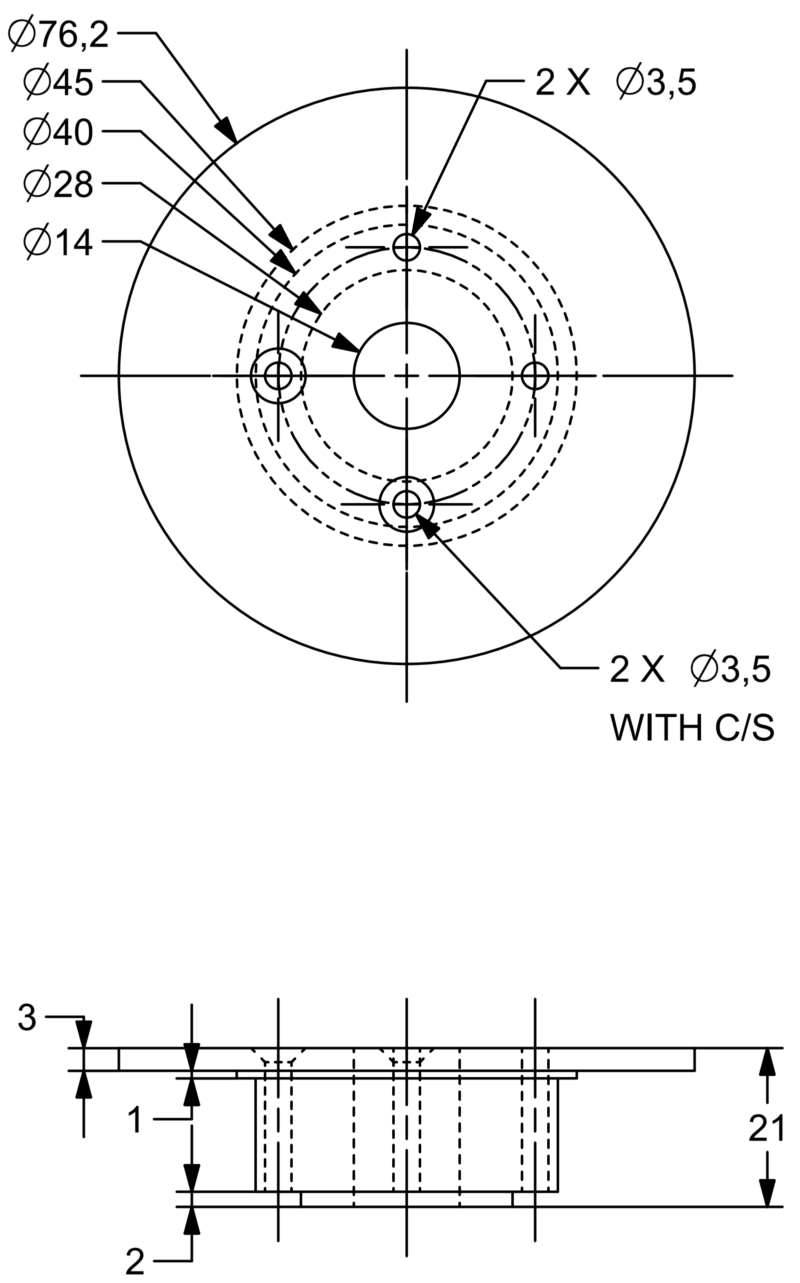


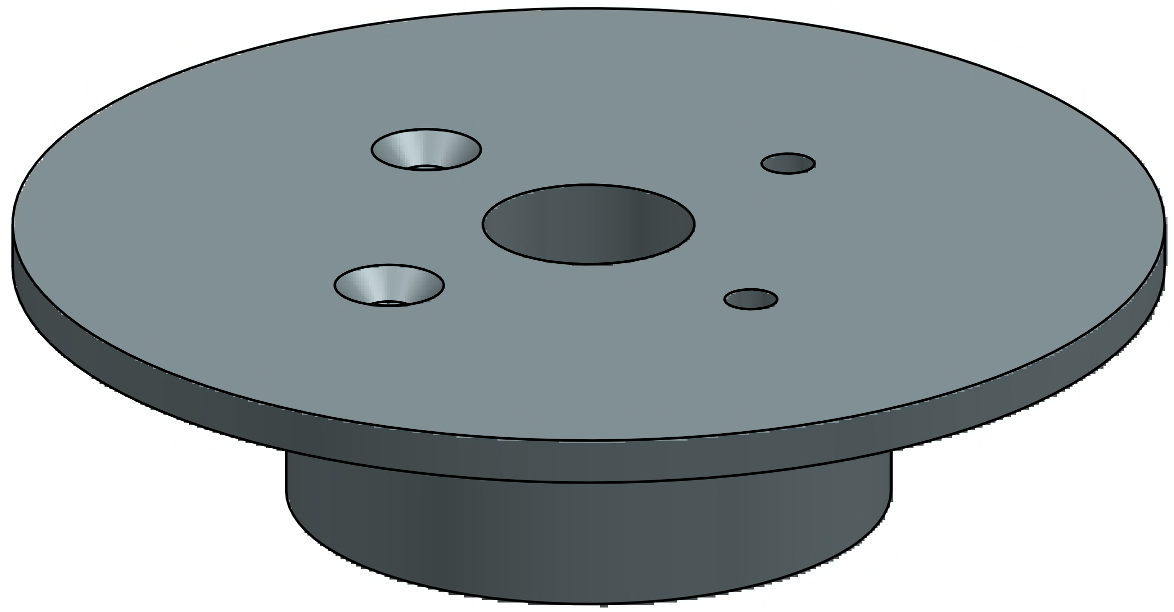
DETAIL A
SCALE 3:1

FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	ALUMINIUM 2 REQD	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	26/08/2020	SCALE 1:1	019-Post-End-Cap_V1	SHEET 19 OF 93

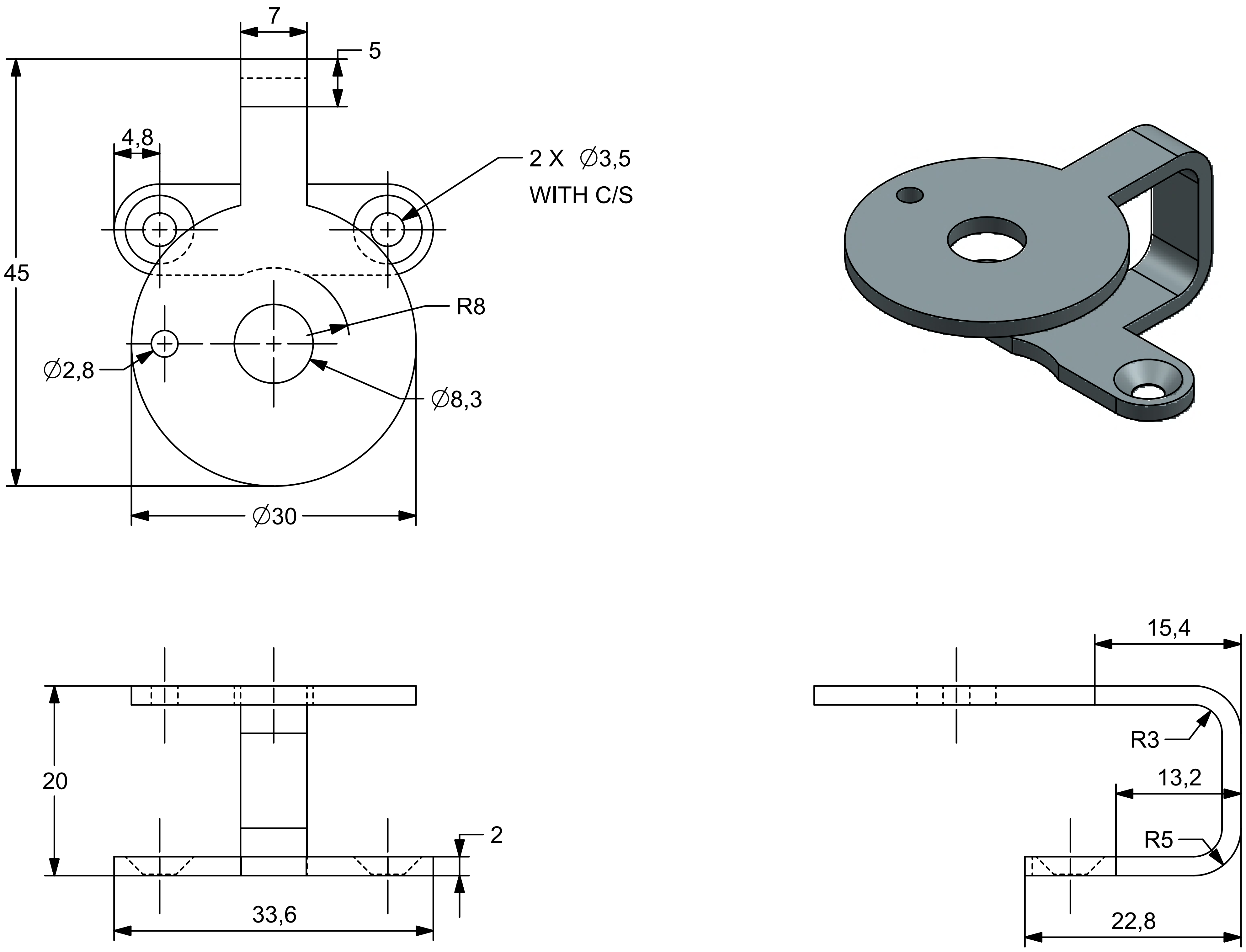
A3





FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL ALUMINIUM 2 REQD	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 020-Post-Bearing-Holder_V1	BLADSY/ SHEET SHEET 20 OF 93

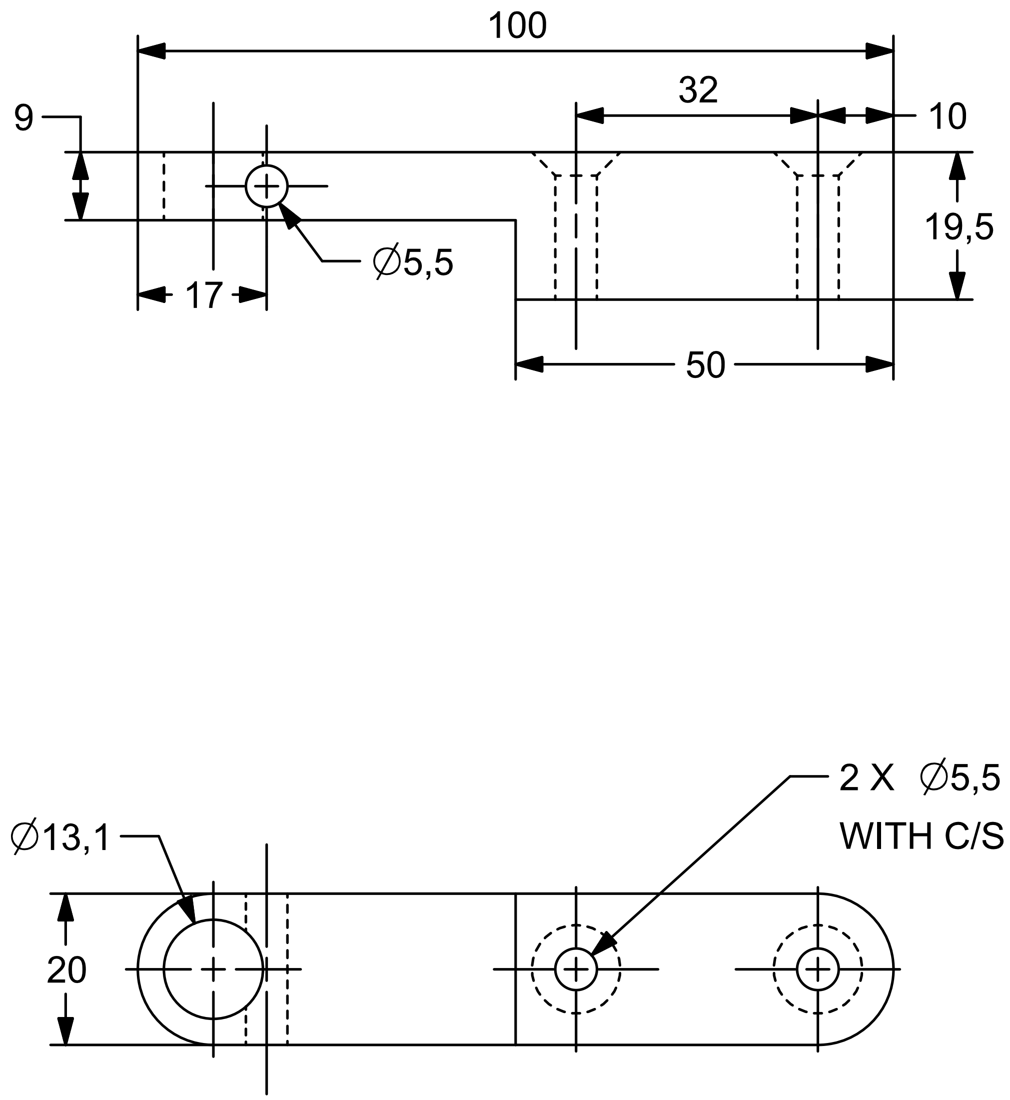
A3

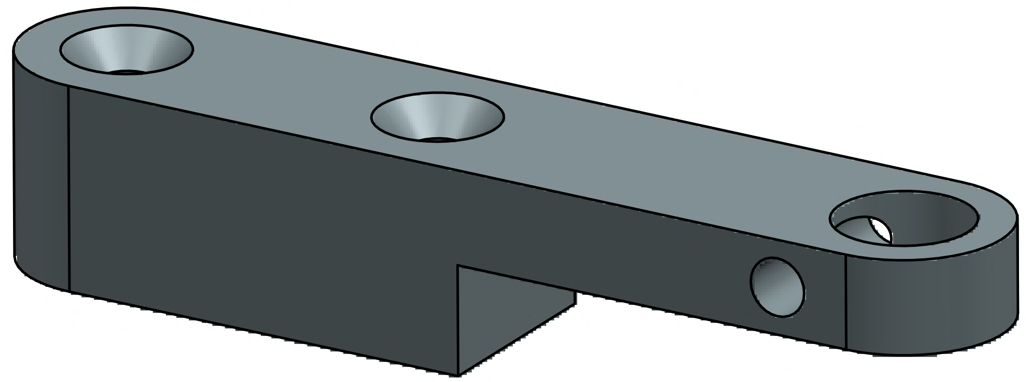


FAKULTEIT INGENIEURSWESE	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	2 MM ALUMINIUM SHEET 2 REQD	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
DRD ENTERPRISES TO FULLY MANUFACTURE PART	26/08/2020	SCALE 1:1	021-Potensiometer-Bracket-1_V1	SHEET 21 OF 93

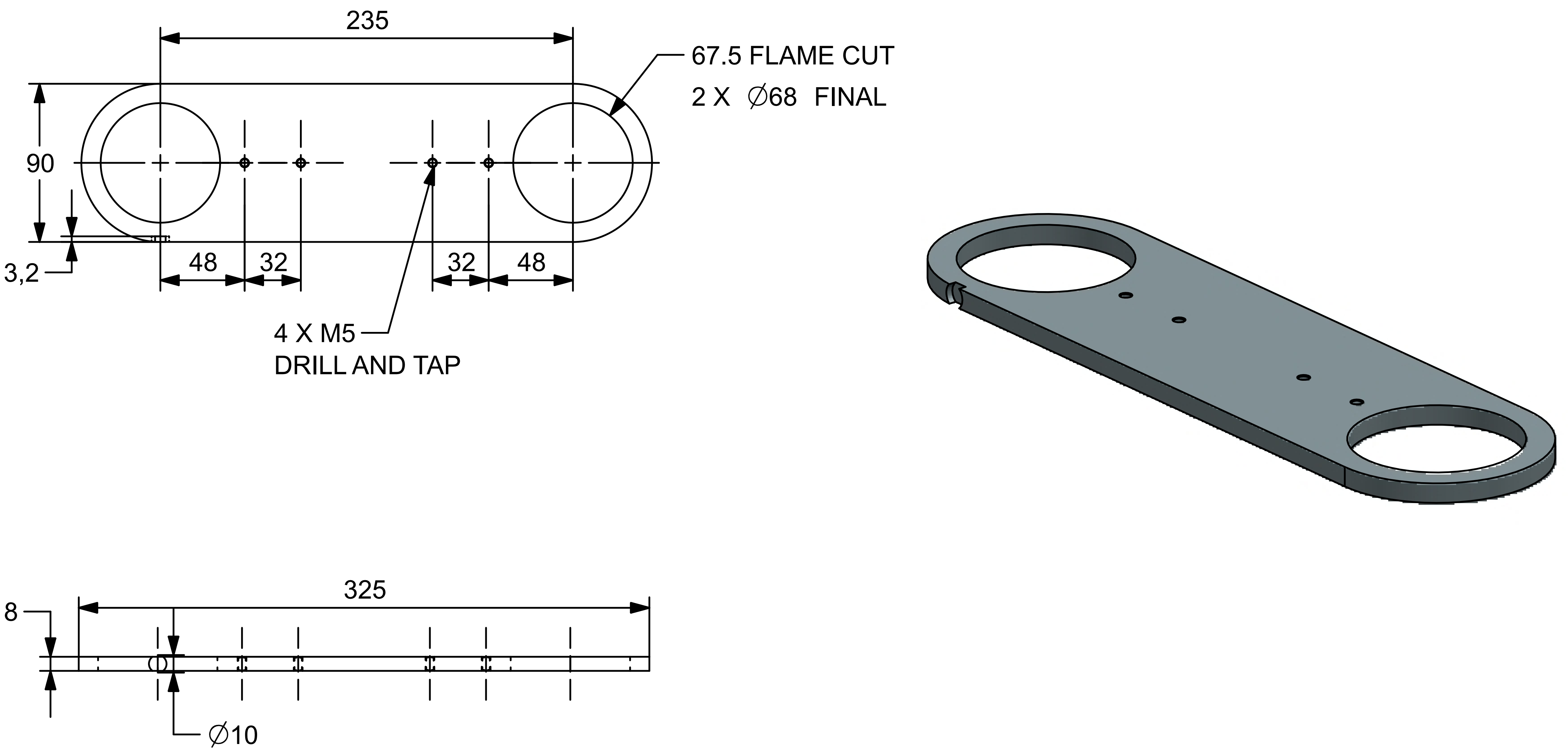
A3





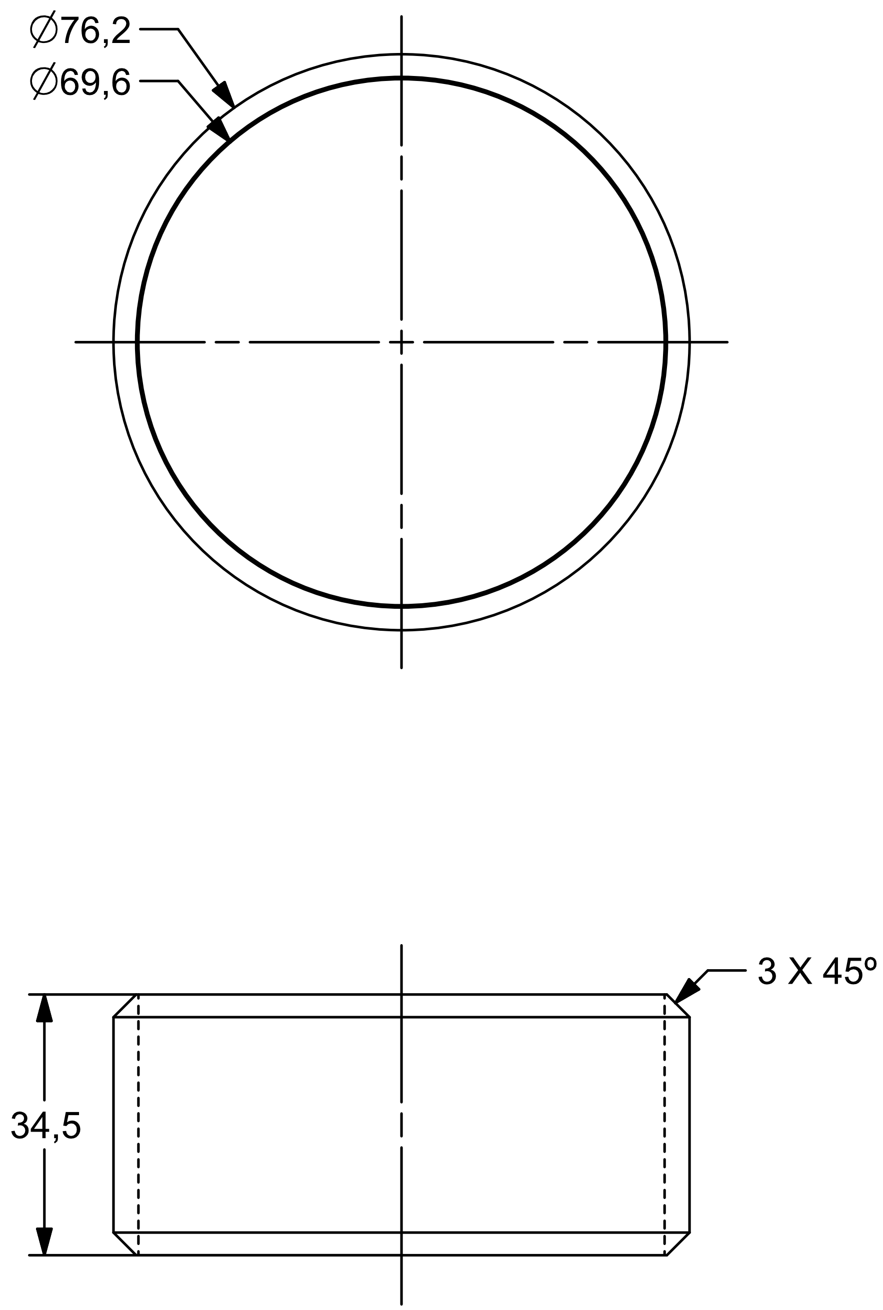
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** ALUMINIUM 2 REQD	**NAAM/ NAME** PIETER MARX		**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	**DATUM/DATE** 26/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 022-Take-Along_V1	**BLADSY/ SHEET** SHEET 22 OF 93

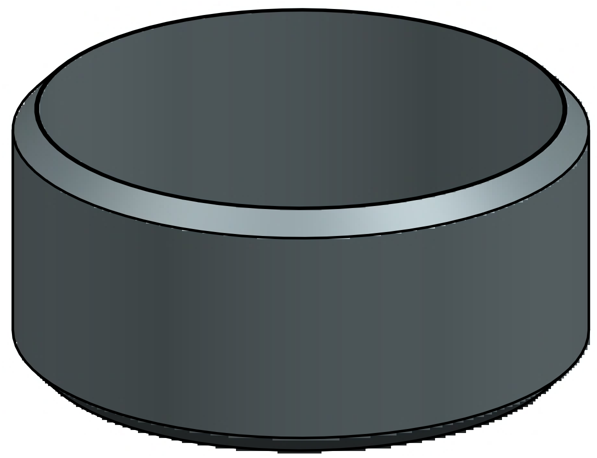
A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 8 MM ALUMINIUM PLATE	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 2970.3662	TITEL/ TITEL MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 023-Arm-1_V1	BLADSY/ SHEET SHEET 23 OF 93

A3

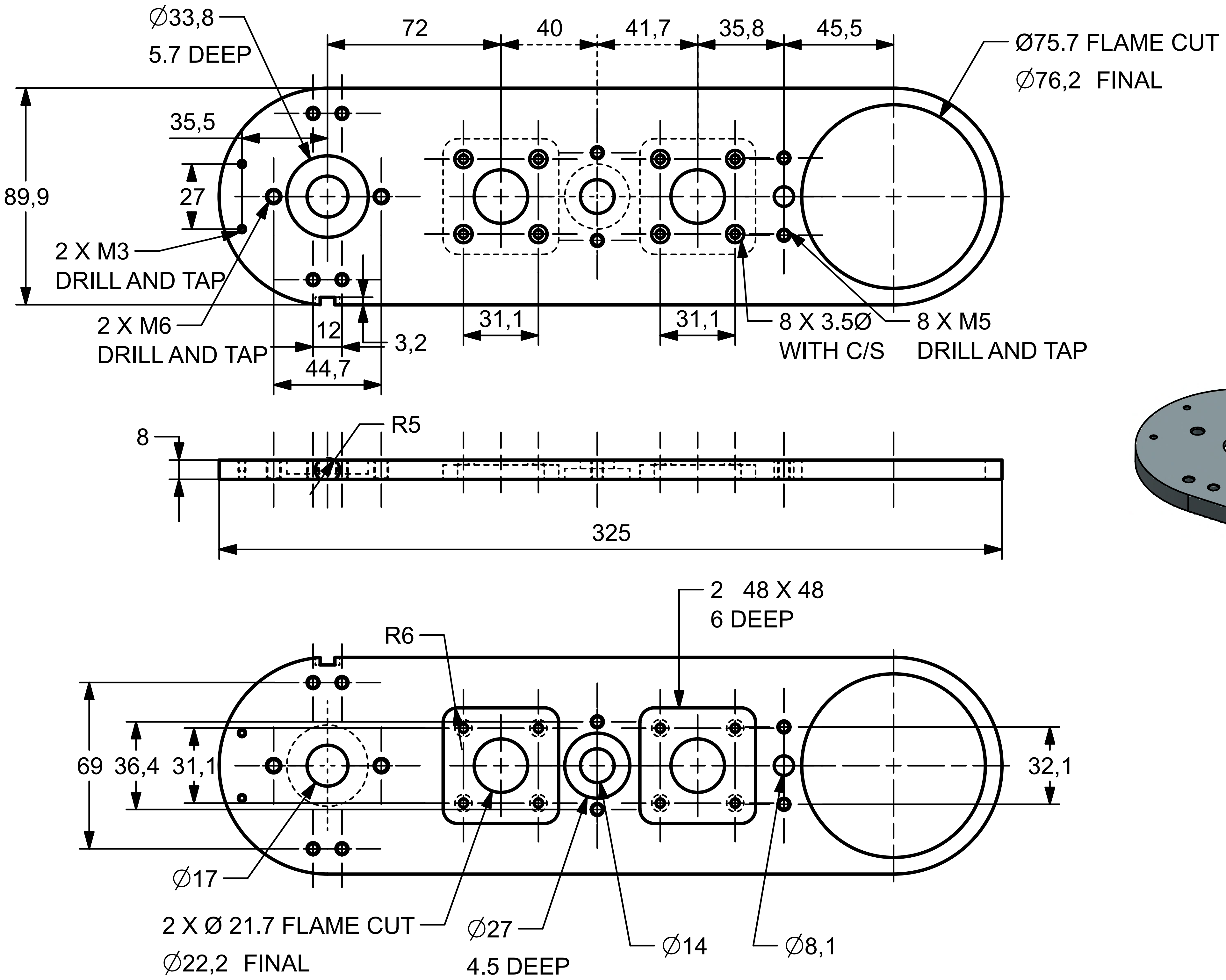


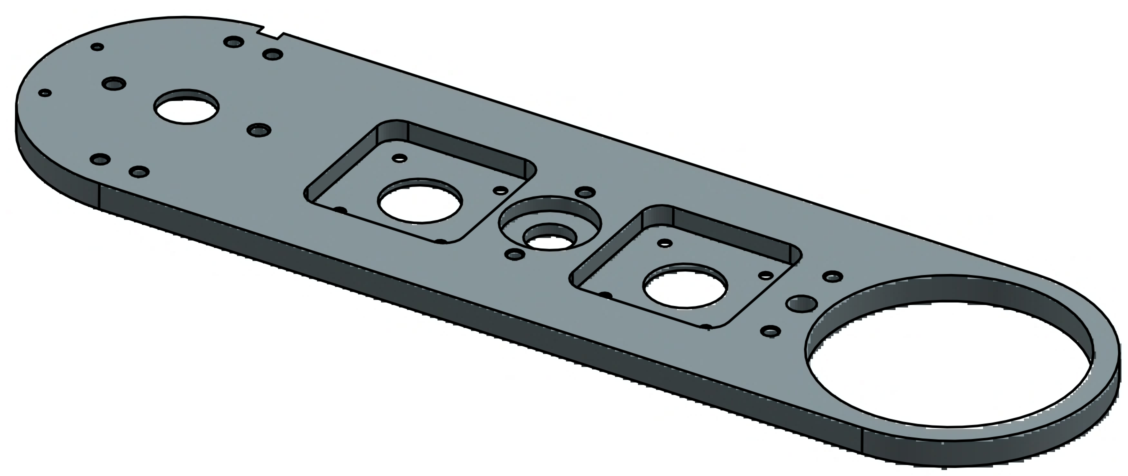


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	3" ALUMINIUM ROUND TUBING	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	024-Spacer_V1	SHEET 24 OF 93

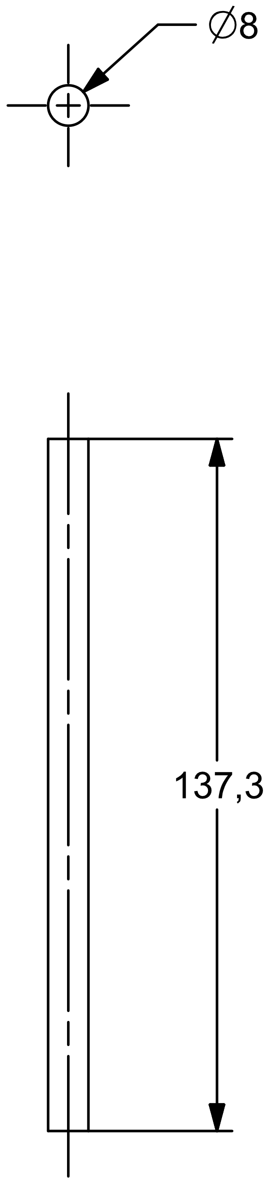
A3

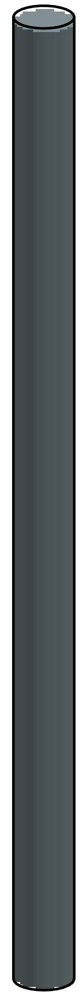




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL 8 MM ALUMINIUM PLATE	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 025-Arm-2_V1	BLADSY/ SHEET SHEET 25 OF 93

A3

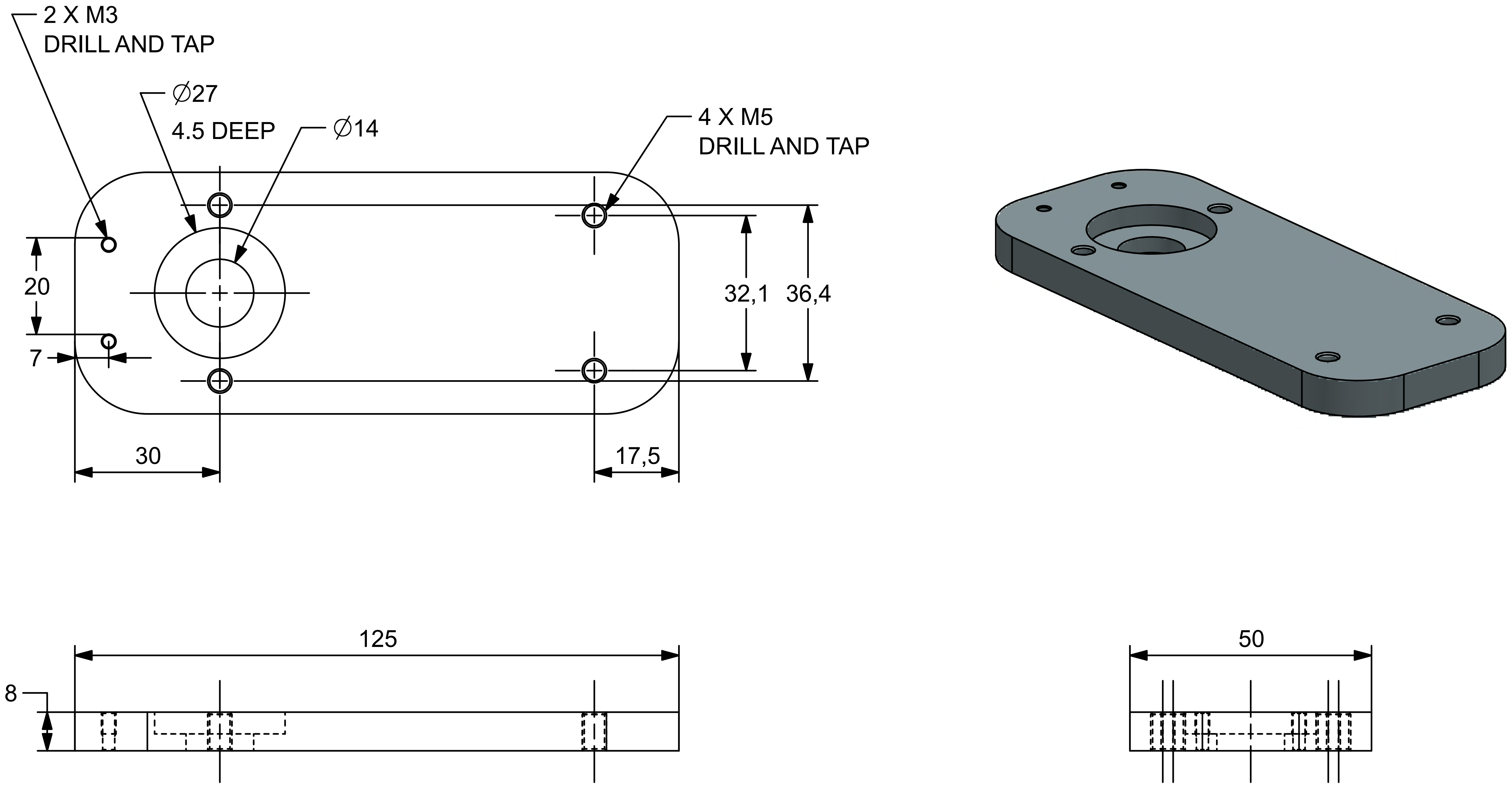




FAKULTEIT INGENIEURSWESE	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	8 MM OD ALUMINIUM ROD	PIETER MARX	29703662	MR

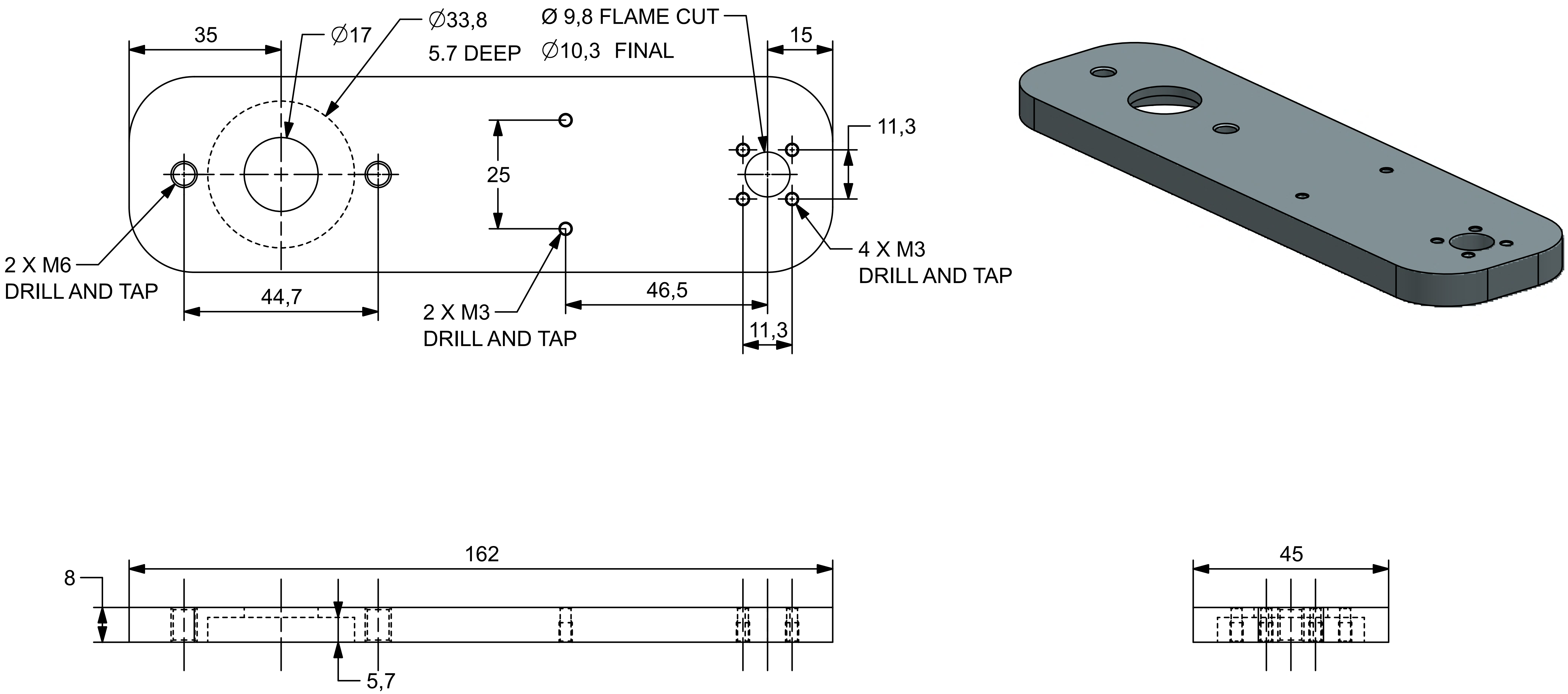
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	026-Pillar_V1	SHEET 26 OF 93

A3



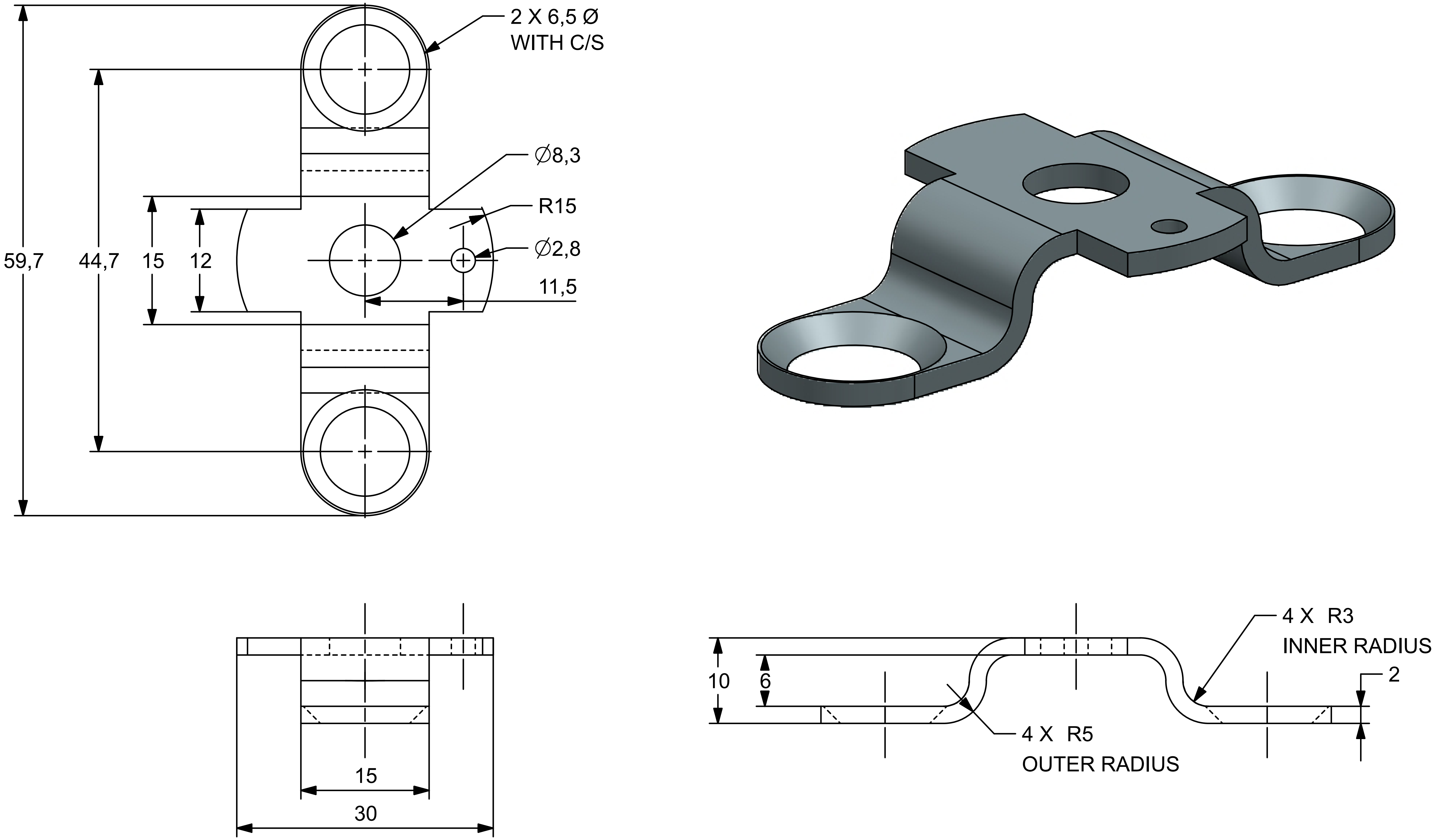
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 8 MM ALUMINIUM PLATE	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR	
	ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL HOLES TO BE MACHINED BY CLIENT	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 027-Lead-Screw-Support_V1	BLADSY/ SHEET SHEET 27 OF 93

A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 8 MM ALUMINIUM PLATE	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR	
	ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL HOLES TO BE MACHINED BY CLIENT	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 028-Drive-Shaft-Support_V1	BLADSY/ SHEET SHEET 28 OF 93

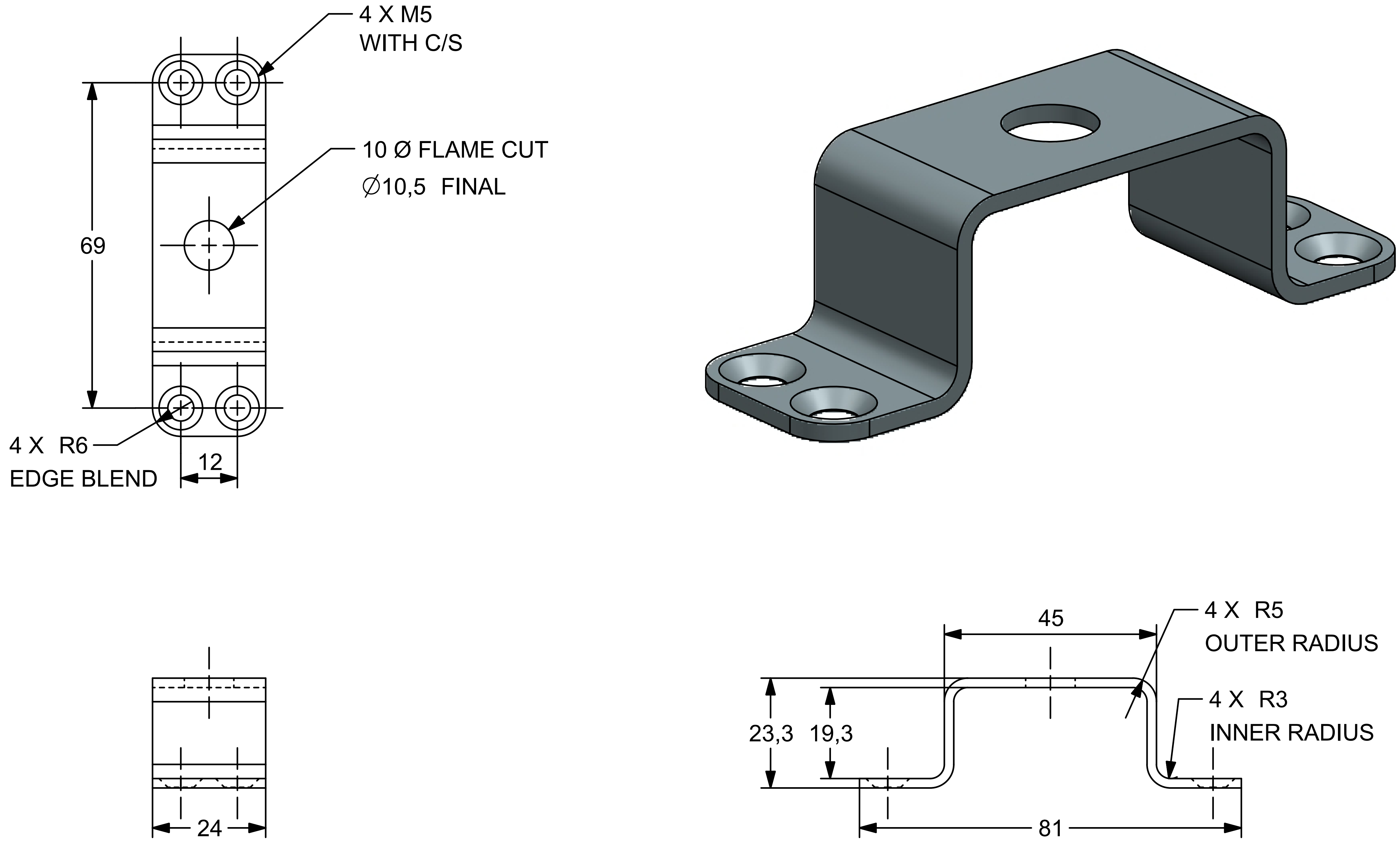
A3



FAKULTEIT INGENIEURSWESE	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	2 MM ALUMINIUM SHEET	PIETER MARX	29703662	MR

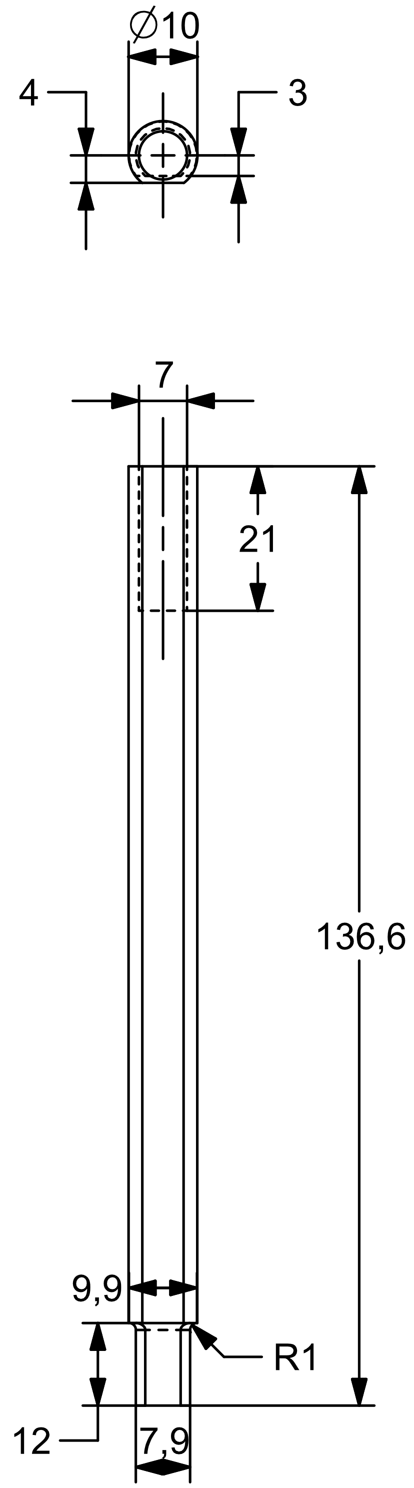
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
LASER MARK CENTER MARKS OF ALL HOLES TO BE MACHINED BY CLIENT	26/08/2020	SCALE 1:1	029-Potensiometer-Bracket-2_V1	SHEET 29 OF 93

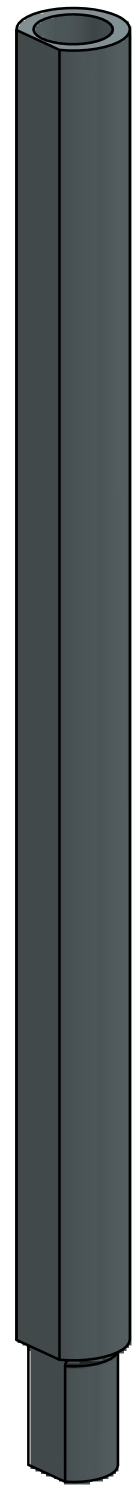
A3



FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 2 MM ALUMINIUM SHEET	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL HOLES TO BE DRILLED AND C/S BY CLIENT	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 030-Rotation-Pulley-Bracket_V1	BLADSY/ SHEET SHEET 30 OF 93

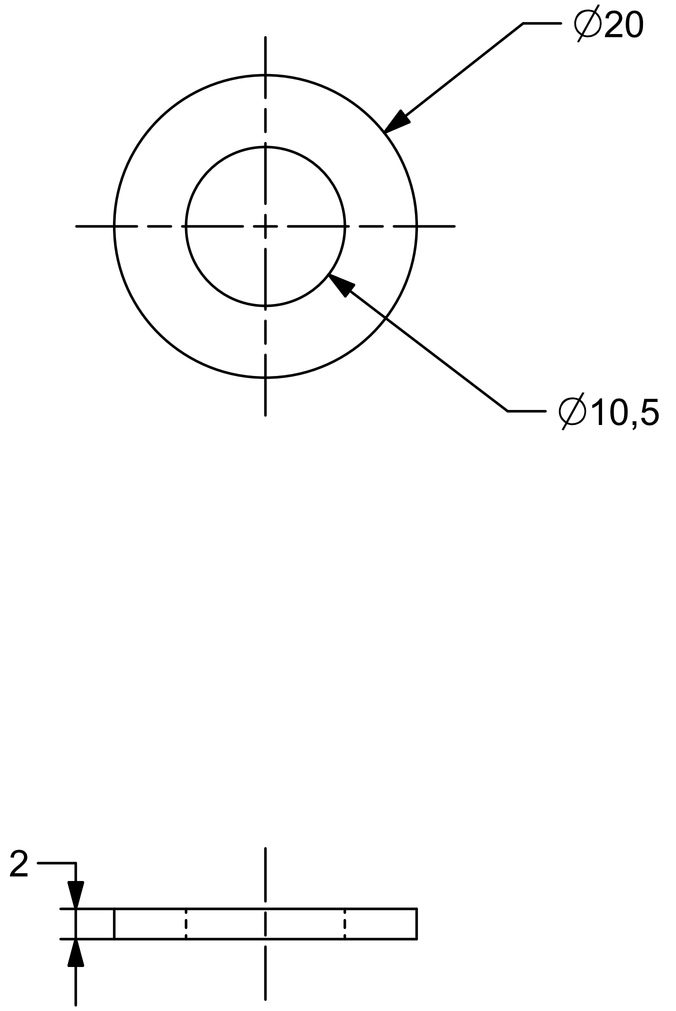
A3

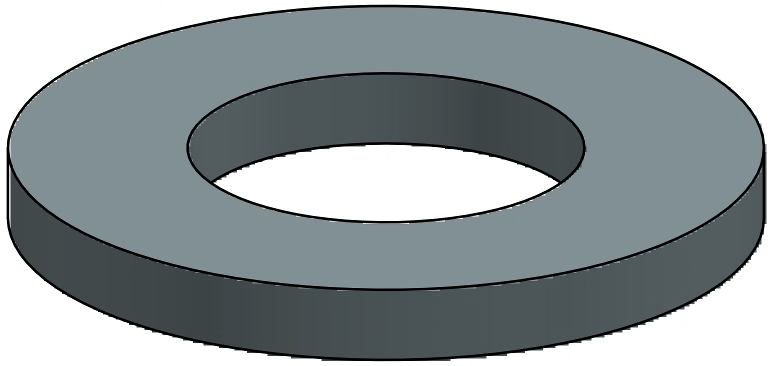




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** 10 MM DIAMETER CHROMED STEEL ROD	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR	
	ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	**DATUM/DATE** 26/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 031-Drive-Shaft_V1	**BLADSY/ SHEET** SHEET 31 OF 93

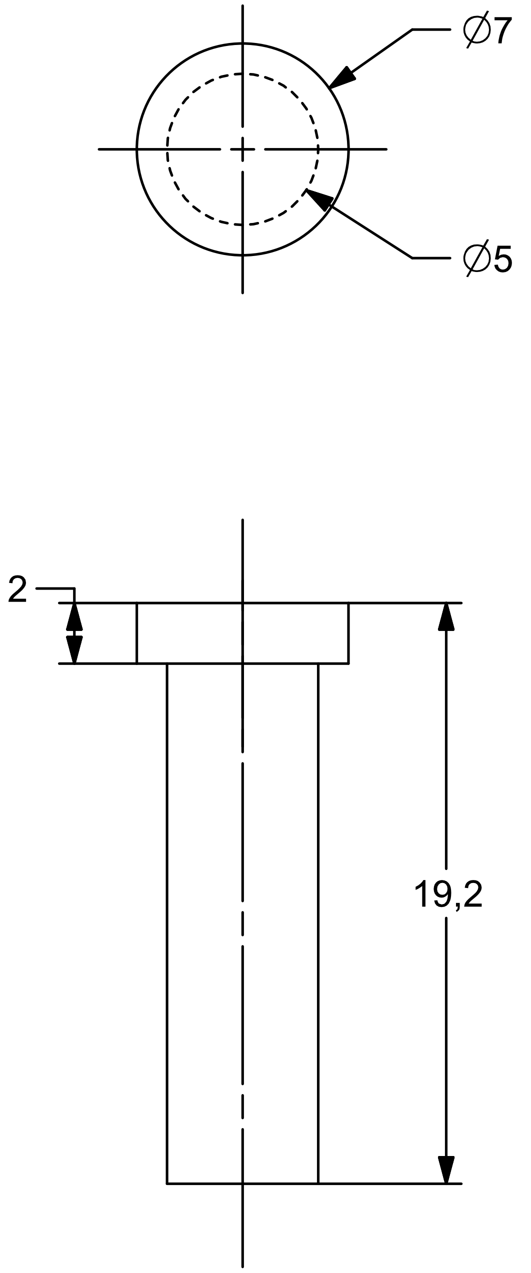
A3

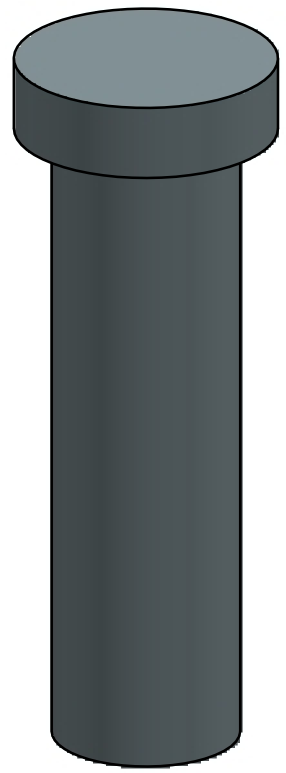




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 2 MM ALUMINIUM SHEET 2 REQD	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES NONE	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 032-Rotation-Pulley-Washer_V1	BLADSY/ SHEET SHEET 32 OF 93

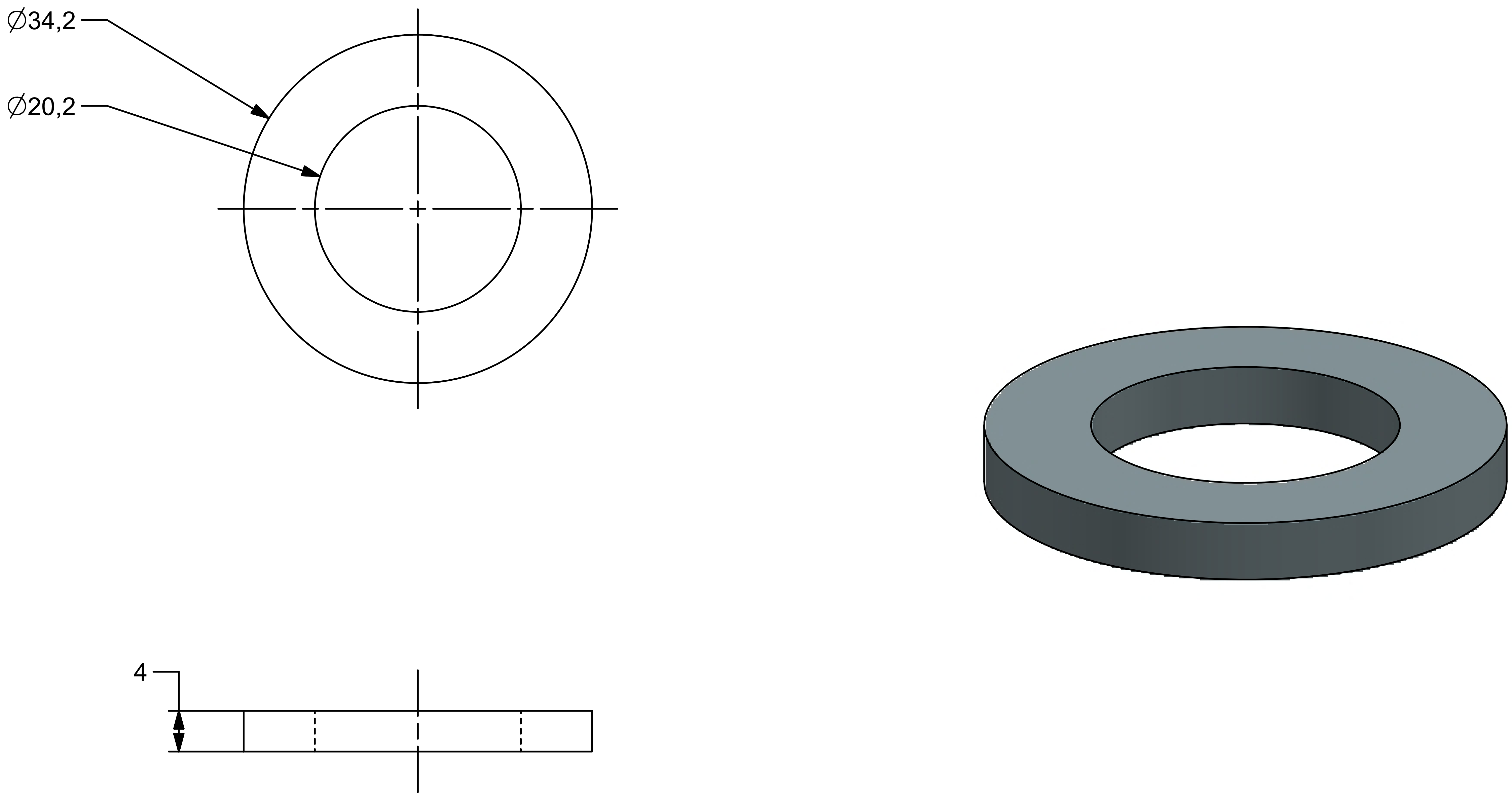
A3





FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL BRASS 4 REQD	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 033-Electric-Contact-Bar_V1	BLADSY/ SHEET SHEET 33 OF 93

A3

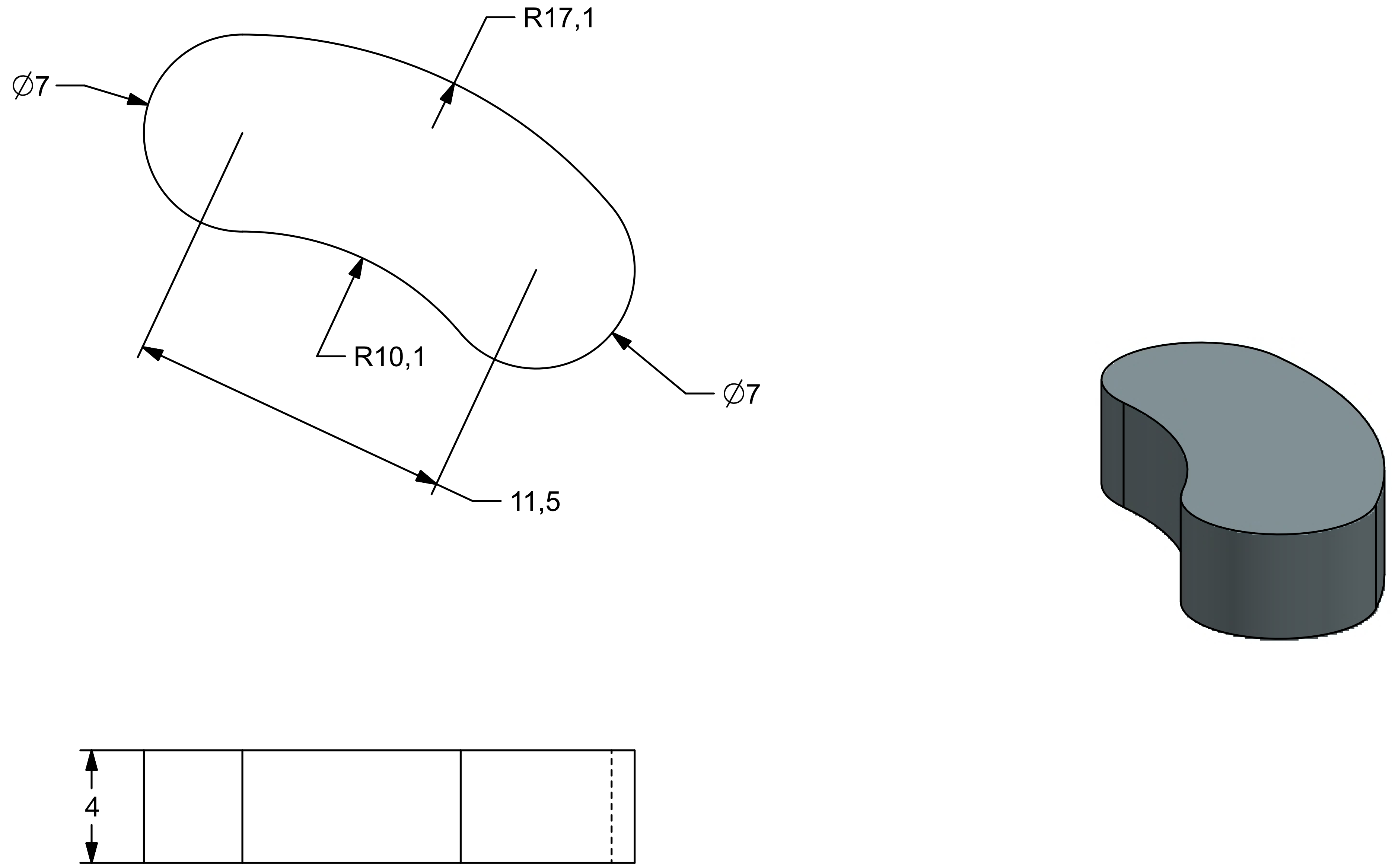


MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
BRASS	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	034-Electric-Contact-Path-Ring_ V1	SHEET 34 OF 93

FAKULTEIT INGENIEURSWESE
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

A3



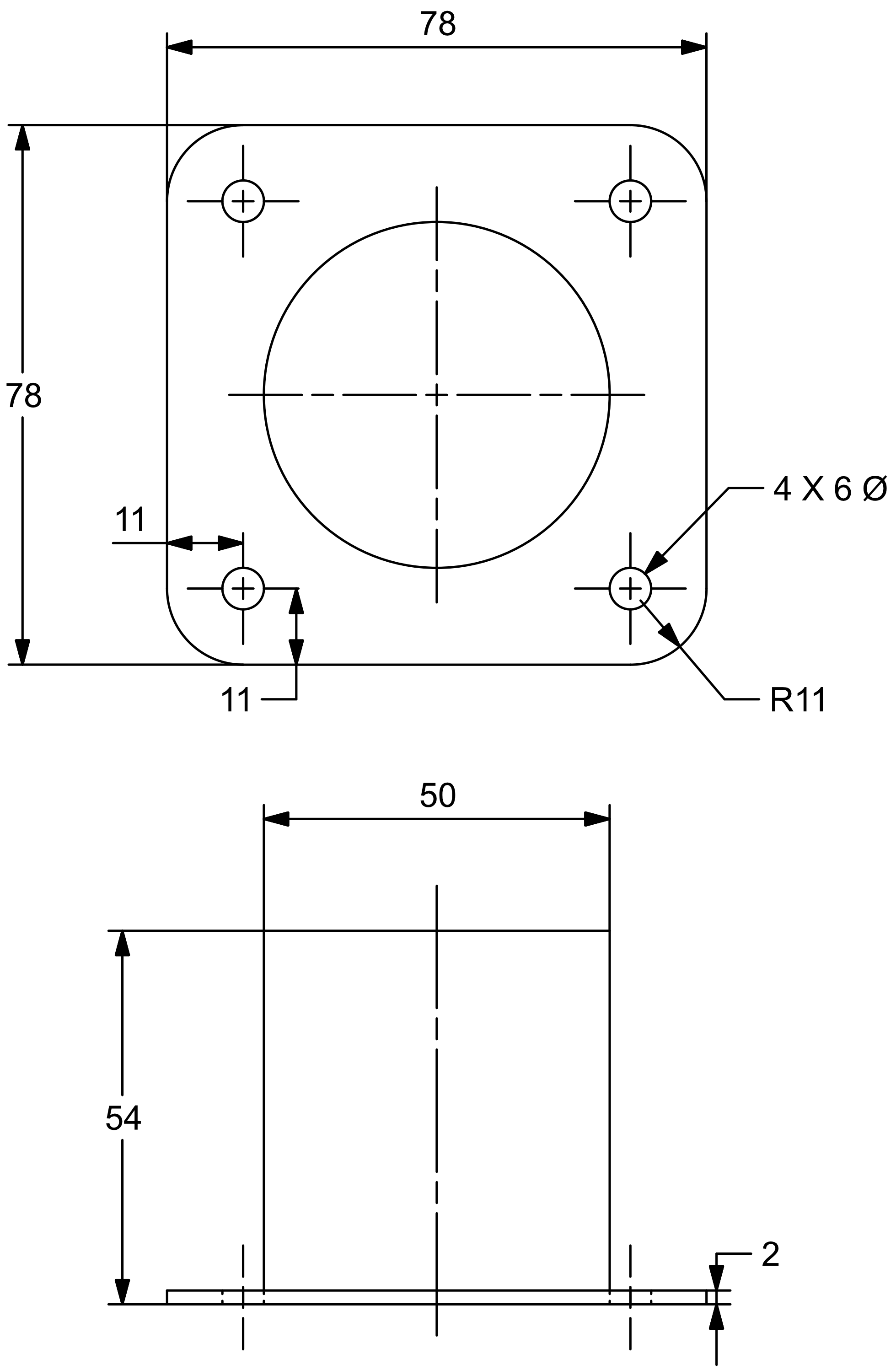
FAKULTEIT INGENIEURSWESE

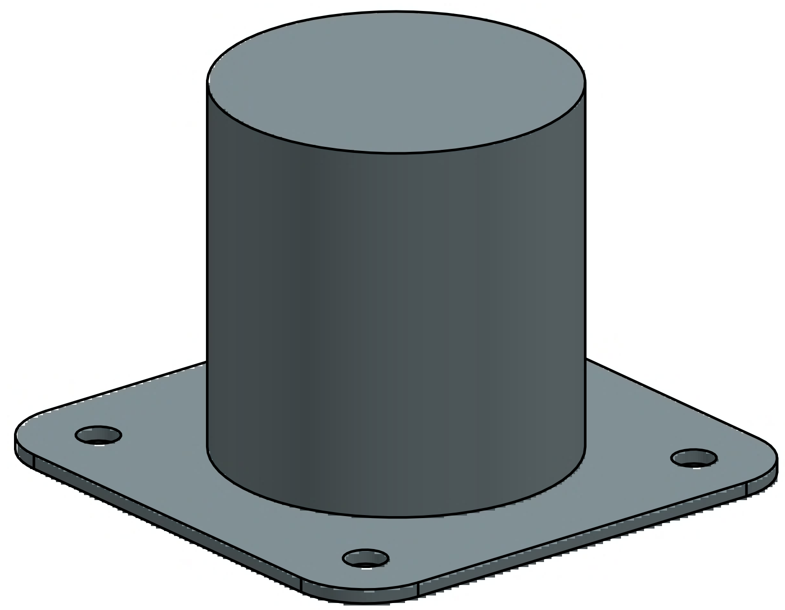
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
034-Electrical-Contact-Path-Ring_V1 4 REQD	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	035-Electric-Contact-Path-Bean_V1	SHEET 35 OF 93

A3

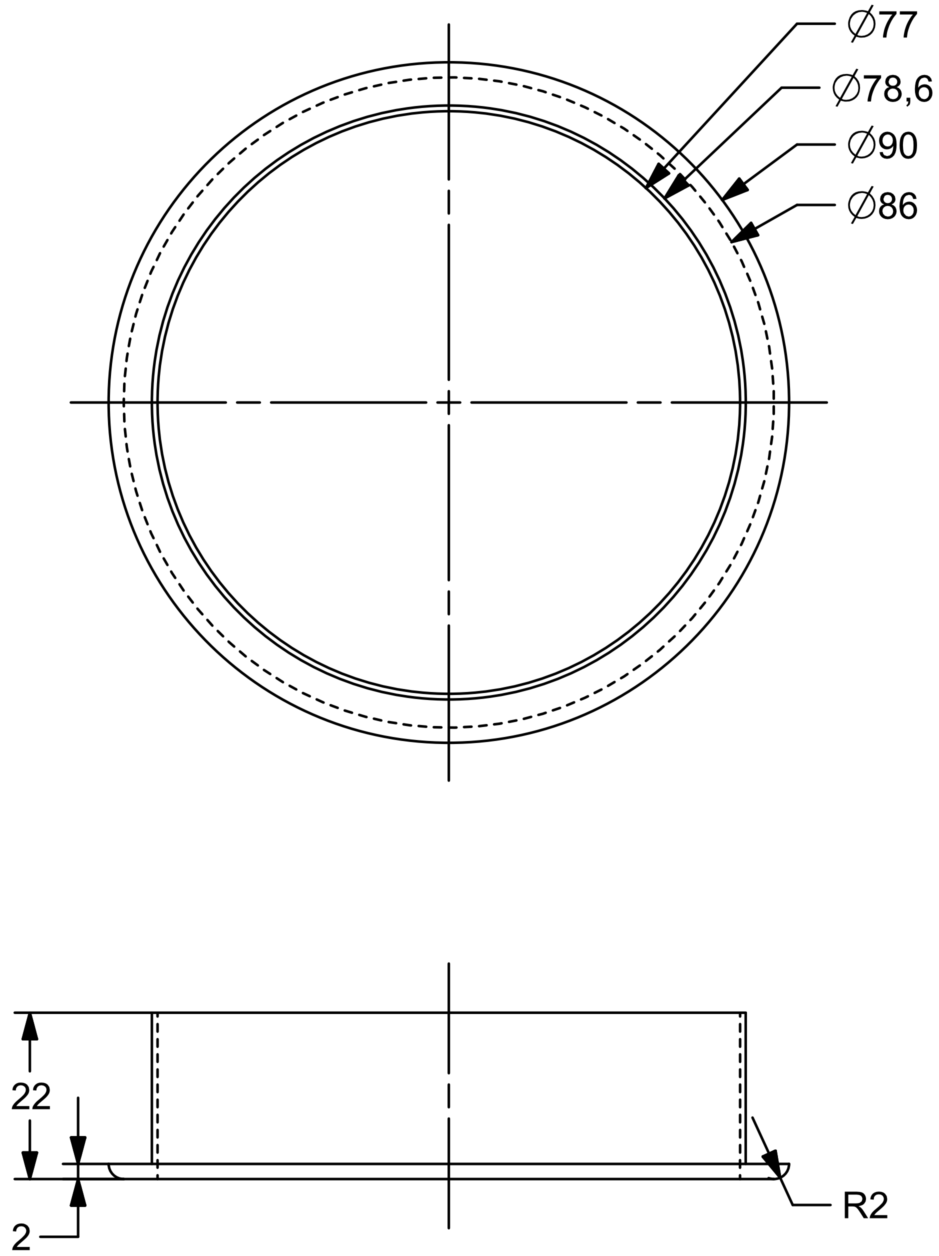


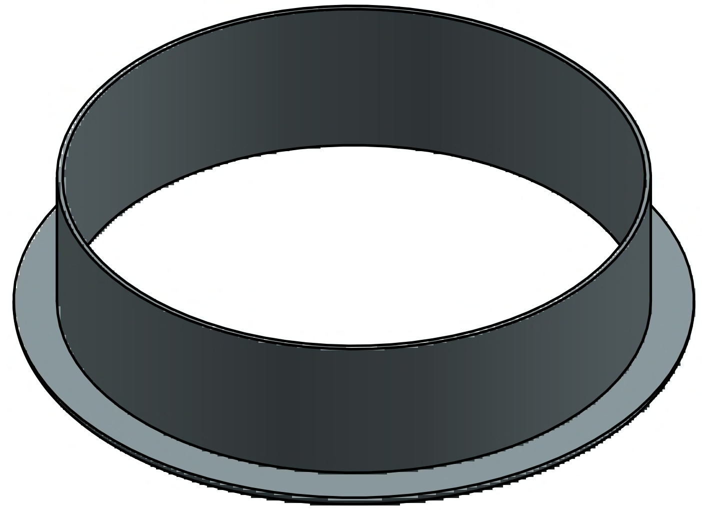


FAKULTEIT INGENIEURSWESE	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	STAINLESS STEEL	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	036-Adjustable-Feet_V1	SHEET 36 OF 93

A3

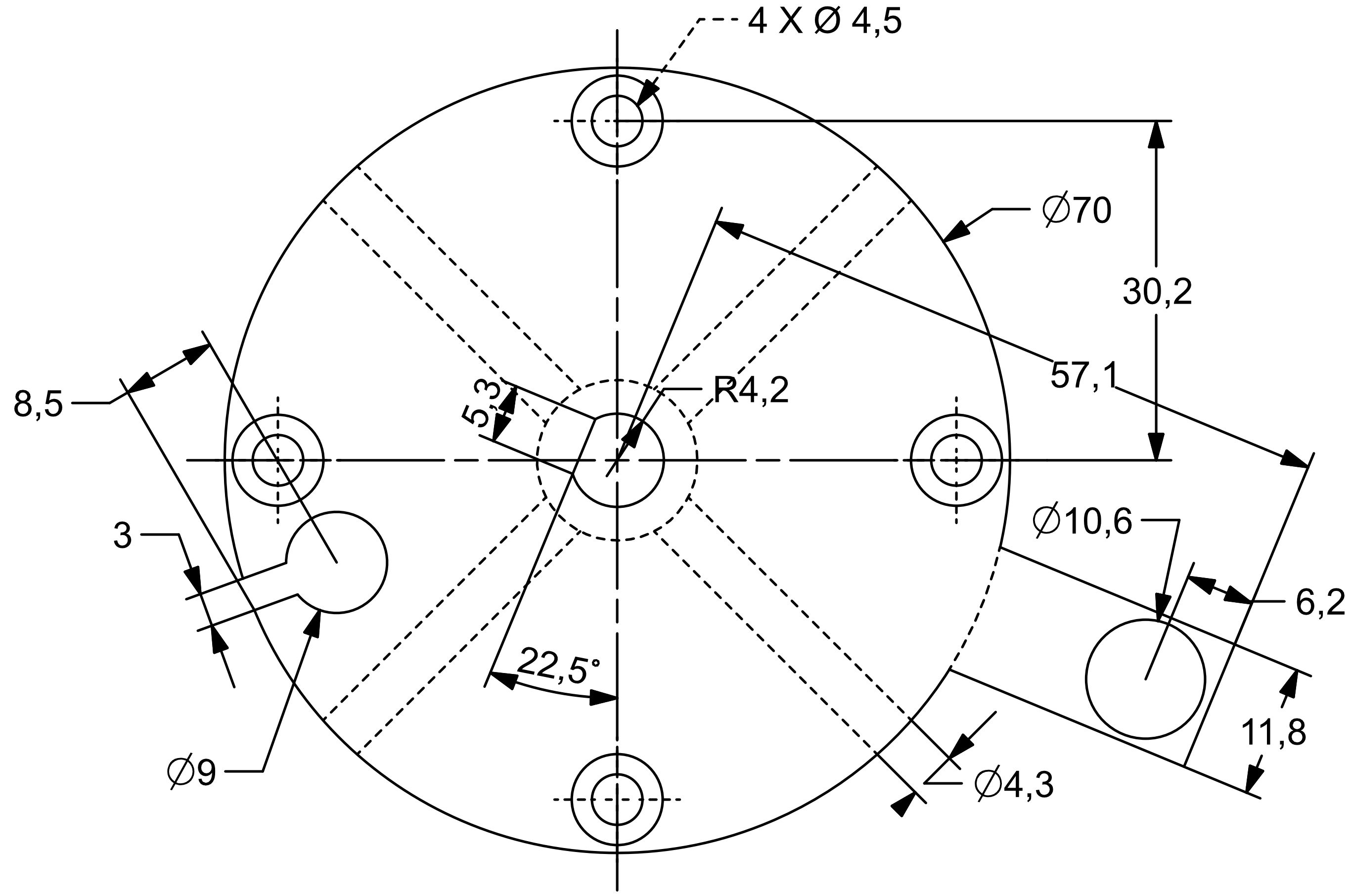


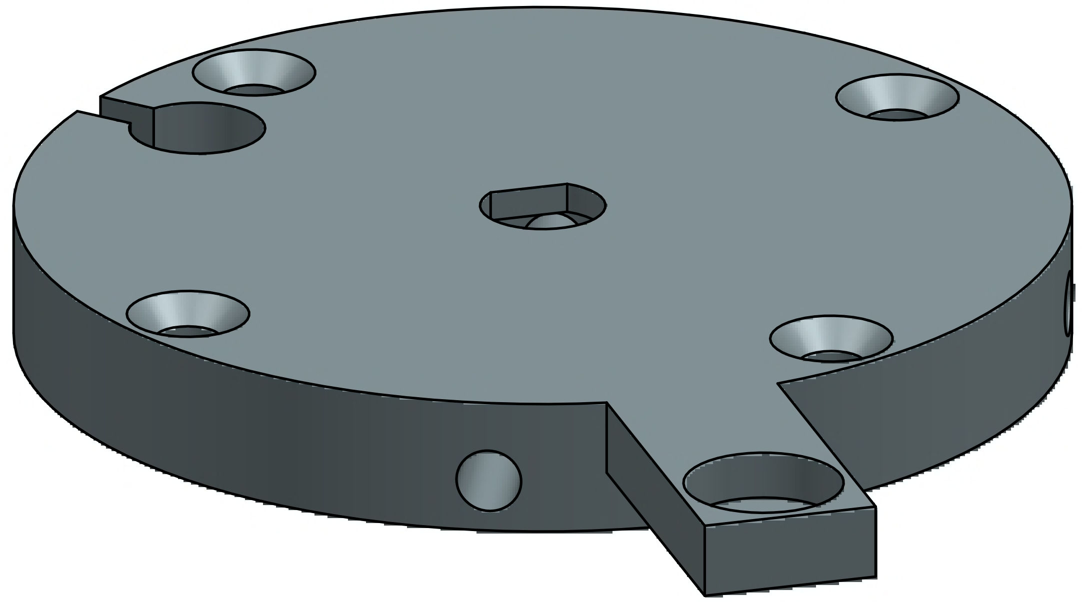


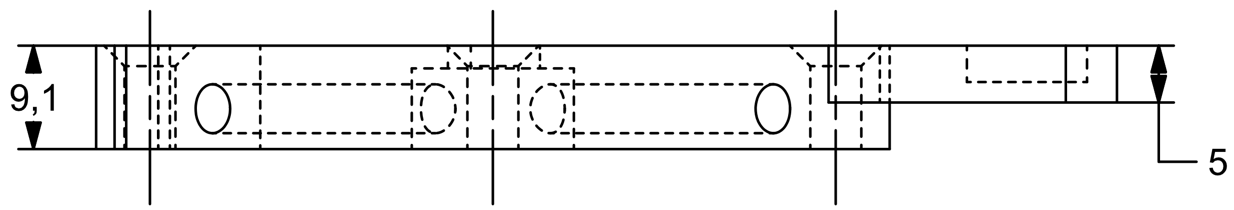
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	ABS PLASTIC	Pieter Marx	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	037-Post-Spigot_V1	SHEET 37 OF 93

A3

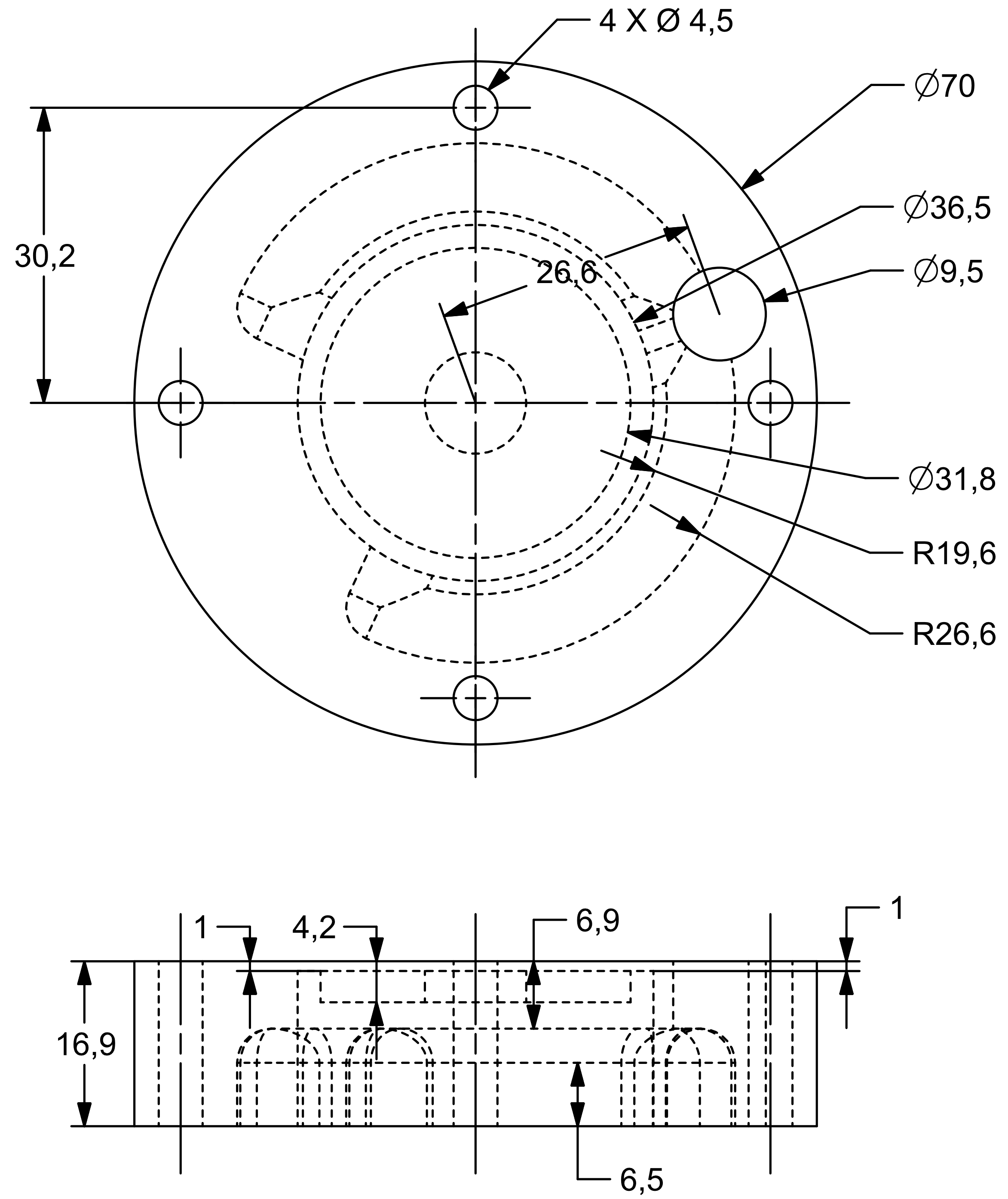


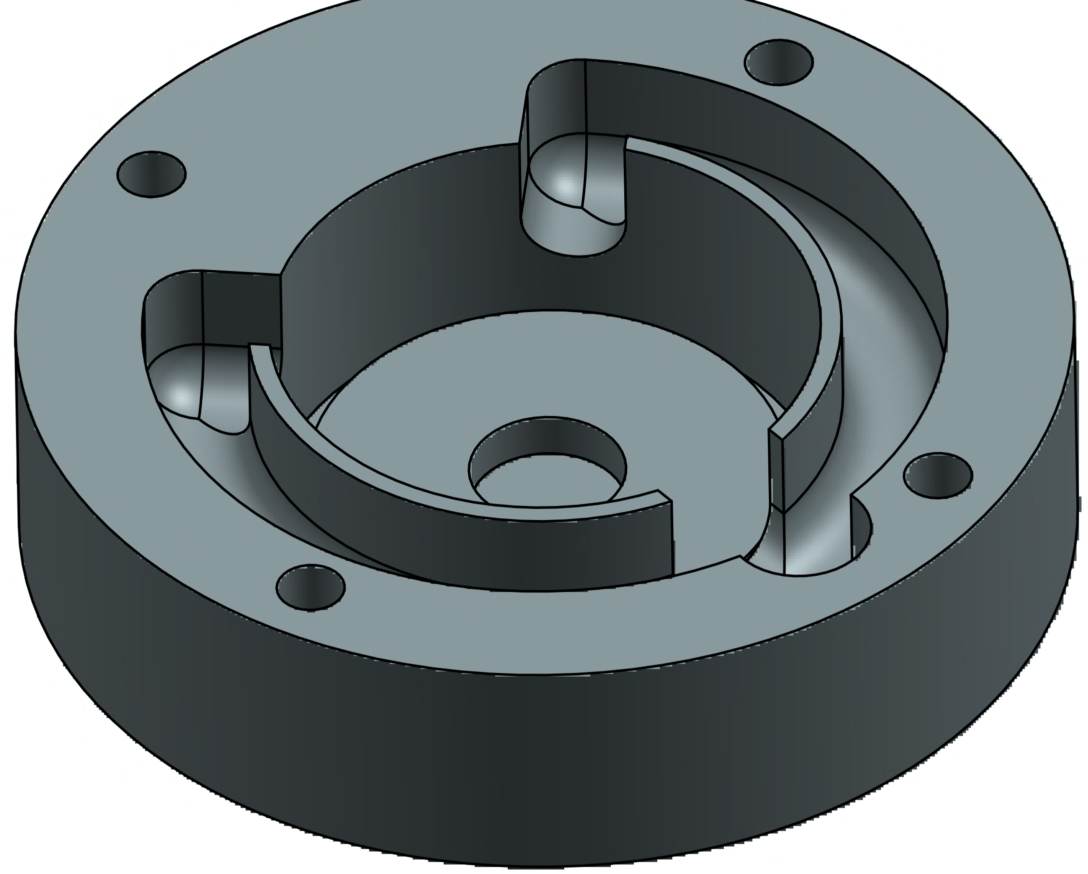




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL	NAAM/ NAME		STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
		ABS PLASTIC	PIETER MARX		29703662	MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
		CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	038-Tool-Changer-Coupling_V1	SHEET 38 OF 93

A3





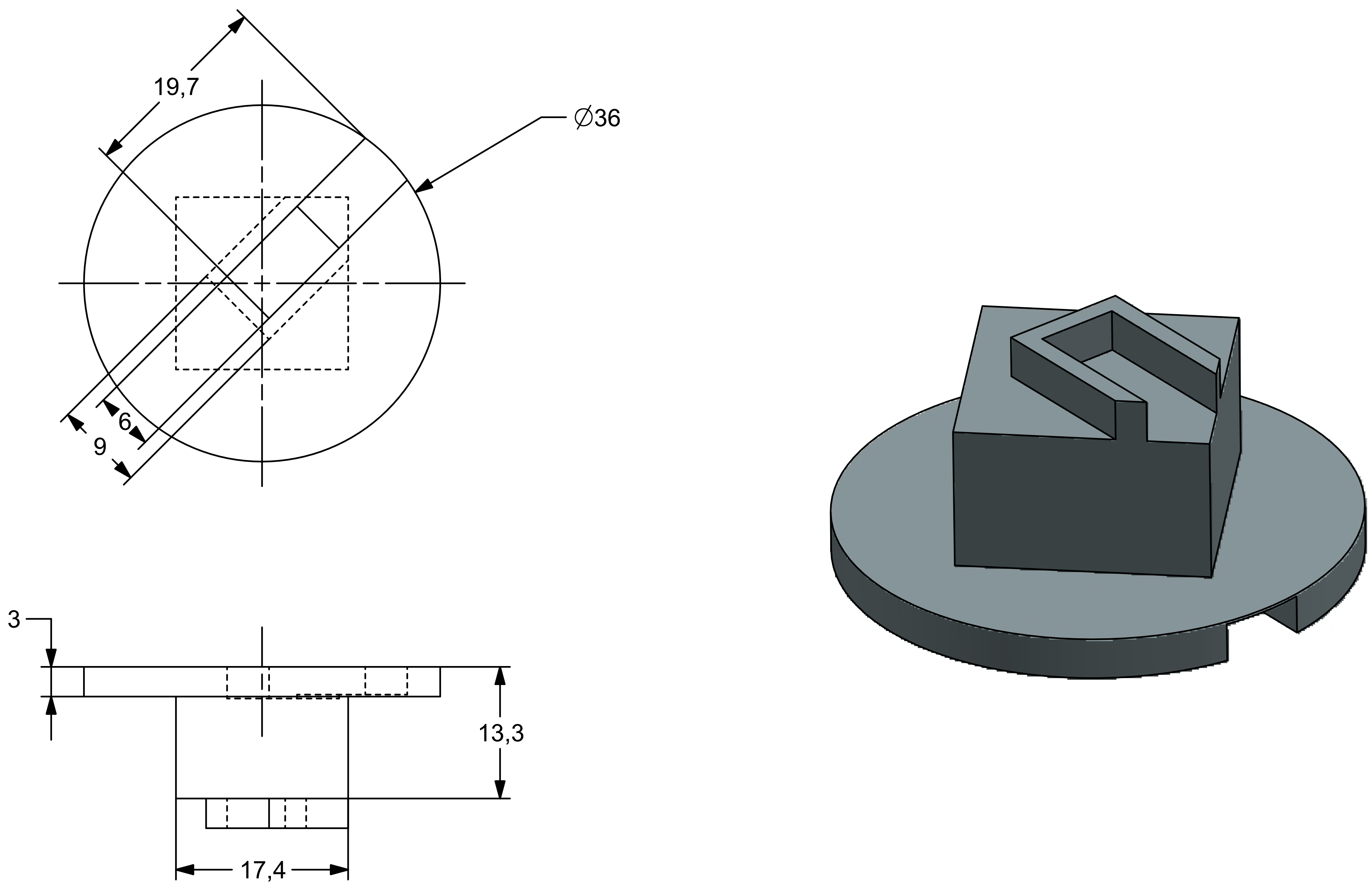
FAKULTEIT INGENIEURSWESE

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	039-Tool-Changer-Chamber_V1	SHEET 39 OF 93

A3



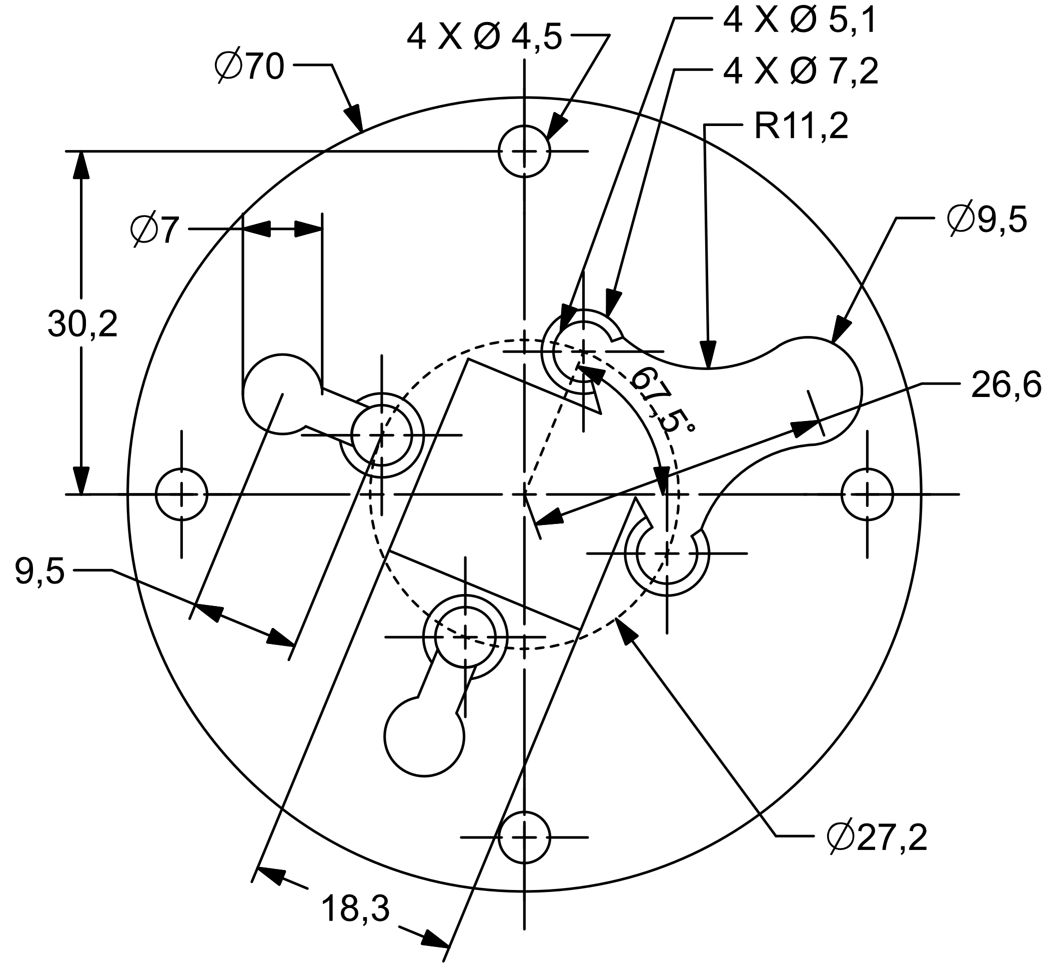
FAKULTEIT INGENIEURSWESE

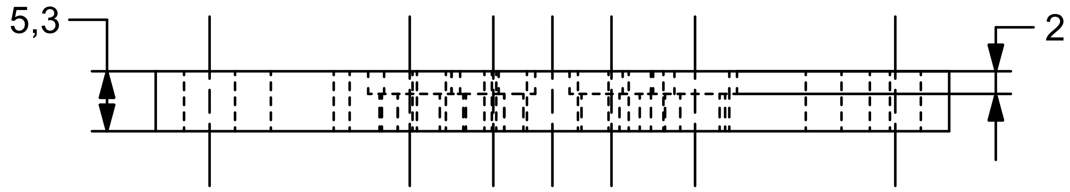
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

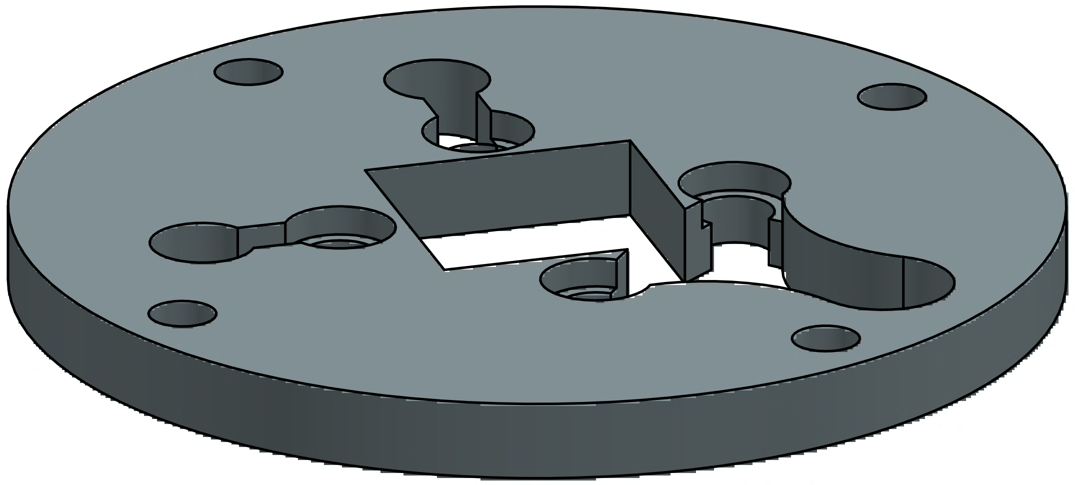
MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	040-Tool-Changer-Disk_V1	SHEET 40 OF 93

A3







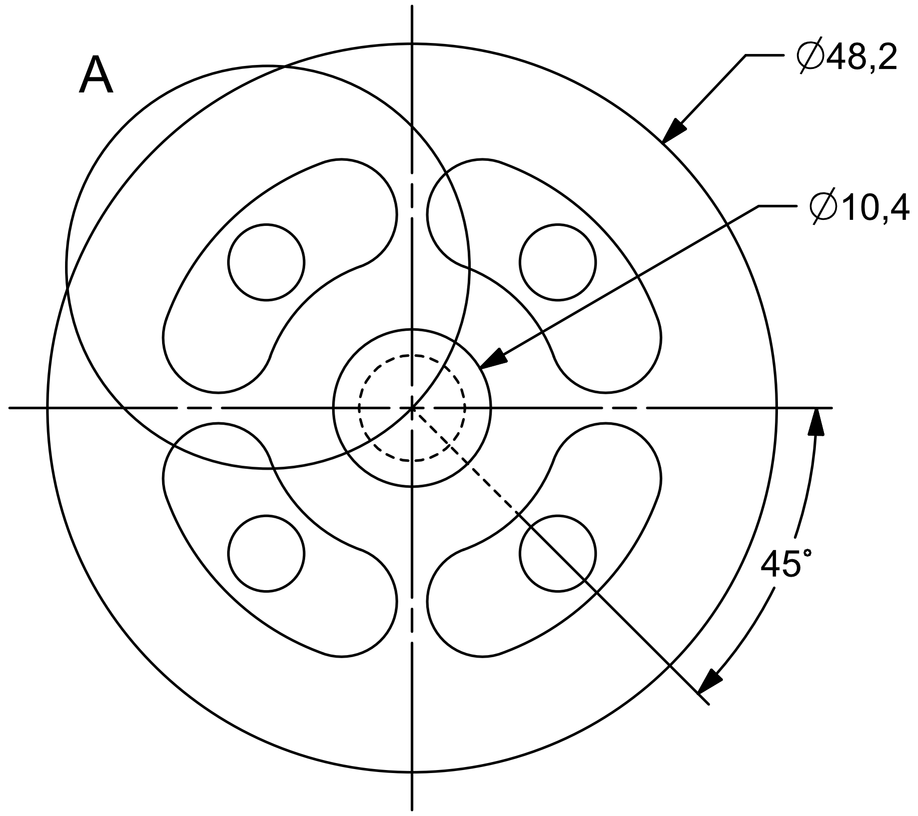
FAKULTEIT INGENIEURSWESE

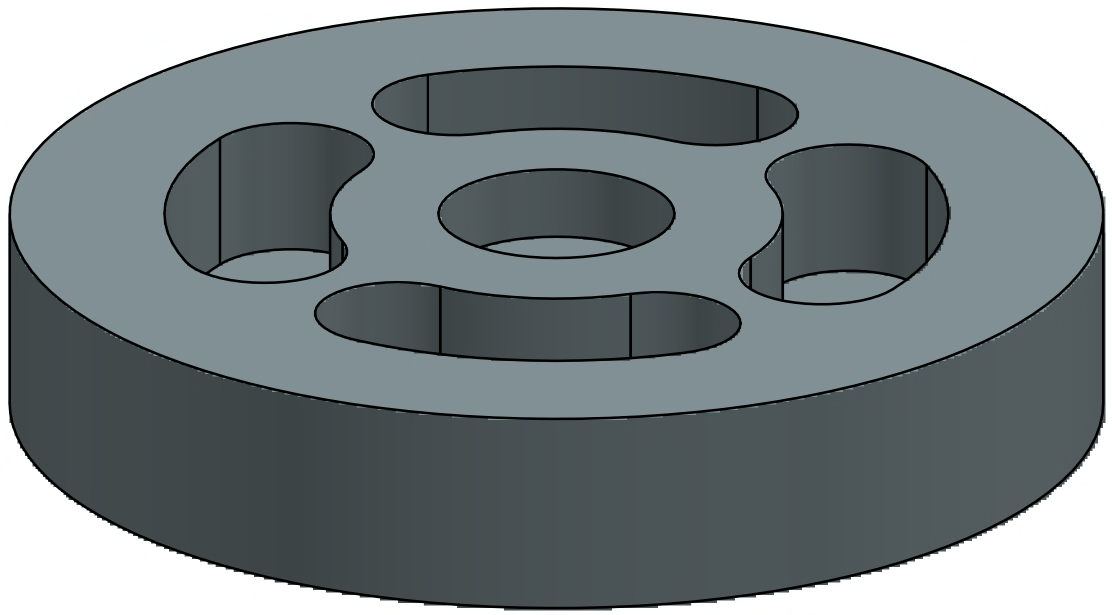
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

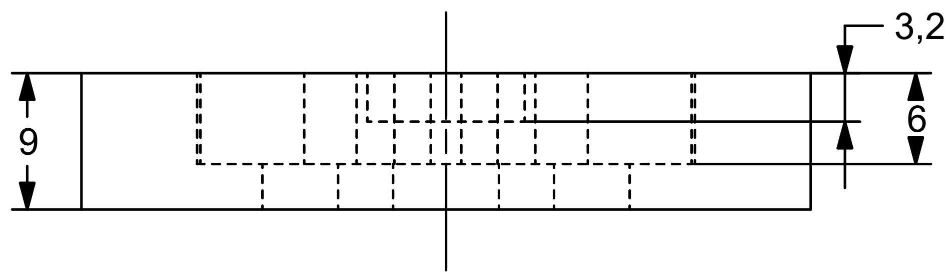
MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
ABS PLASTIC	PIETER MARX	29703662	MR

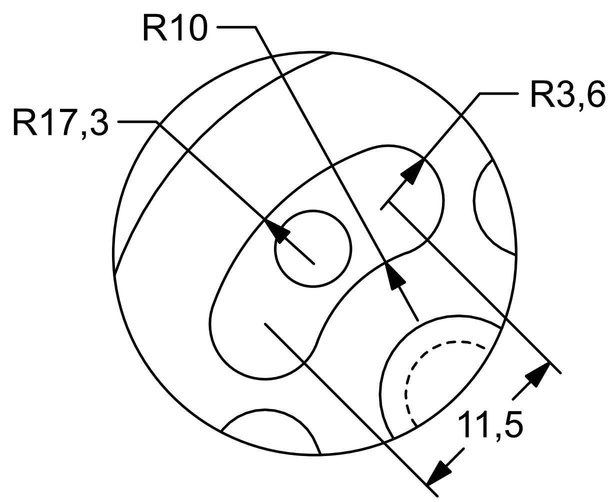
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	041-Tool-Changer-Disk-Stopper_ V1	SHEET 41 OF 93

A3





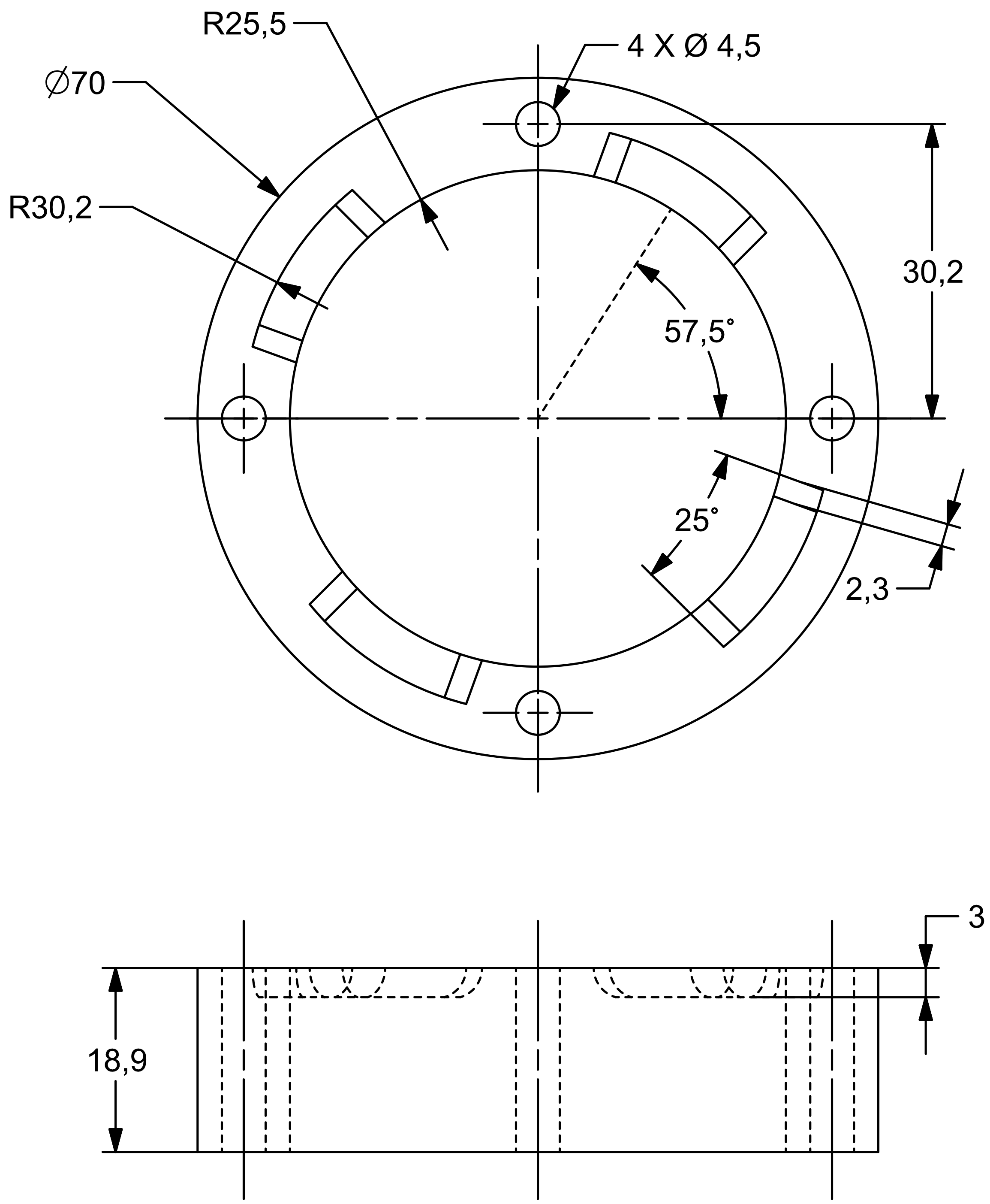


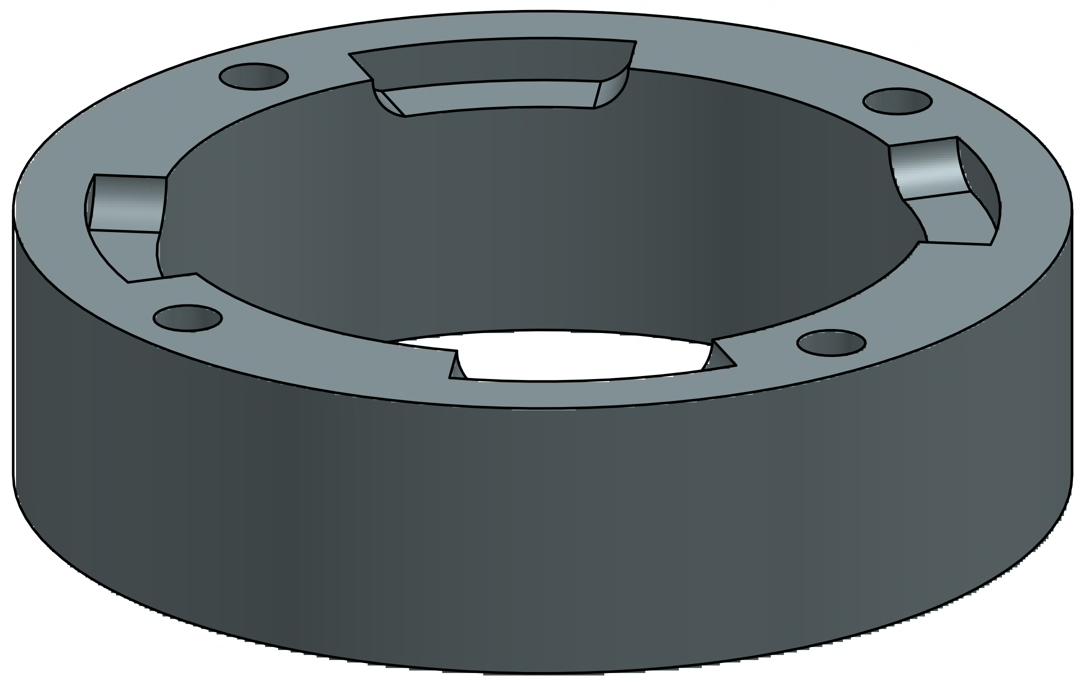


DETAIL A
SCALE 2:1

FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL ABS PLASTIC	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR	
	ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 042-Tool-Electrical-Contacts-Guide_V1	BLADSY/ SHEET SHEET 42 OF 93

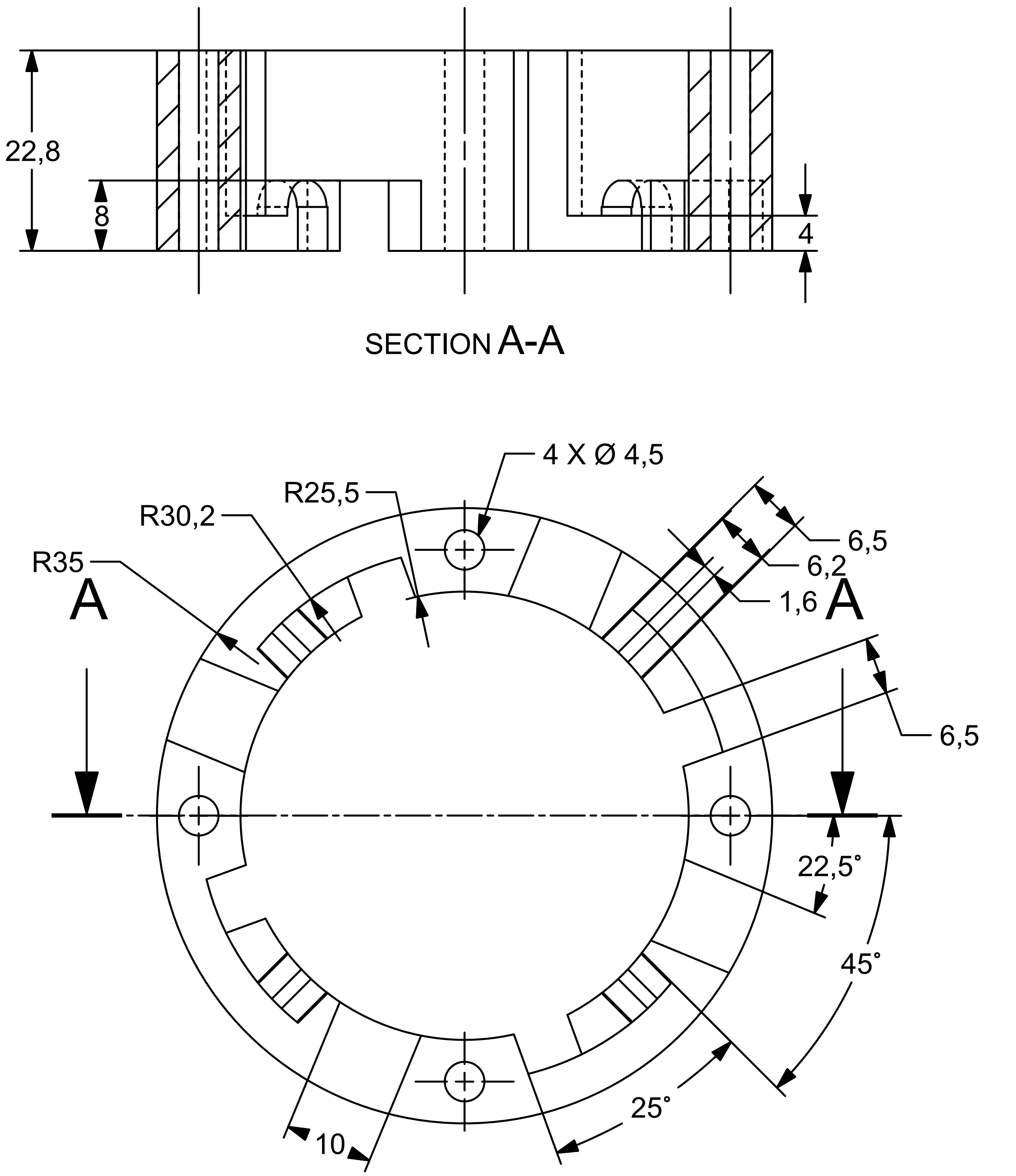
A3

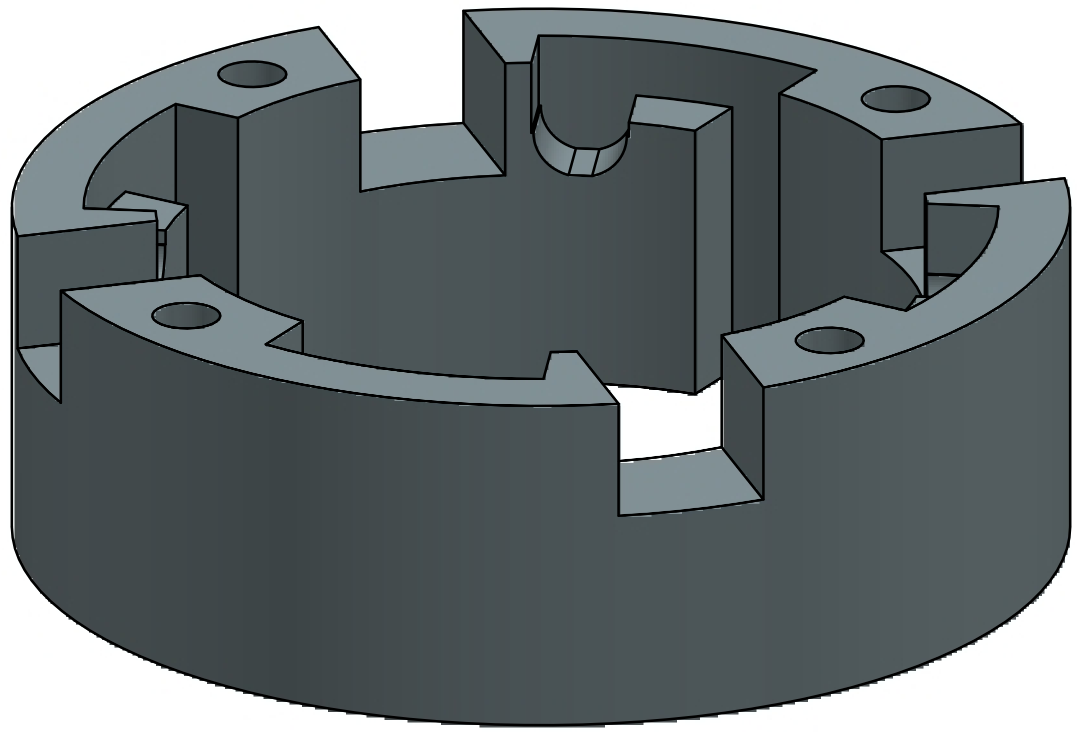




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL ABS PLASTIC	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 043-Tool-Changer-Fastener-Link_V1	BLADSY/ SHEET SHEET 43 OF 93

A3

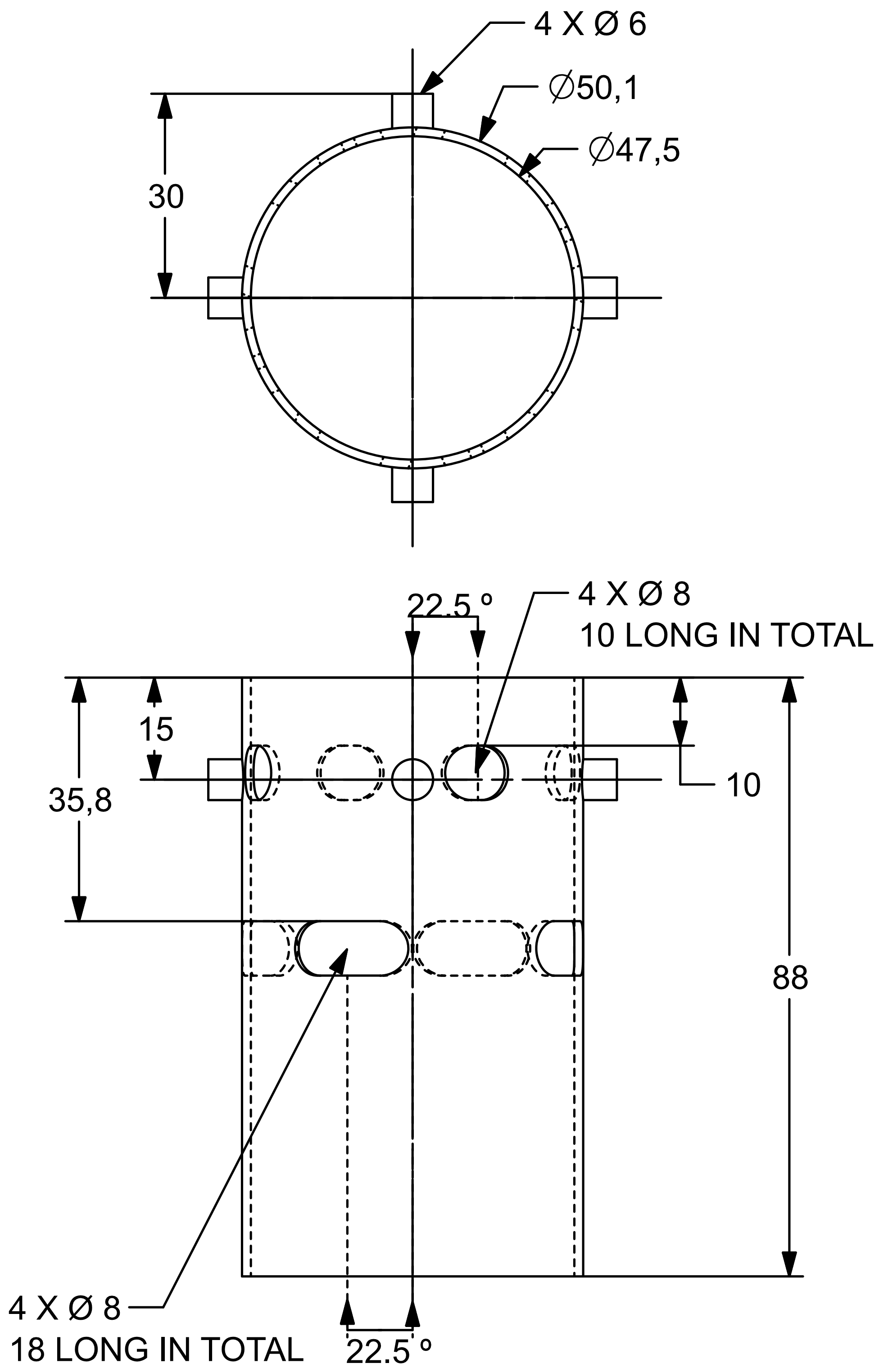


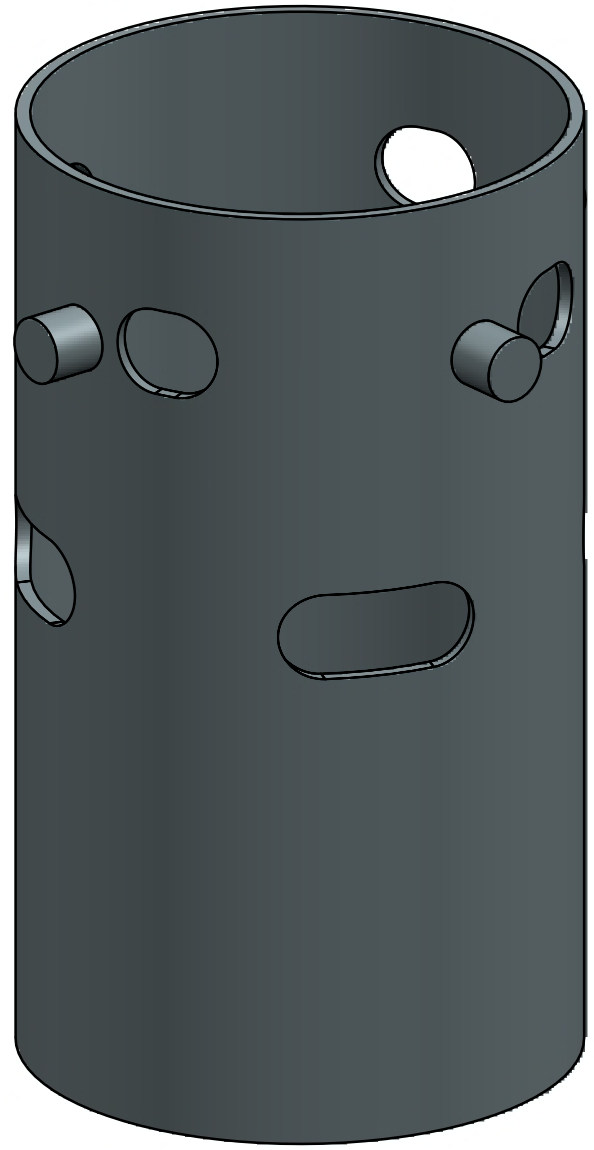


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
		ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	044-Tool-Changer-Fastener_V1	SHEET 44 OF 93

A3

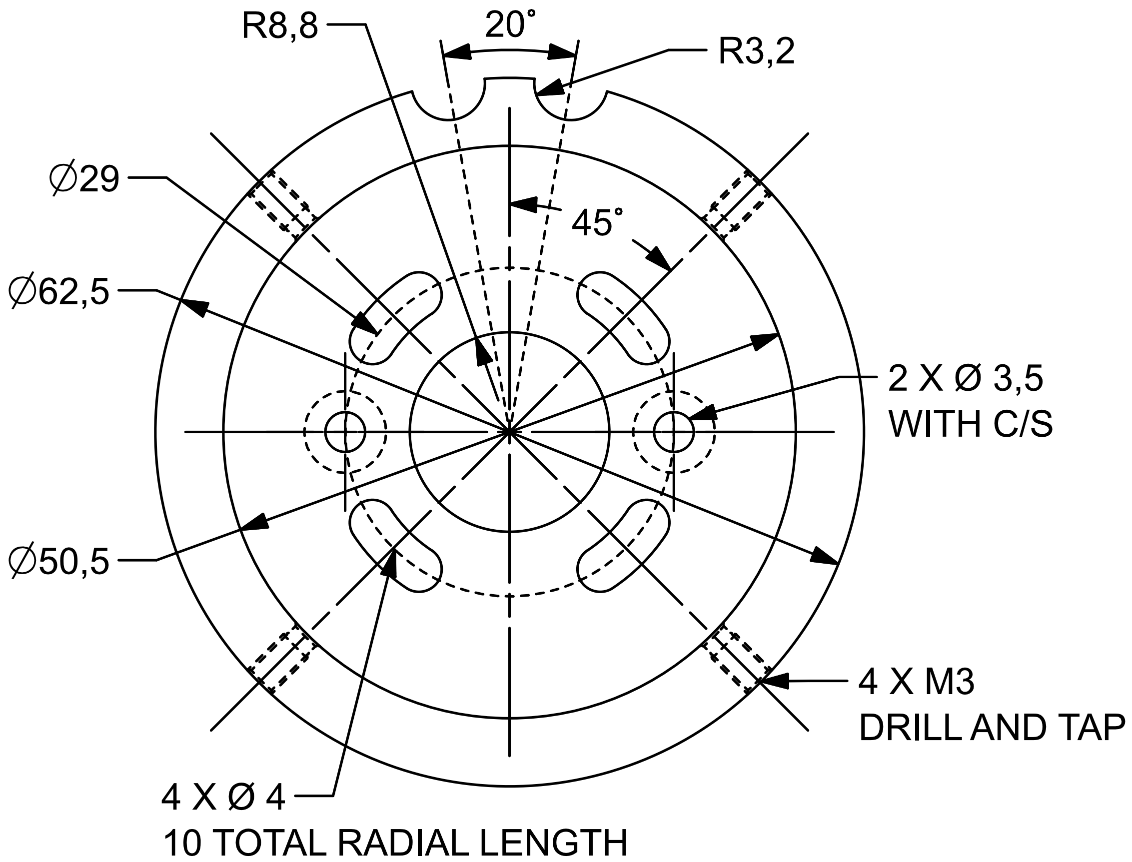


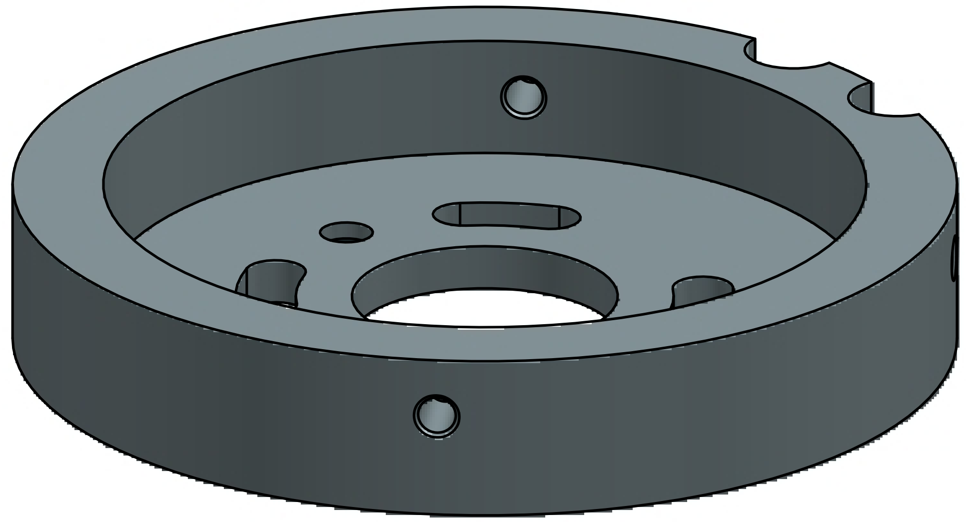


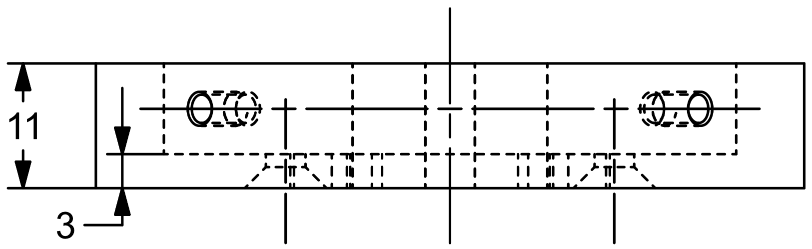
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	STAINLESS STEEL	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	045-Tool-Housing_V1	SHEET 45 OF 93

A3

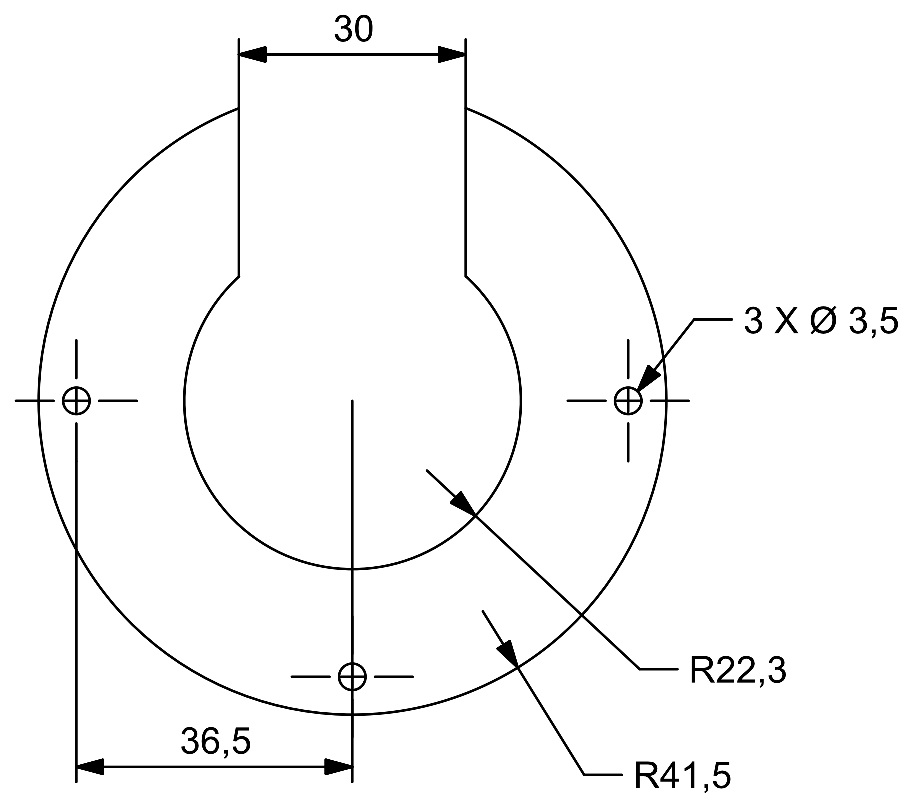


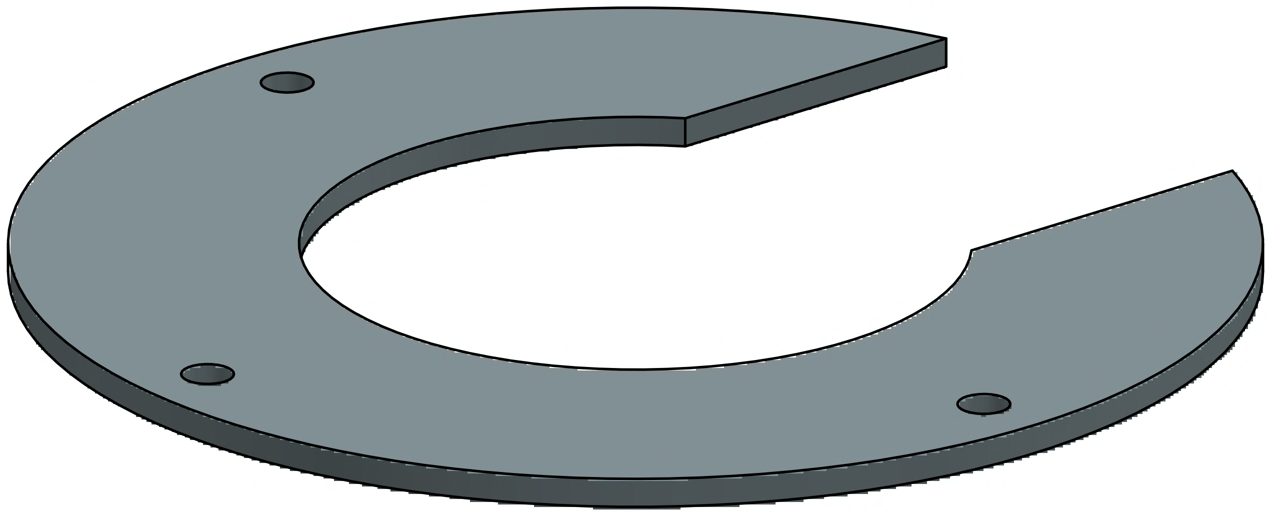


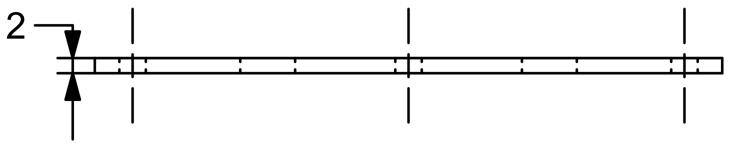


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL ALUMINIUM	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 046-Motor-Mount_V1	BLADSY/ SHEET SHEET 46 OF 93

A3



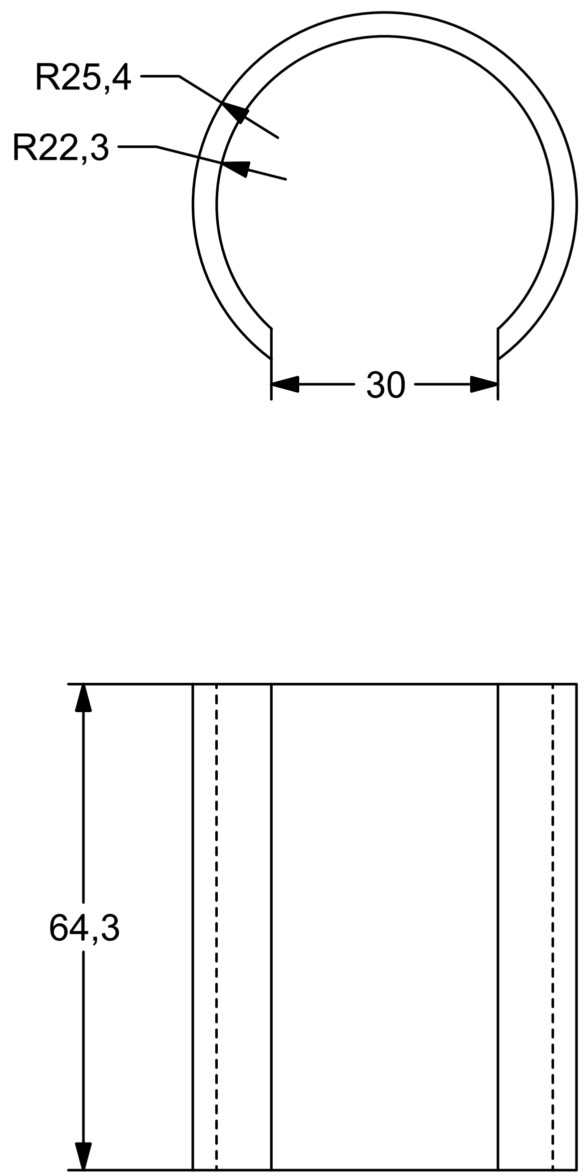


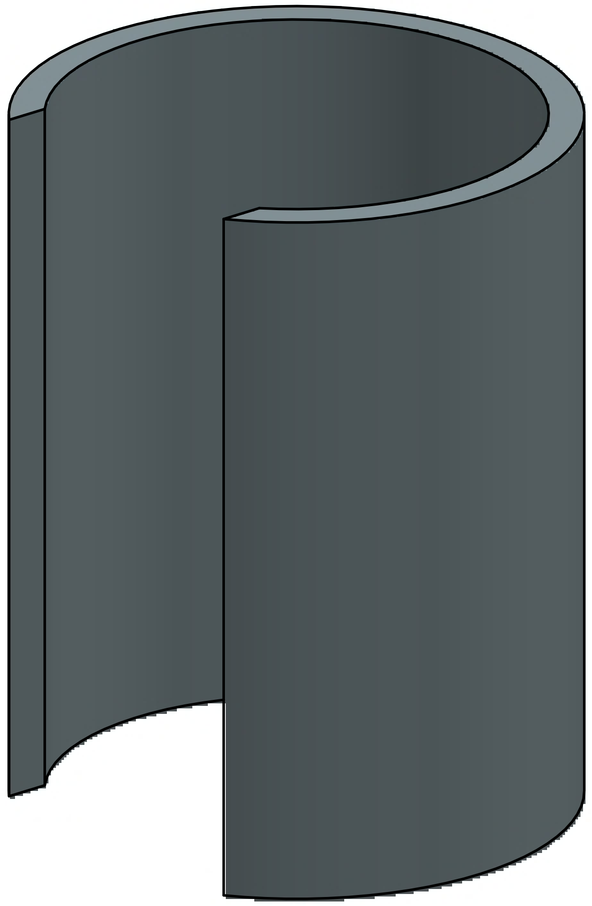


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	2 MM ALUMINIUM SHEET 4 REQD	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	26/08/2020	SCALE 1:1	047-Tool-Holder-Coupling-Plate_V1	SHEET 47 OF 93

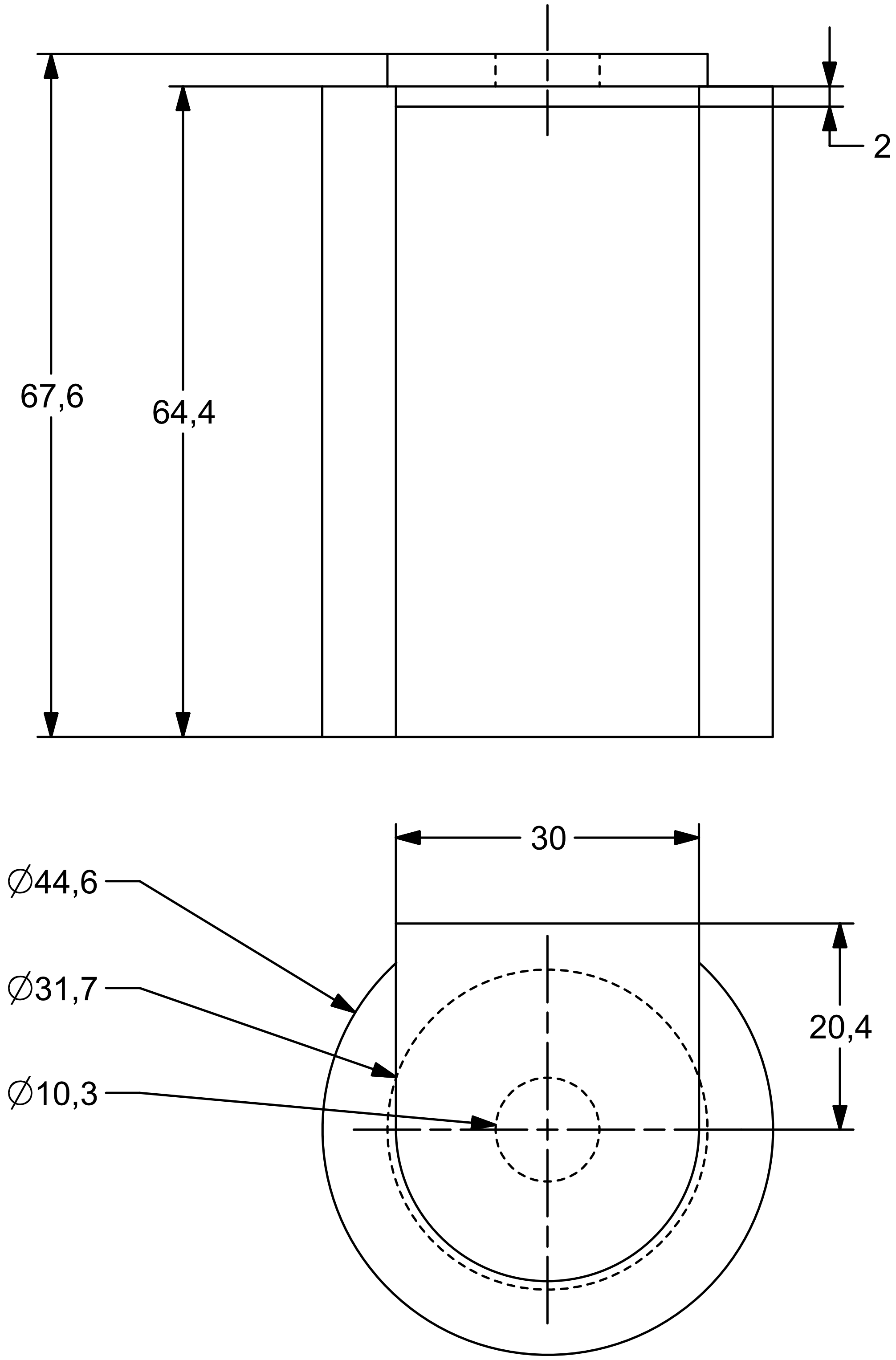
A3

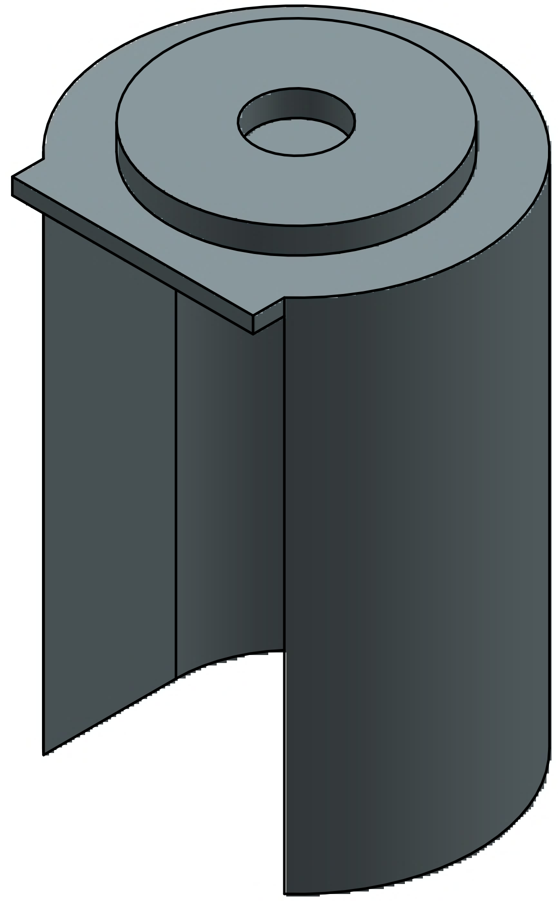




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 2" ALUMINIUM ROUND TUBE 2 REQD	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 048-Tool-Holder-Post_V1	BLADSY/ SHEET SHEET 48 OF 93

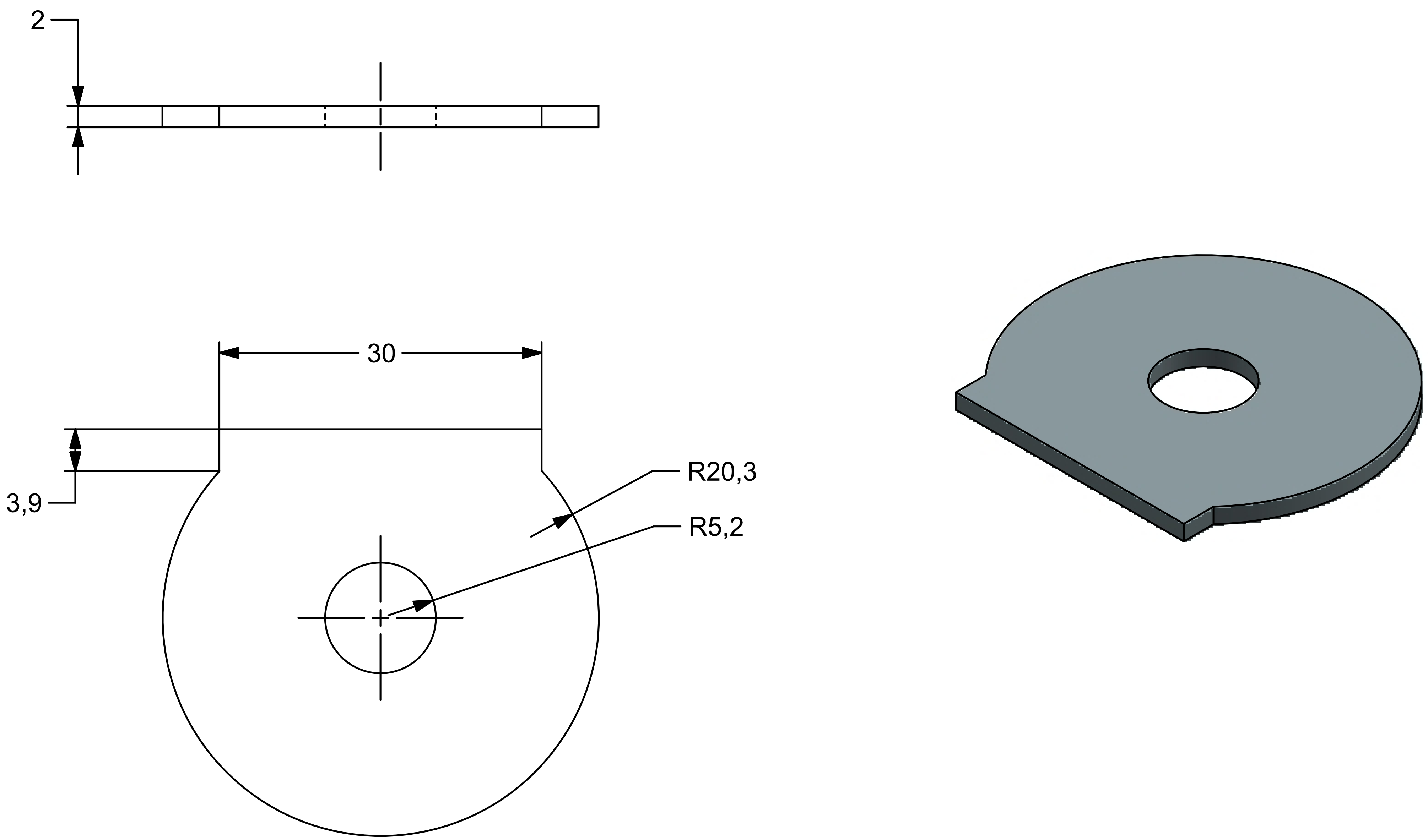
A3





FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** ABS PLASTIC 2 REQD	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR	
	ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	**DATUM/DATE** 28/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 049-Tool-Sensor_V1	**BLADSY/ SHEET** SHEET 49 of 93

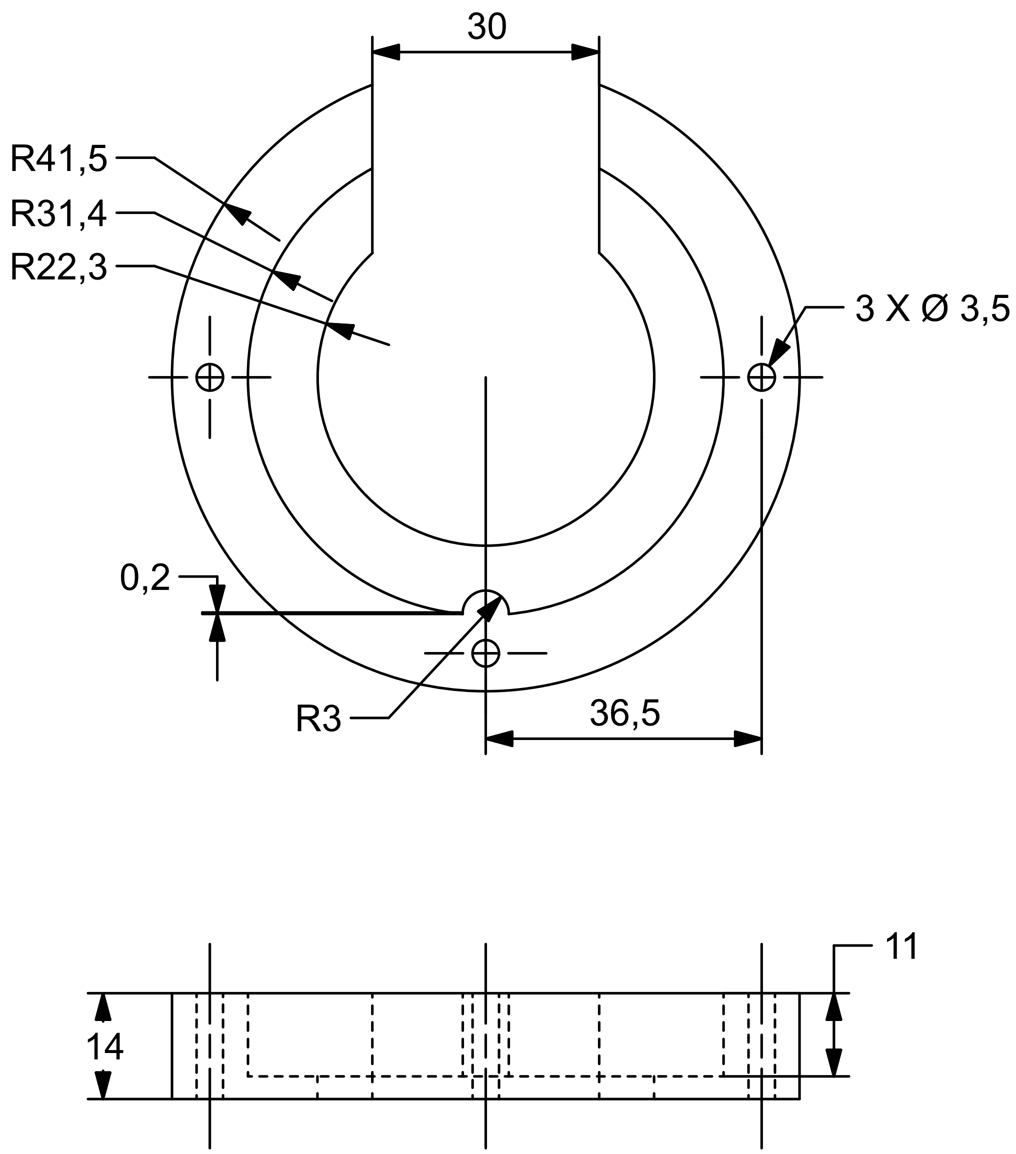
A3

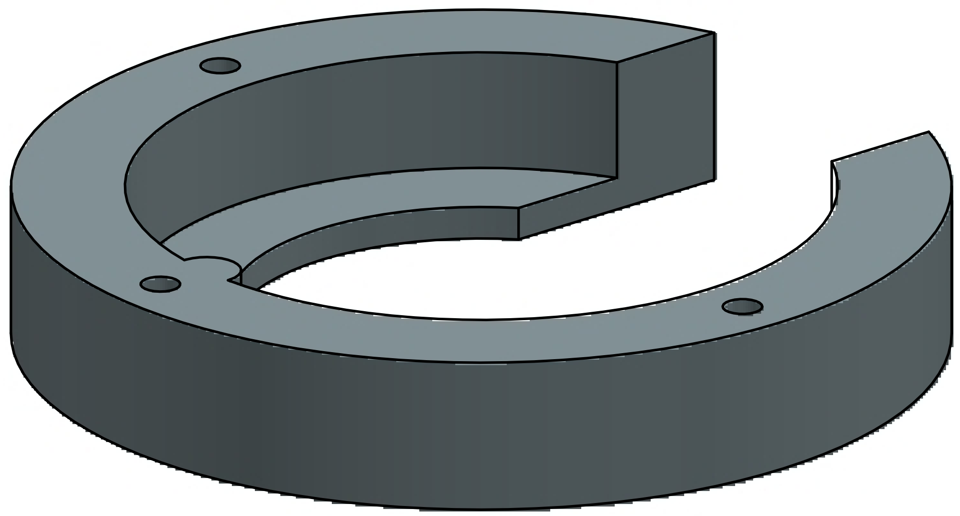


MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL	
ABS PLASTIC 2 REQD	PIETER MARX	29703662	MR	
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	050-Tool-Sensor_Spacer_v1	SHEET 50 OF 93

FAKULTEIT INGENIEURSWESE
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

A3

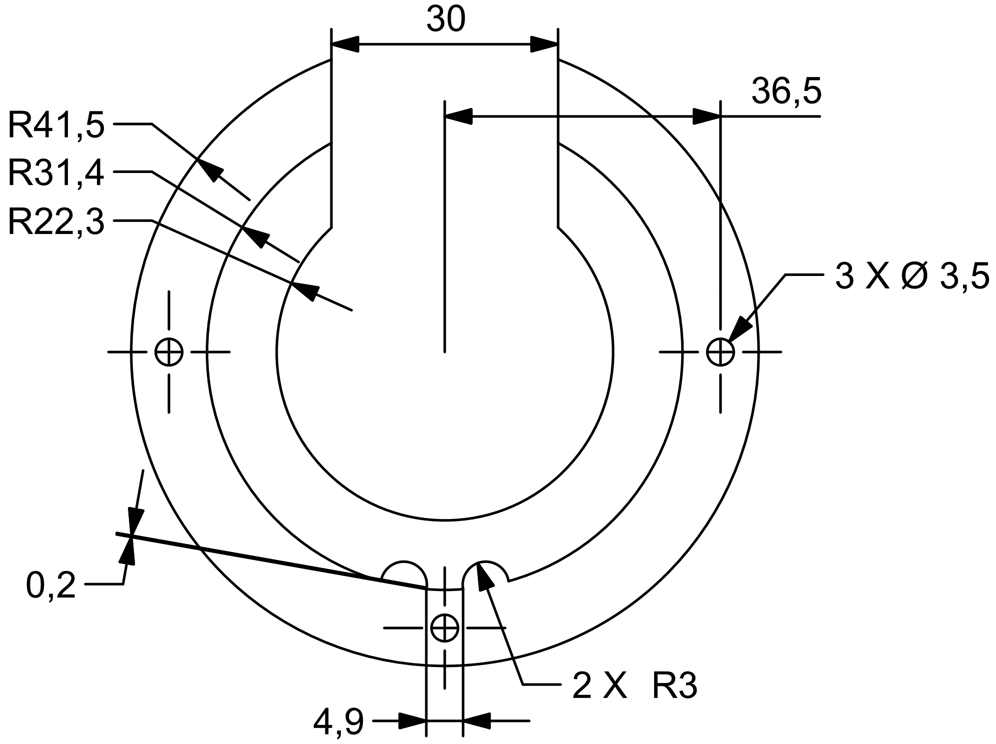


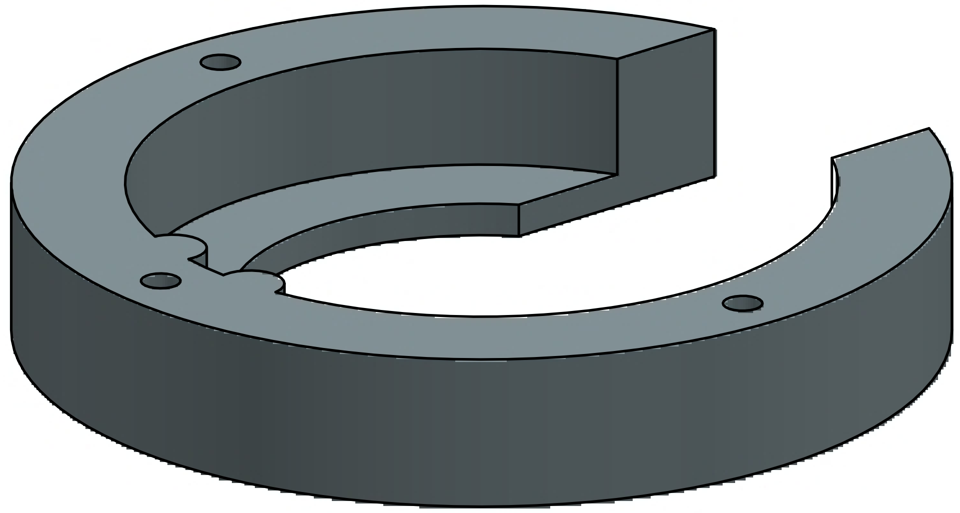


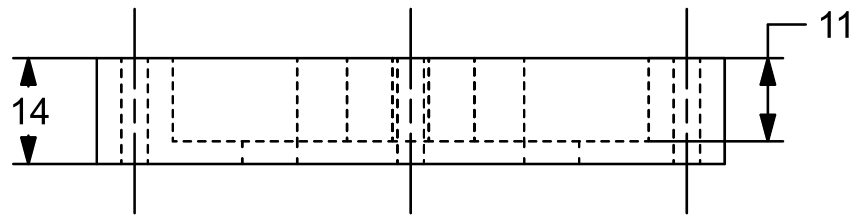
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** ABS PLASTIC	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	051-Tool-Holder-1_V1	SHEET 51 OF 93

A3



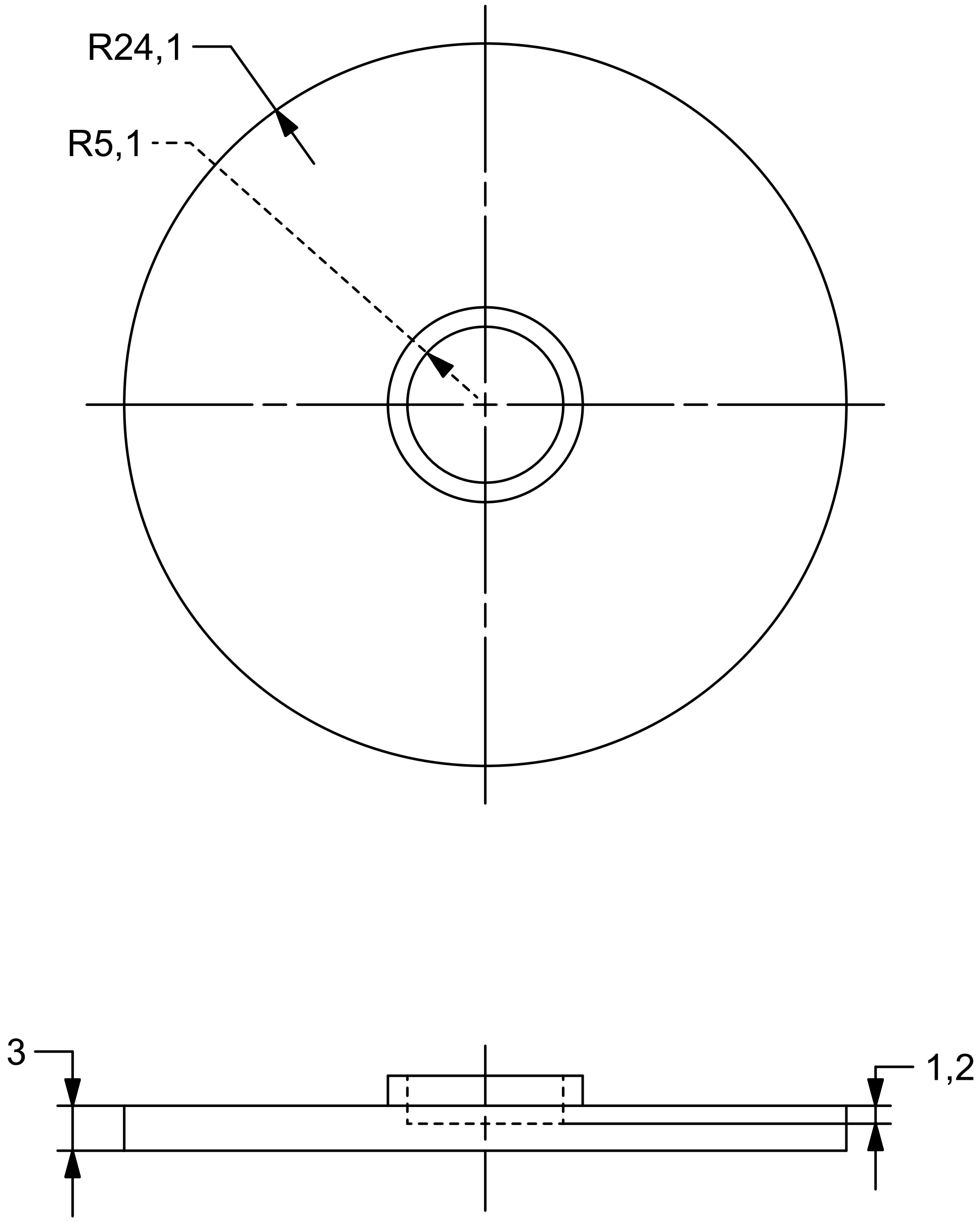


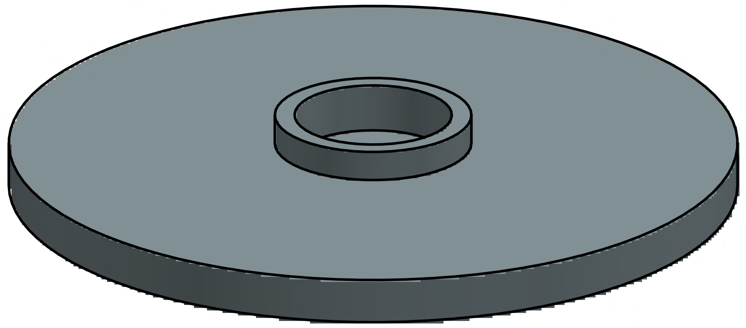


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
		ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	052-Tool-Holder-2_V1	SHEET 52 OF 93

A3





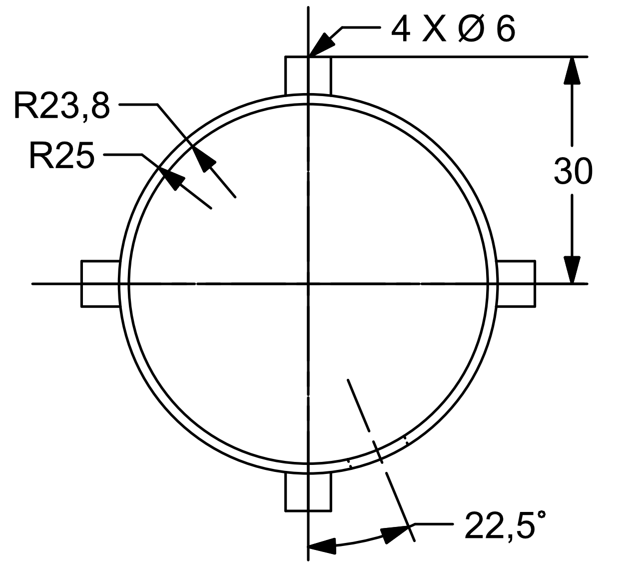
FAKULTEIT INGENIEURSWESE

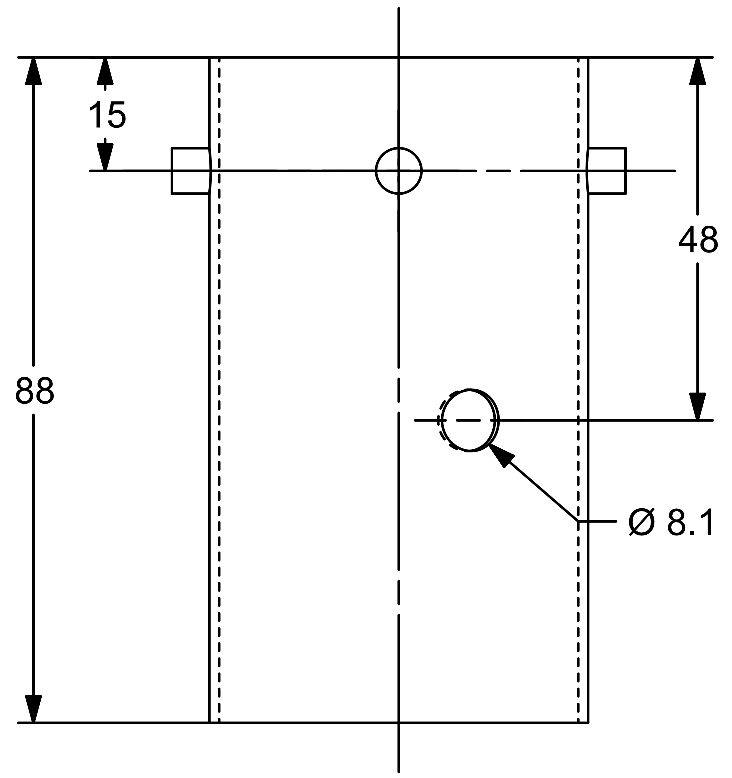
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	053-PUT-Disk_V1	SHEET 53 OF 93

A3

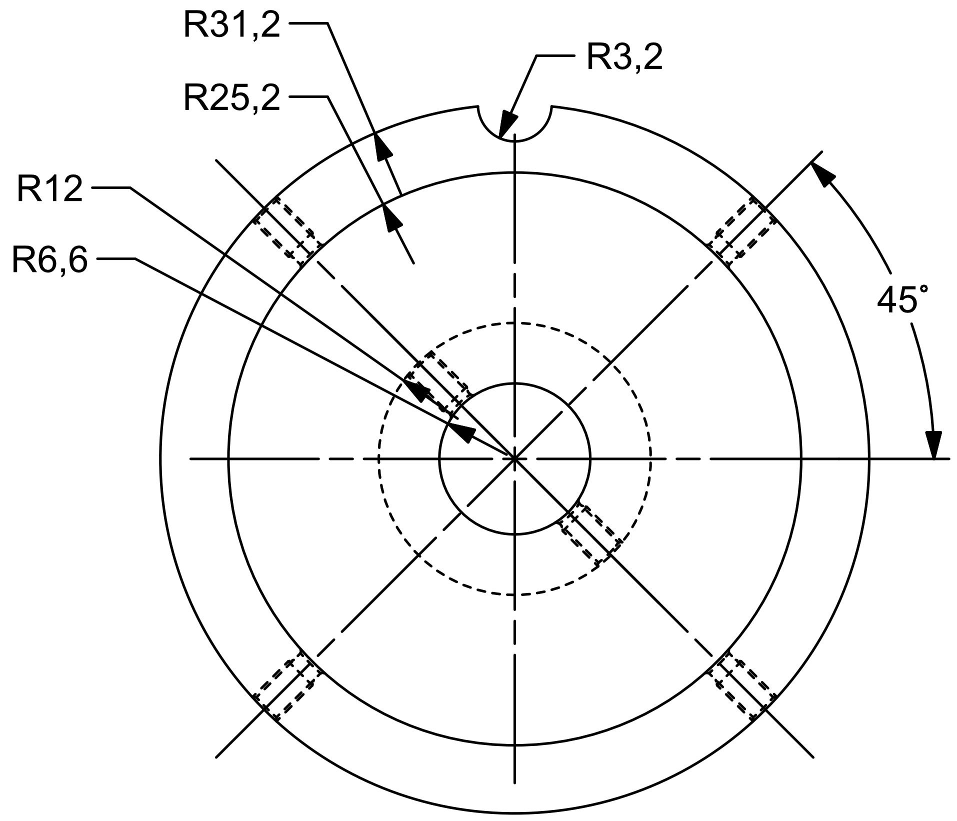


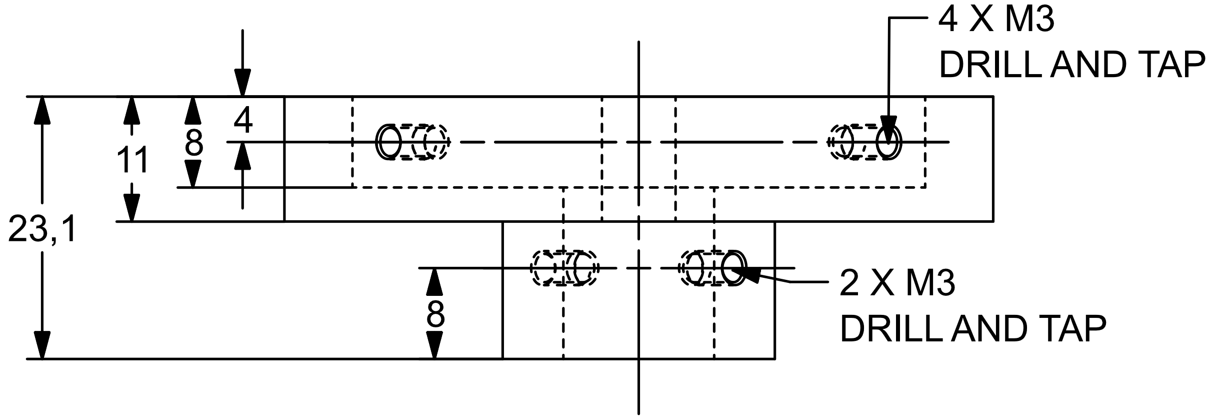


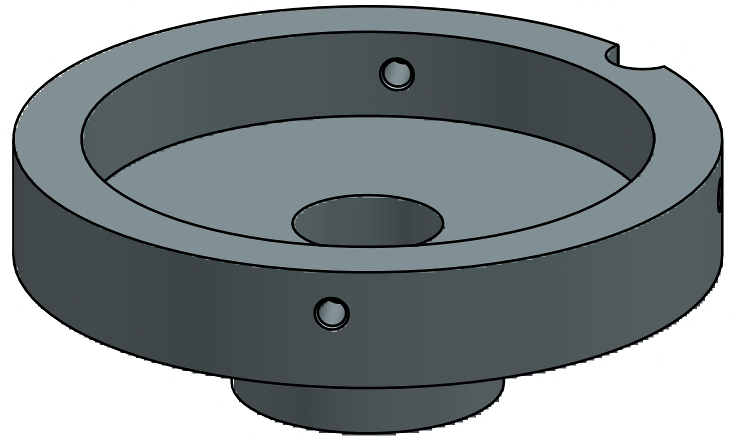
FAKULTEIT INGENIEURSWESE	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	STAINLESS STEEL	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	054-Tool-Housing-PUT_V1	SHEET 54 OF 93

A3

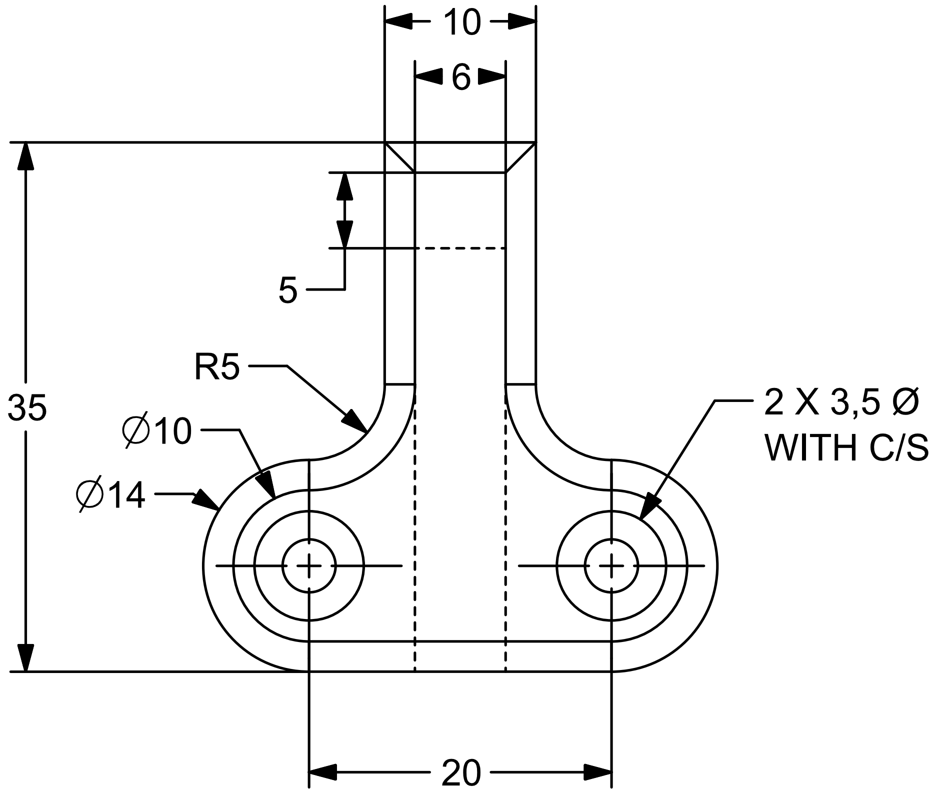


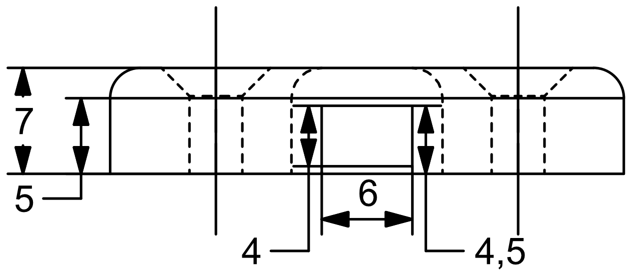


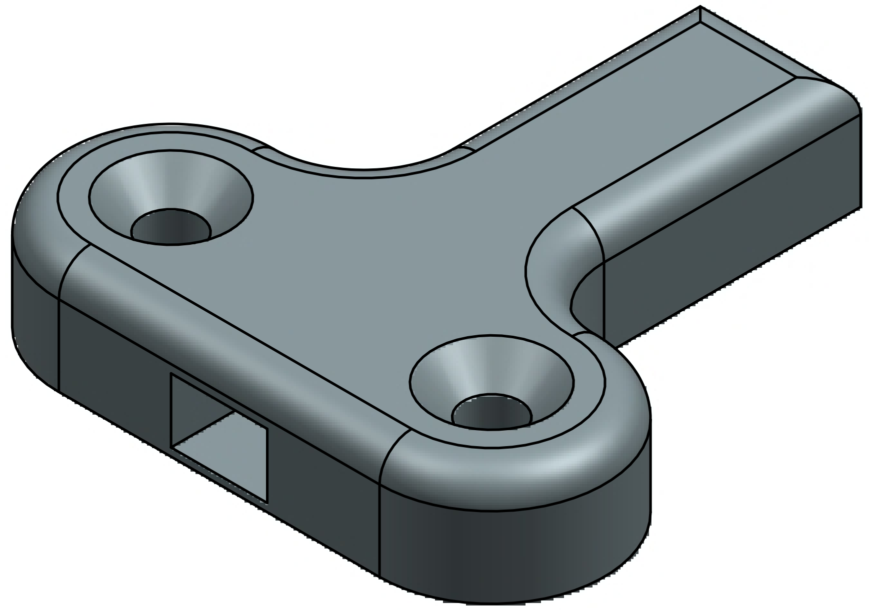


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL ALUMINIUM	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES LASER MARK CENTER MARKS OF ALL SMALL HOLES TO BE DRILLED AND TAPPED BY CLIENT	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 055-PUT-Mount_V1	BLADSY/ SHEET SHEET 55 OF 93

A3

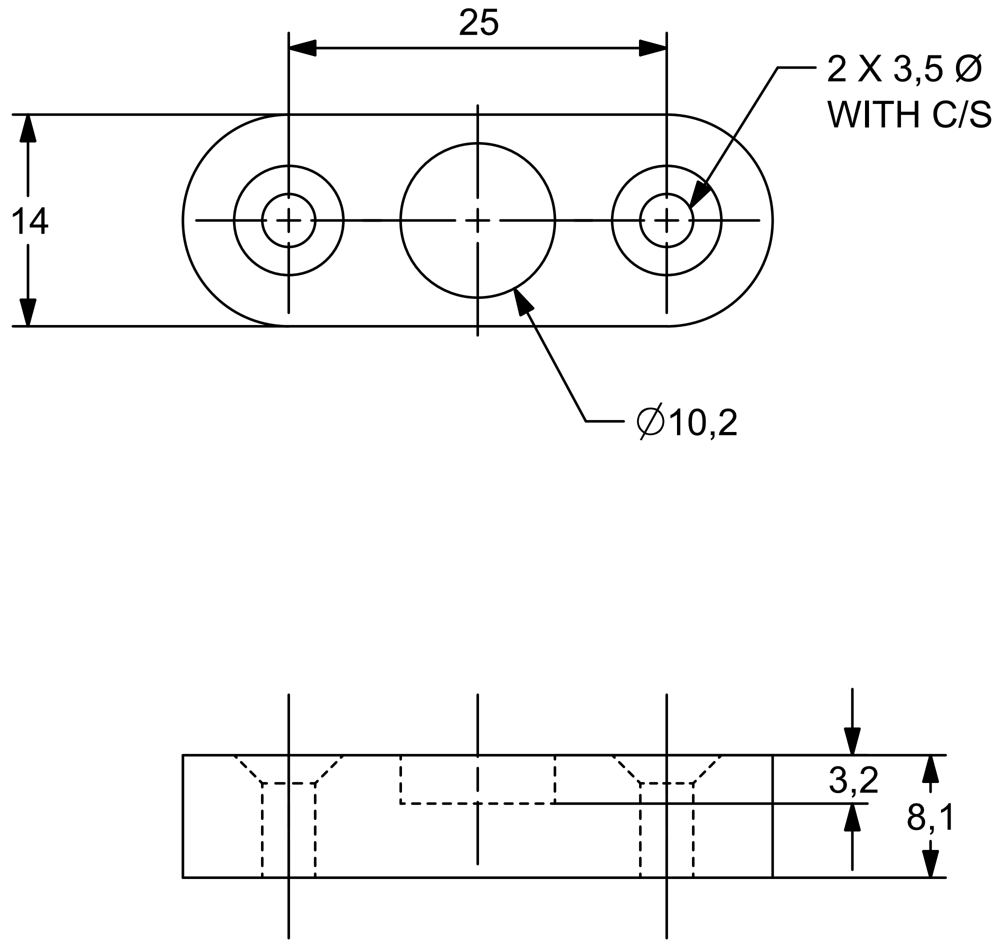


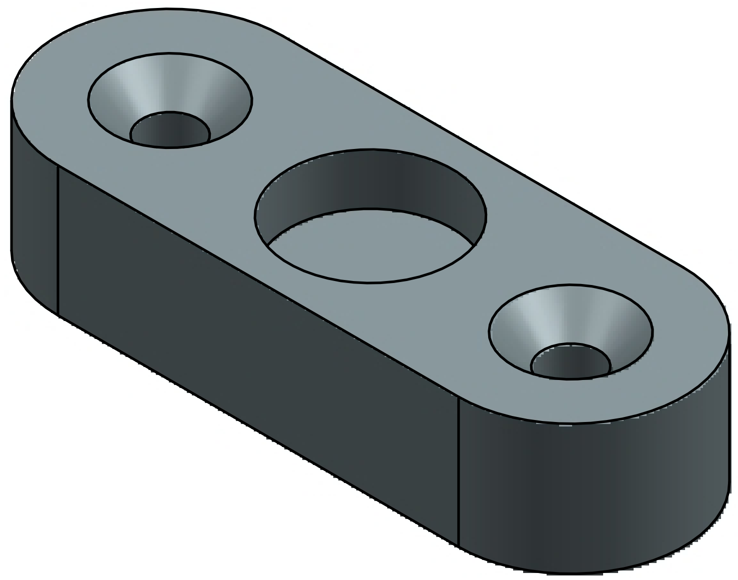




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
		ABS PLASTIC	PIETER MARX	29703662	MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
		CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	056-Hall-Effect-Sensor-Bracket-Height_V1	SHEET 56 OF 93

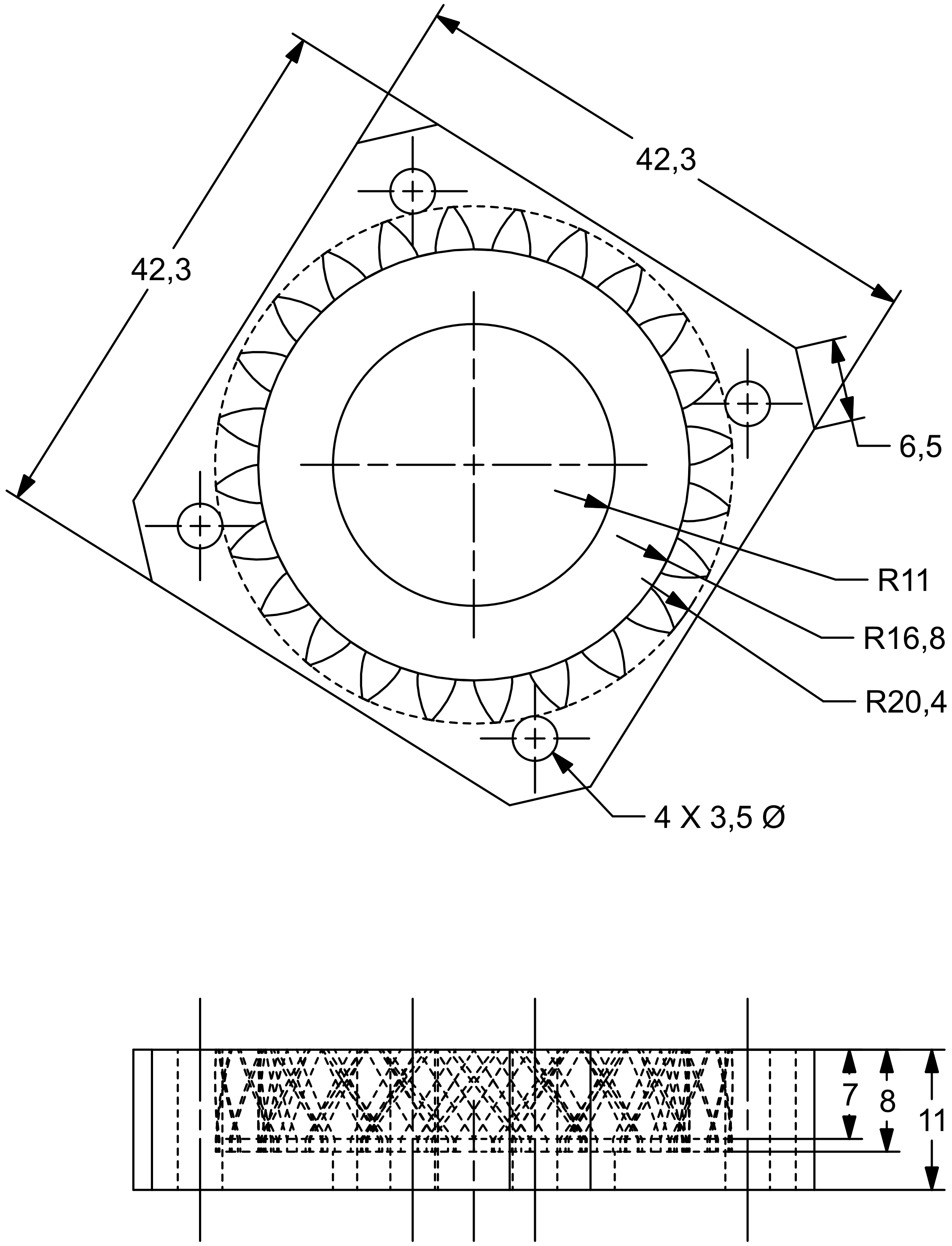
A3

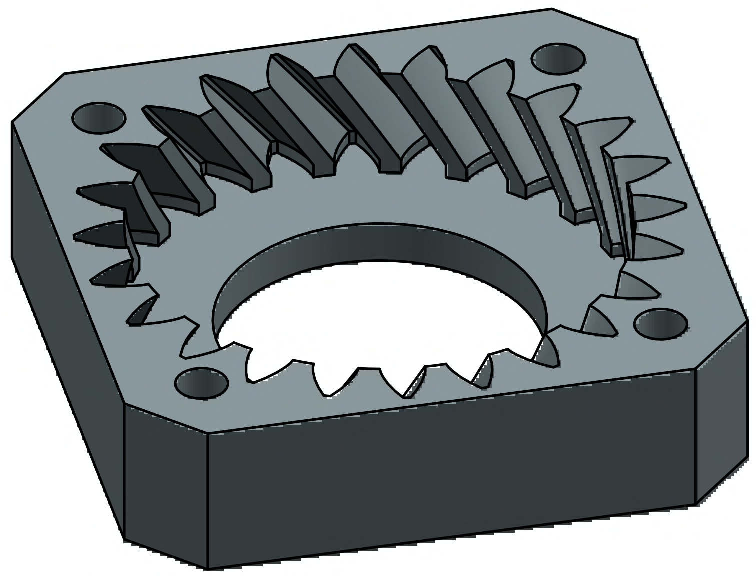




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL ABS PLASTIC	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 057-Hall-Effect-Sensor-Magnet-Bracket-Height_V1	BLADSY/ SHEET SHEET 57 OF 93

A3

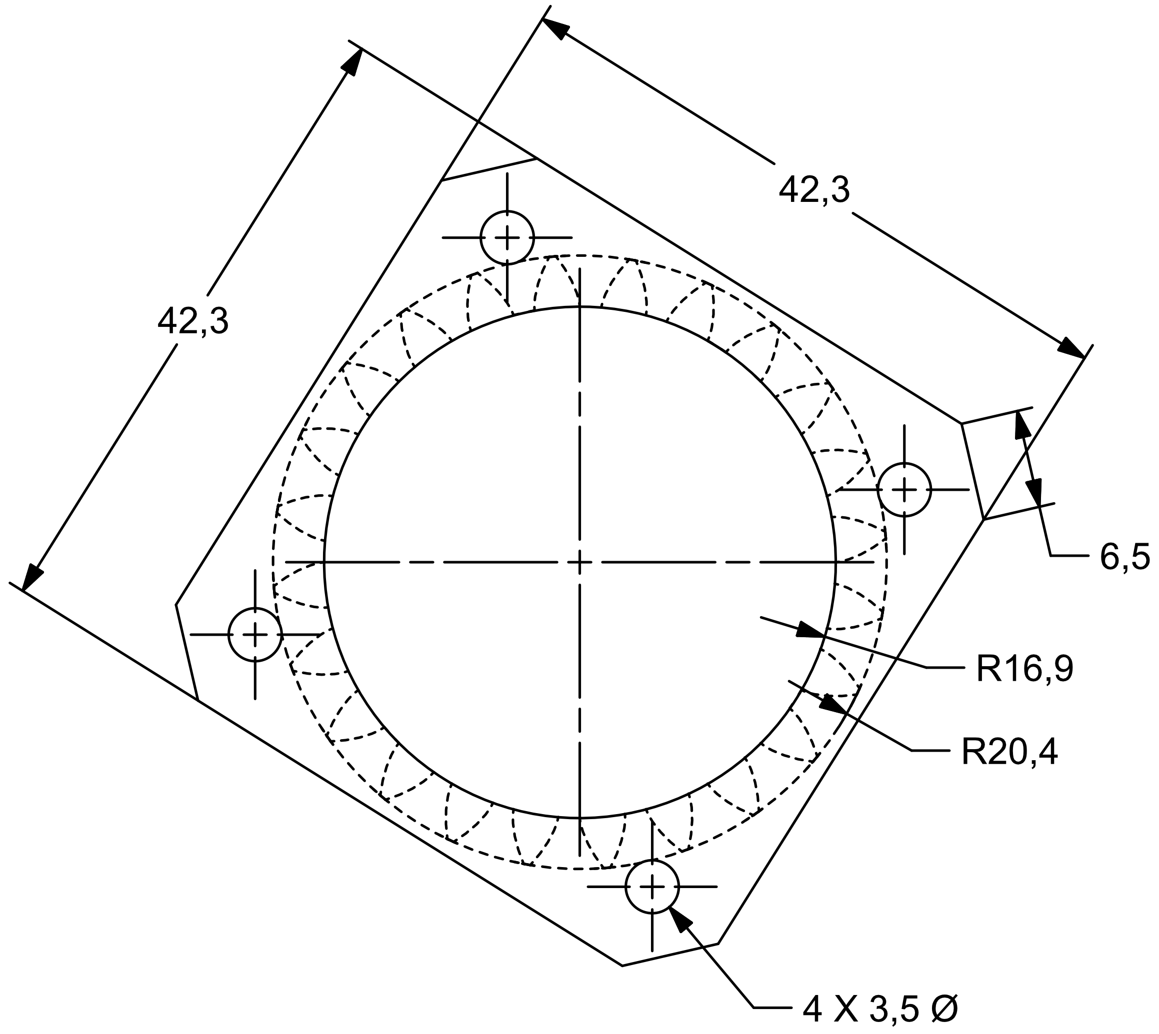


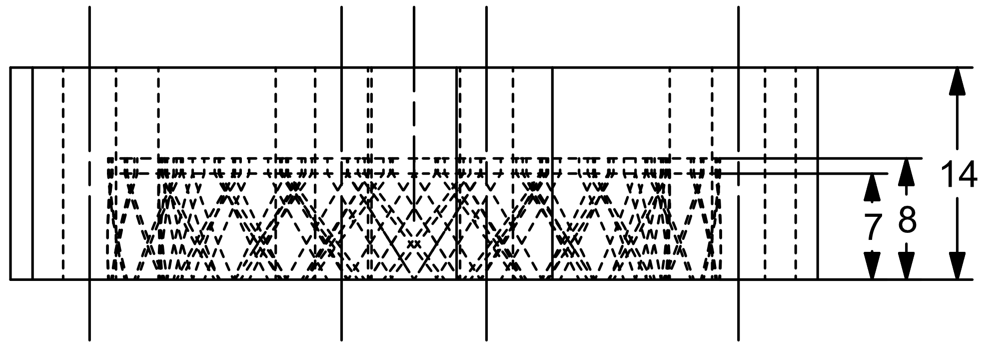


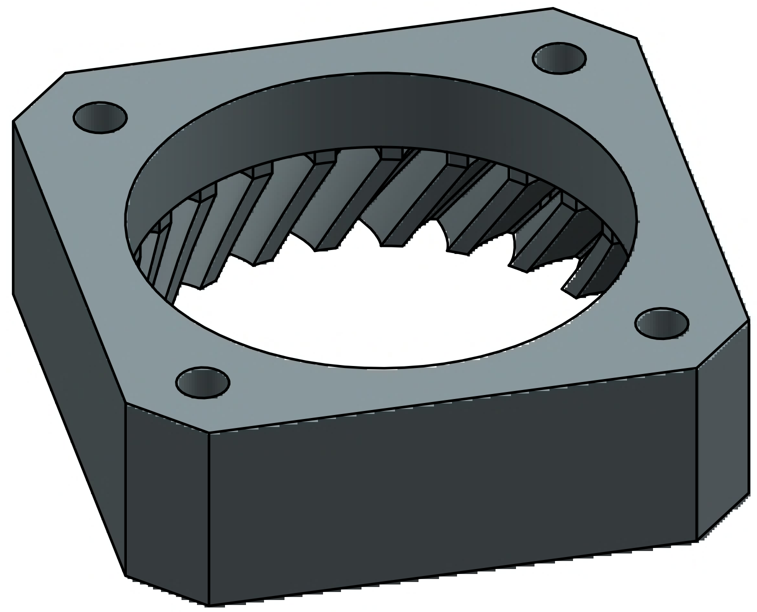
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** NYLON PLASTIC 2 REQD	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	**DATUM/DATE**	**SKAAL/SCALE**	**TEKENINGNOMMER/ DRAWING NUMBER**	**BLADSY/ SHEET**
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	058-Annular-Ring-Gear-Bottom_ V1	SHEET 58 OF 93

A3

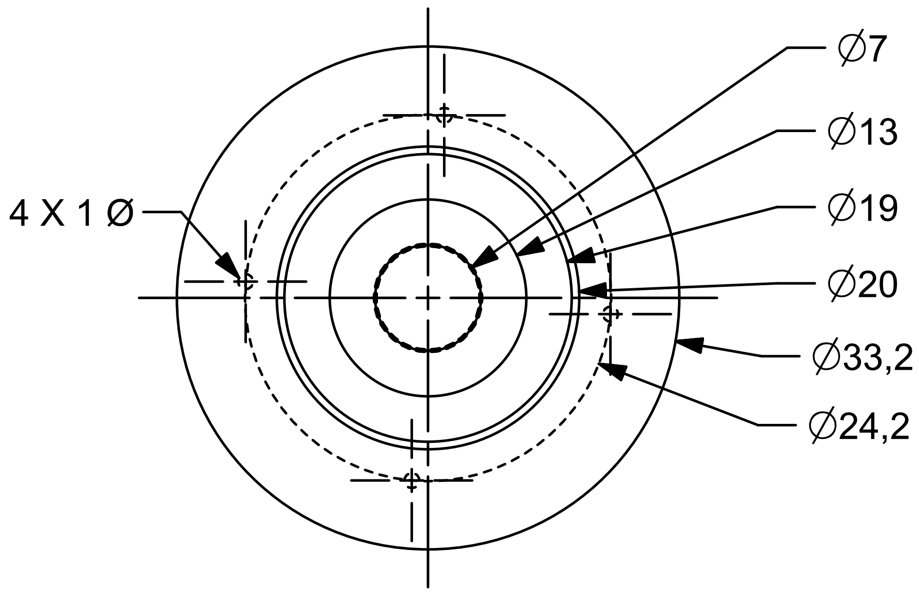


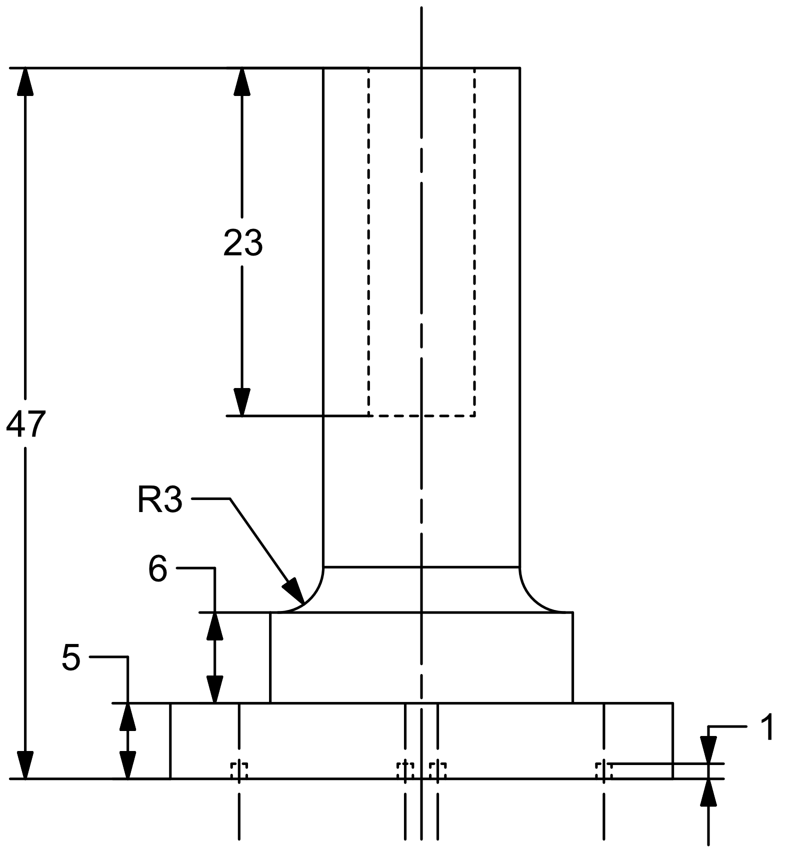


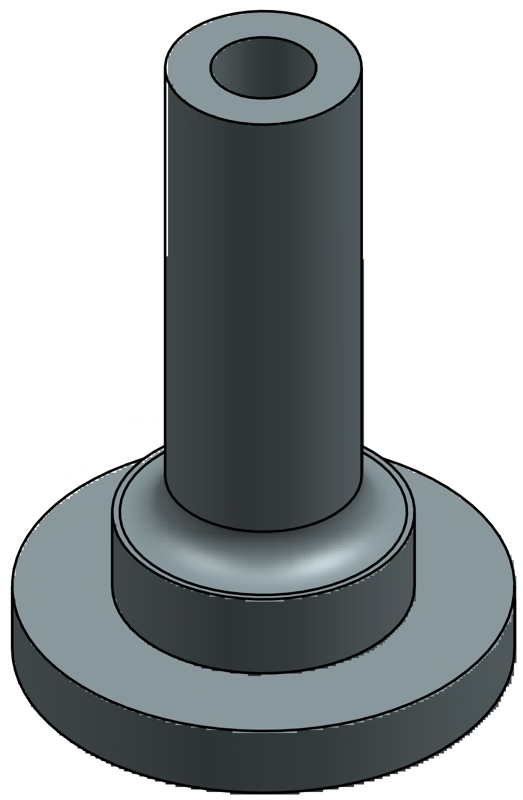


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		**MATERIAAL/MATERIAL** NYLON PLASTIC 2 REQD	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	**DATUM/DATE** 26/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 059-Annular-Ring-Gear-Top_V1
					BLADSY/ SHEET SHEET 59 OF 93

A3

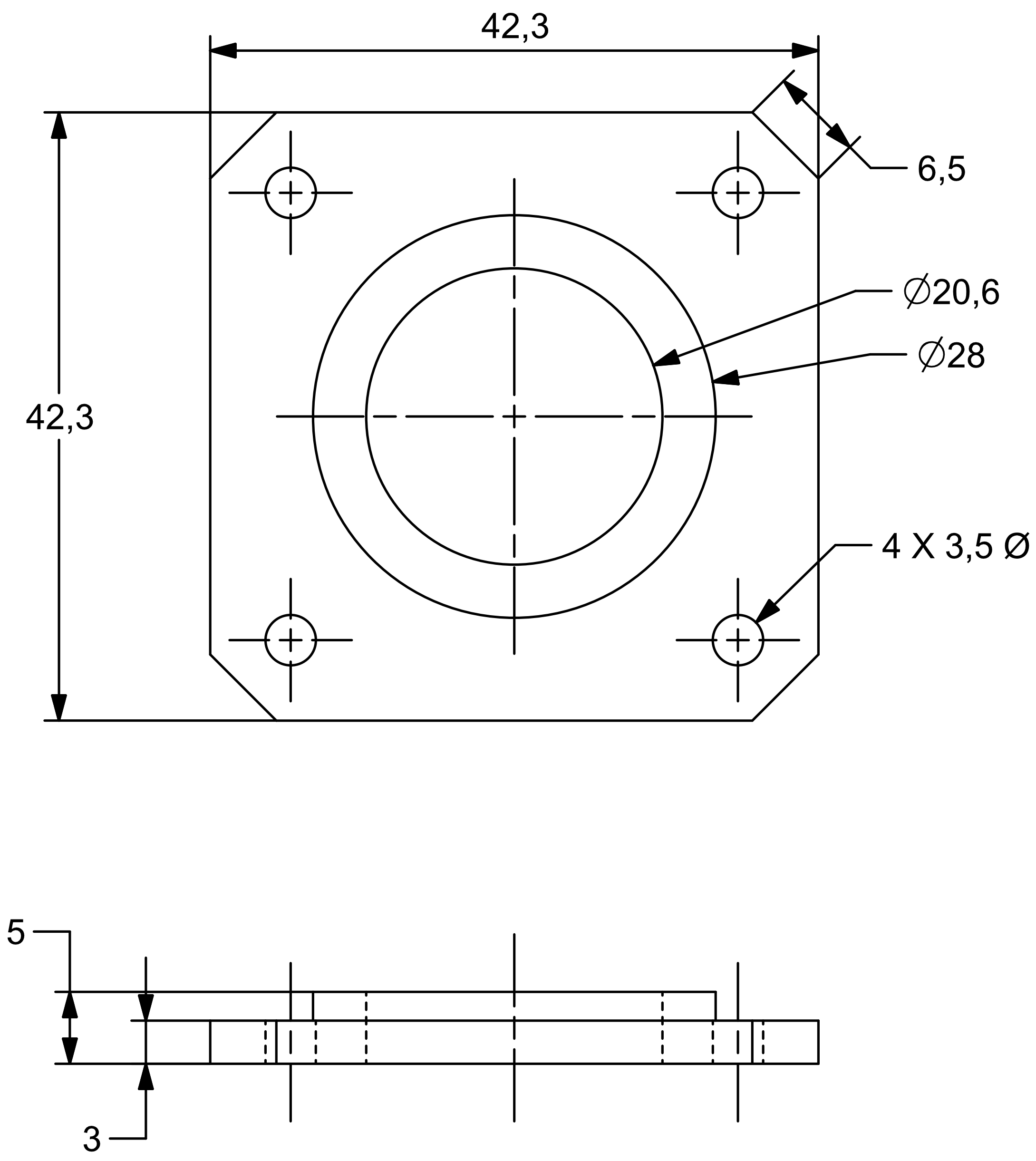


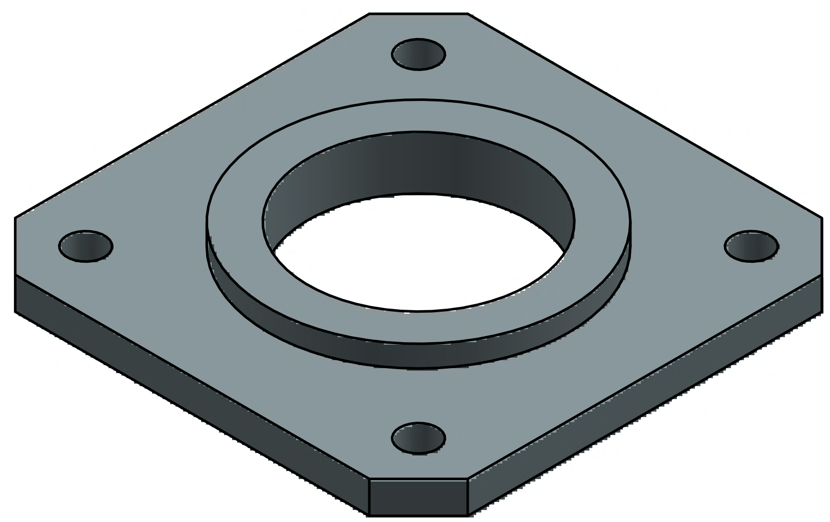




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL NYLON PLASTIC 2 REQD	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 060-Gearbox-Disk_V1	BLADSY/ SHEET SHEET 60 OF 93

A3

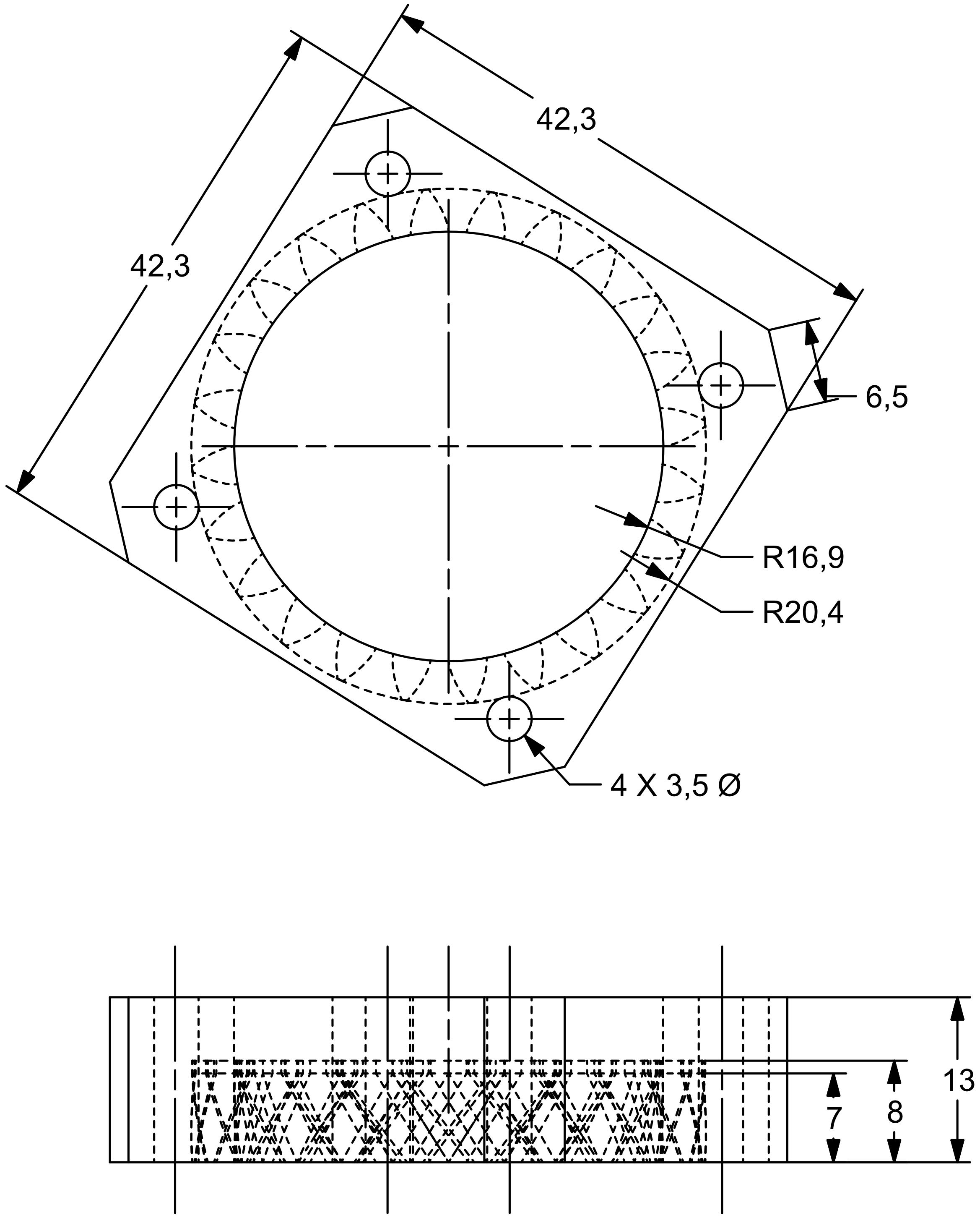


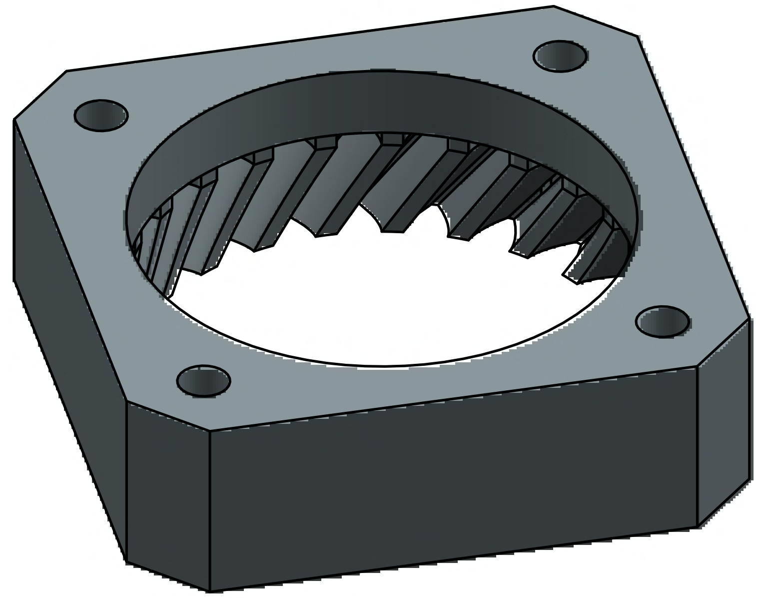


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	NYLON PLASTIC 2 REQD	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	061-Gearbox-Lid_V1	SHEET 61 OF 93

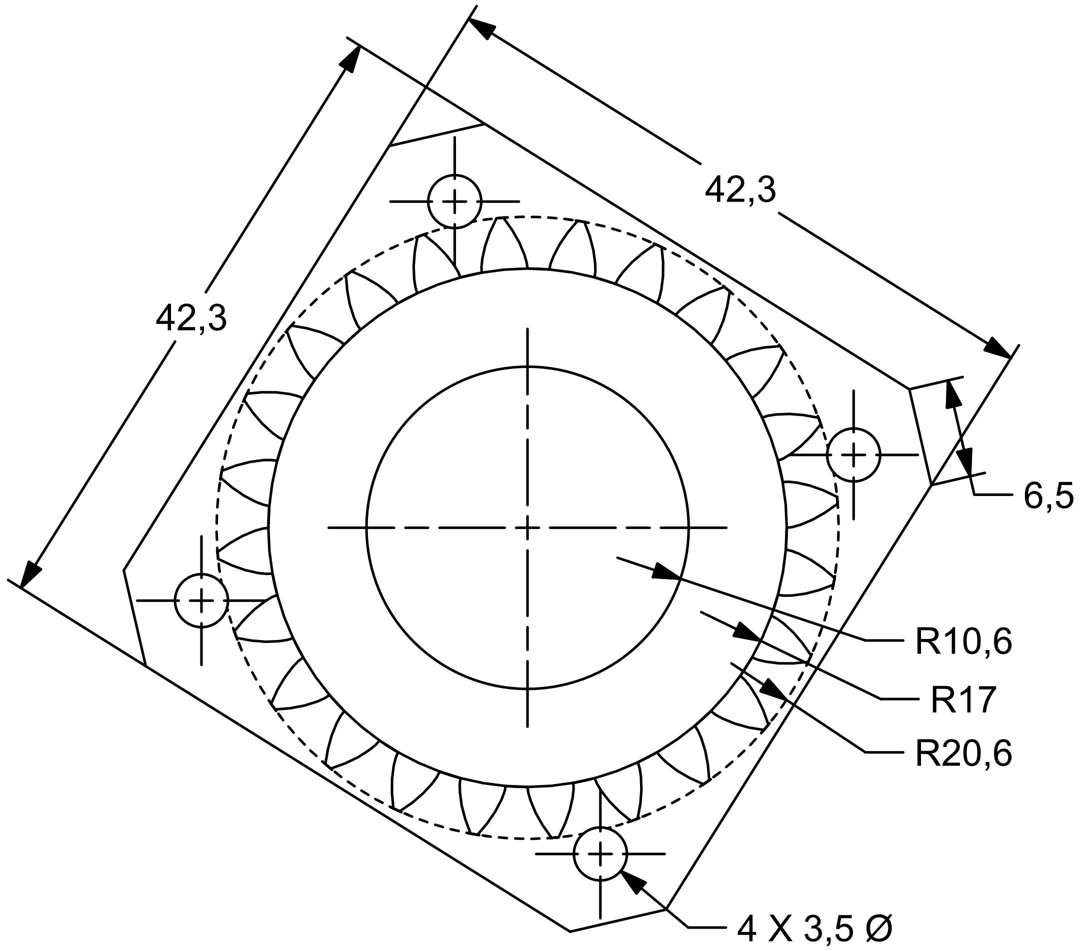
A3

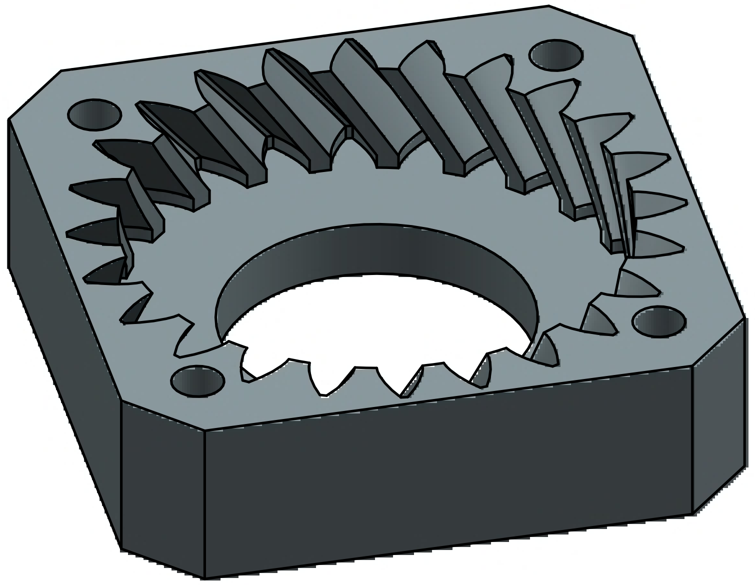


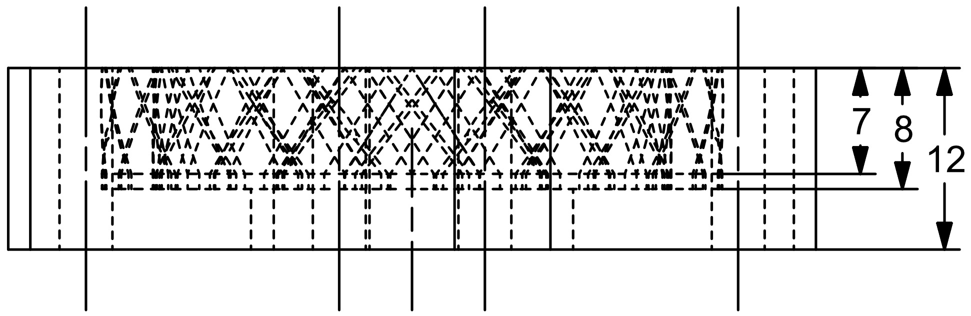


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL NYLON PLASTIC 2 REQD	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 062-Link-Annular-Ring-Gear-Bottom_V1	BLADSY/ SHEET SHEET 62 OF 93

A3

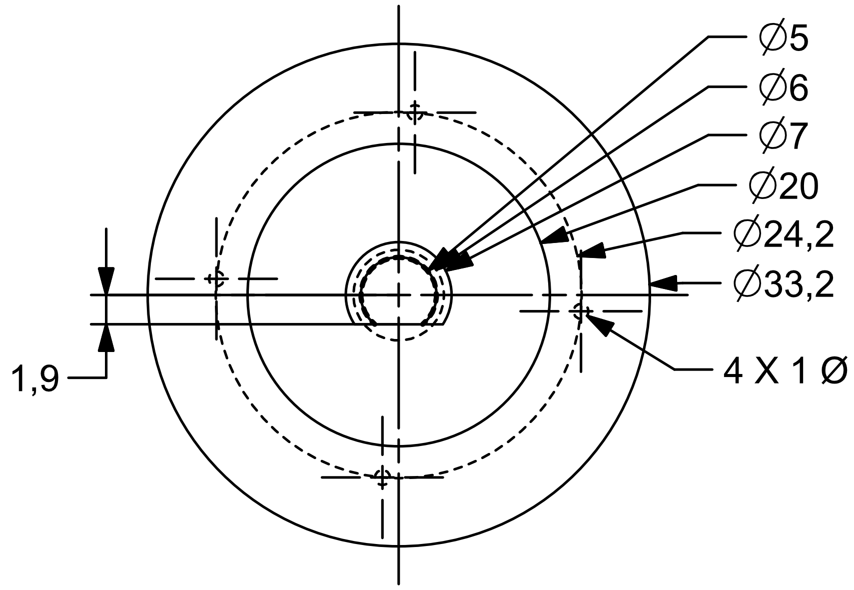


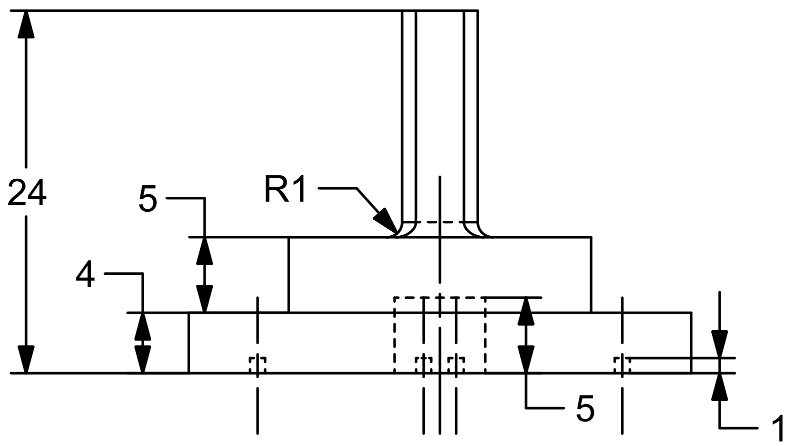


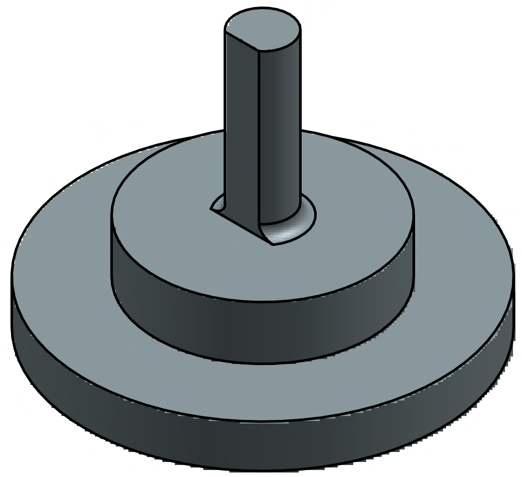


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL NYLON PLASTIC 2 REQD	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR	
	ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 063-Link-Annular-Ring-Gear-Top_V1	BLADSY/ SHEET SHEET 63 OF 93

A3

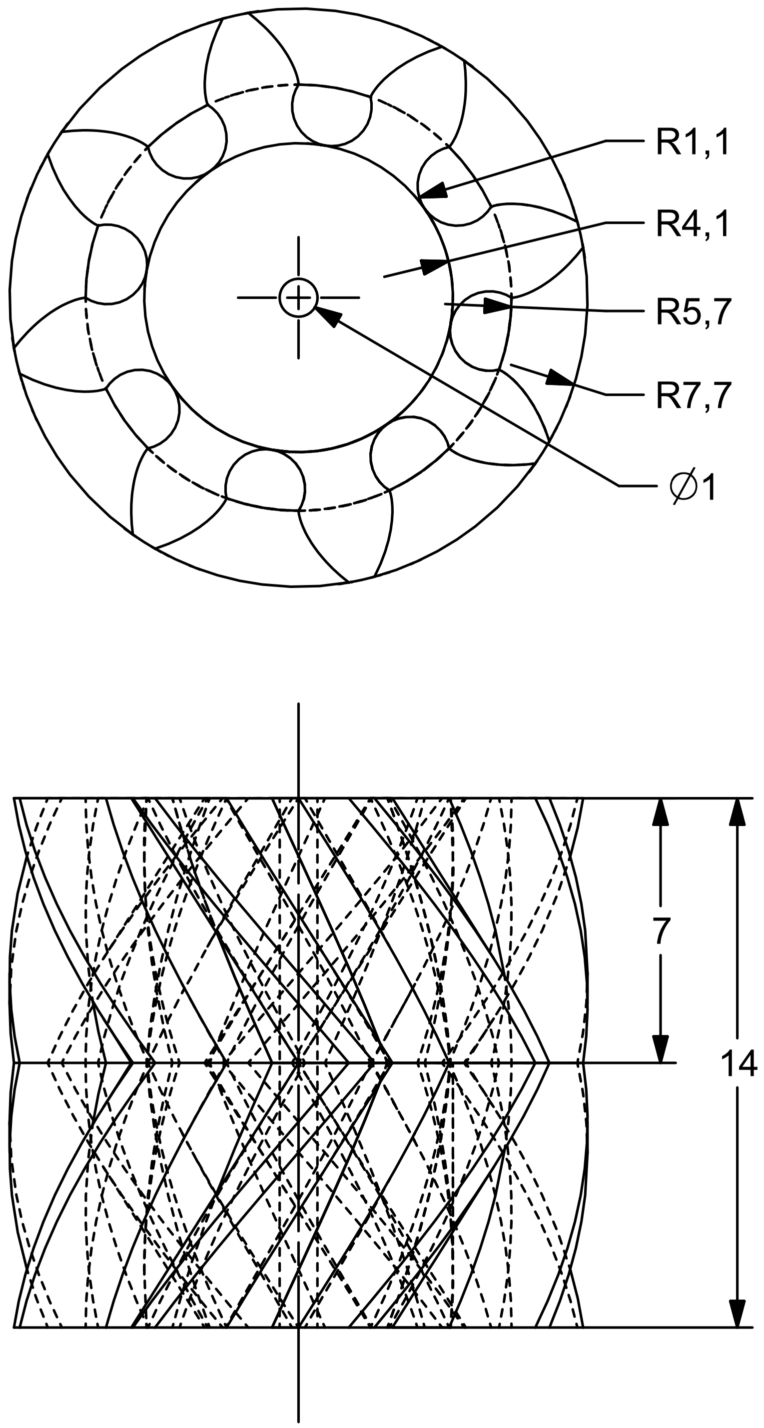


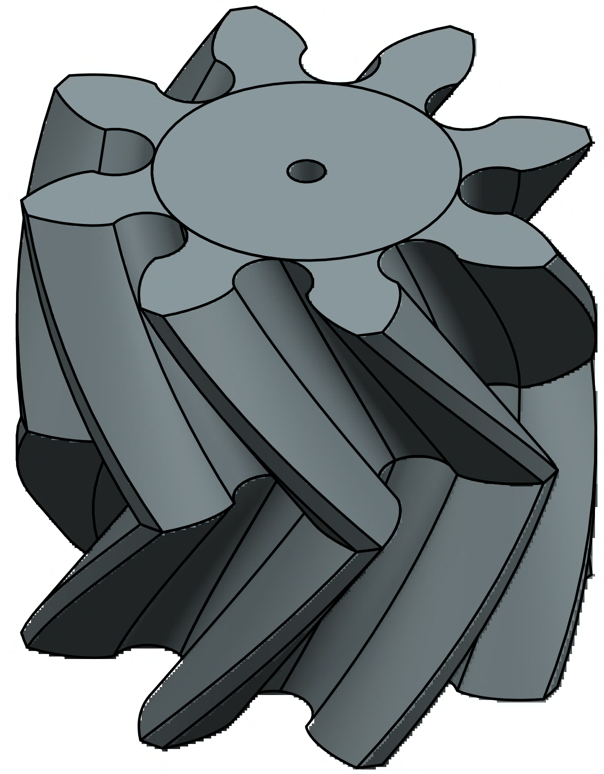




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** NYLON PLASTIC 2 REQD	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	**DATUM/DATE** 26/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 064-Gearbox-Link-Disk_V1	**BLADSY/ SHEET** SHEET 64 OF 93

A3

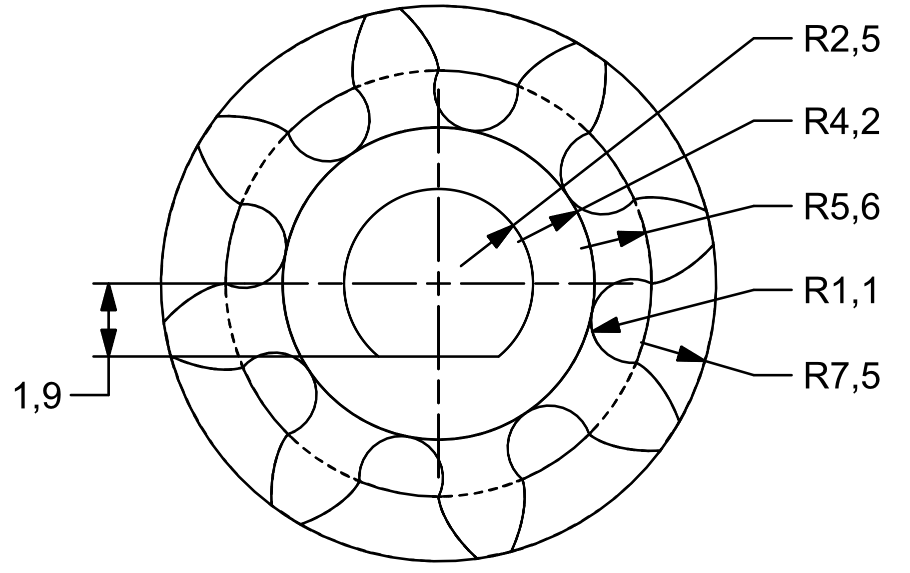


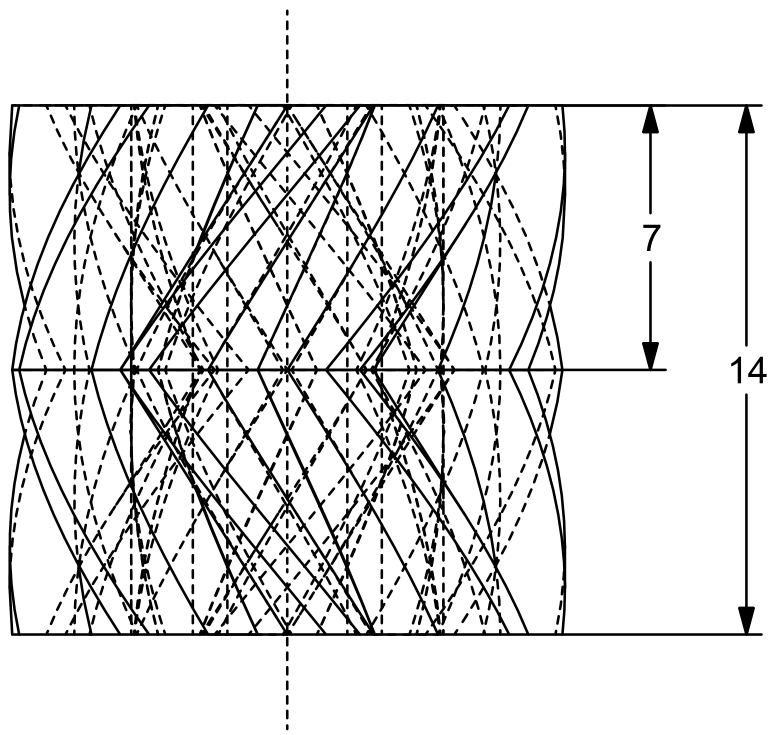


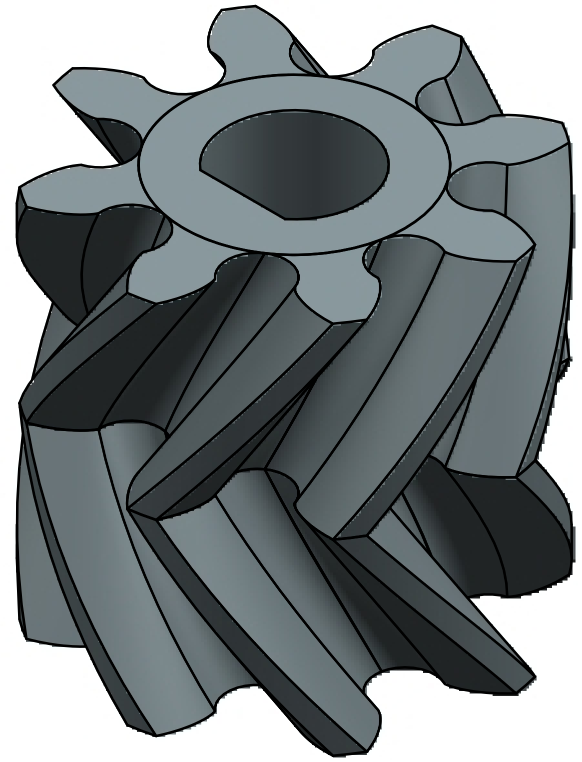
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL NYLON PLASTIC 16 REQD	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	065-Gearbox-Planet-Gear_v1	SHEET 65 OF 93

A3

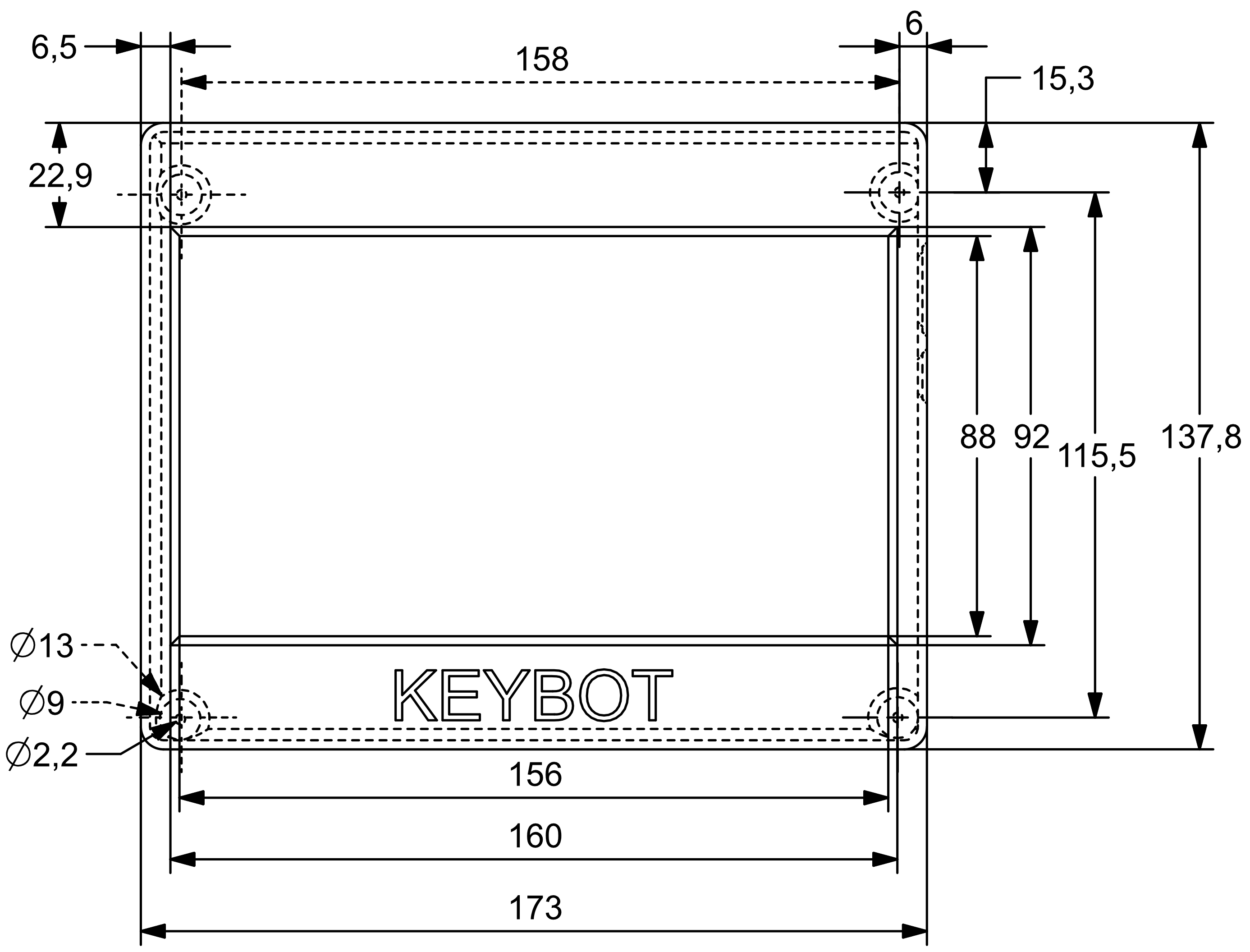


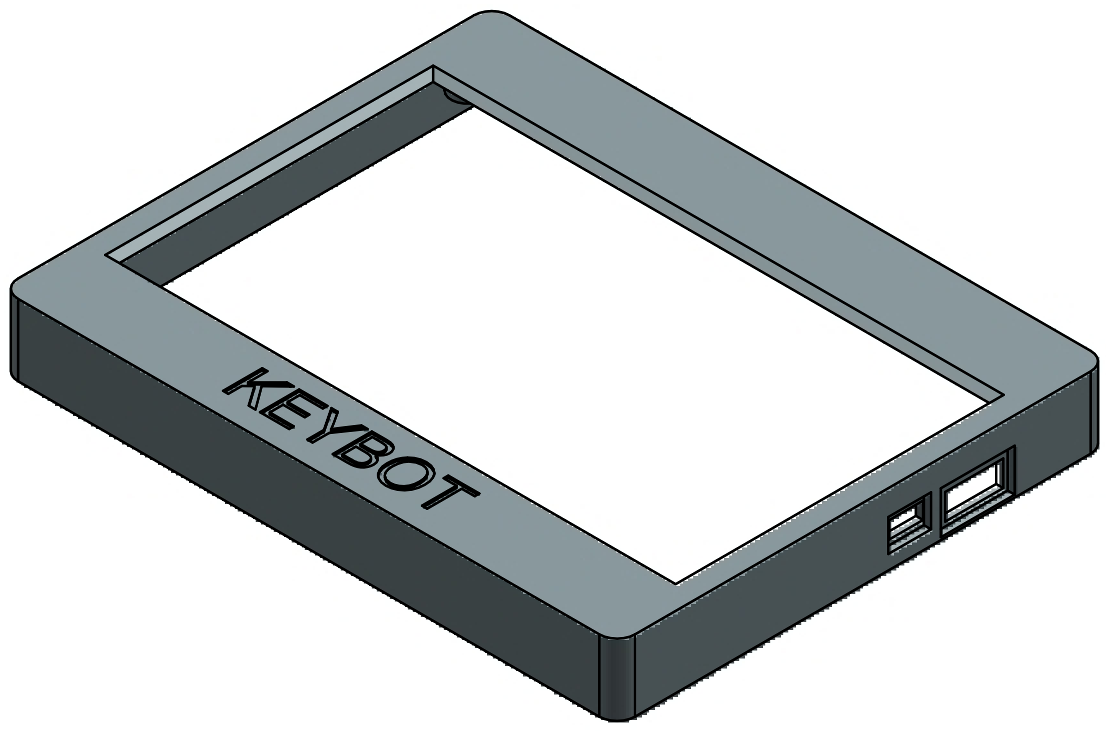


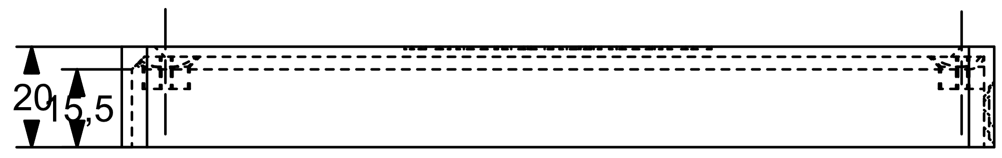


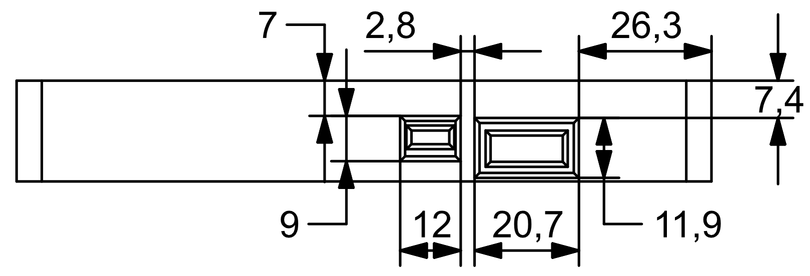
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL NYLON PLASTIC 4 REQD	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662		TITEL/ TITEL MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART		DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 066-Gearbox-Sun-Gear_V1	BLADSY/ SHEET SHEET 66 OF 93

A3



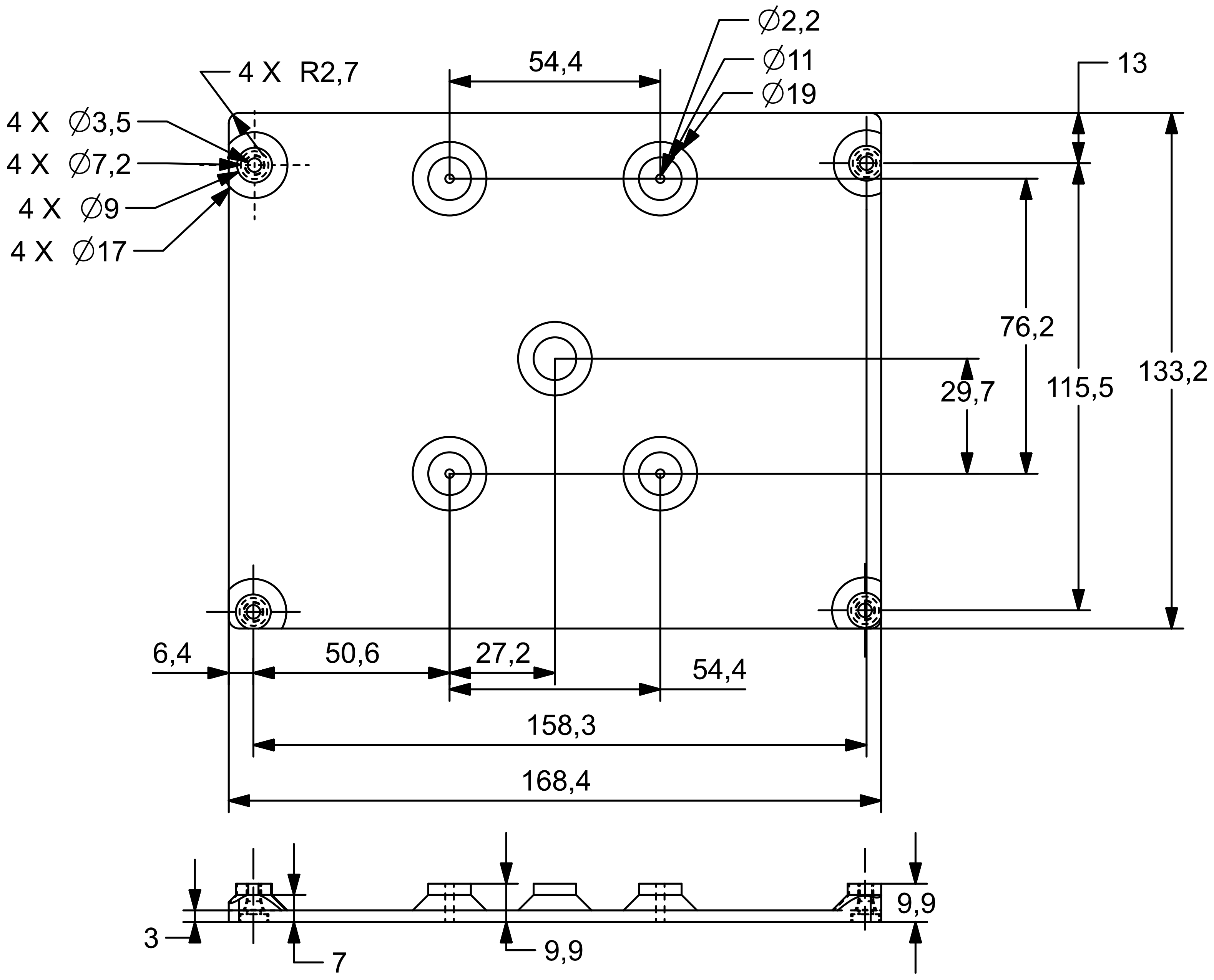


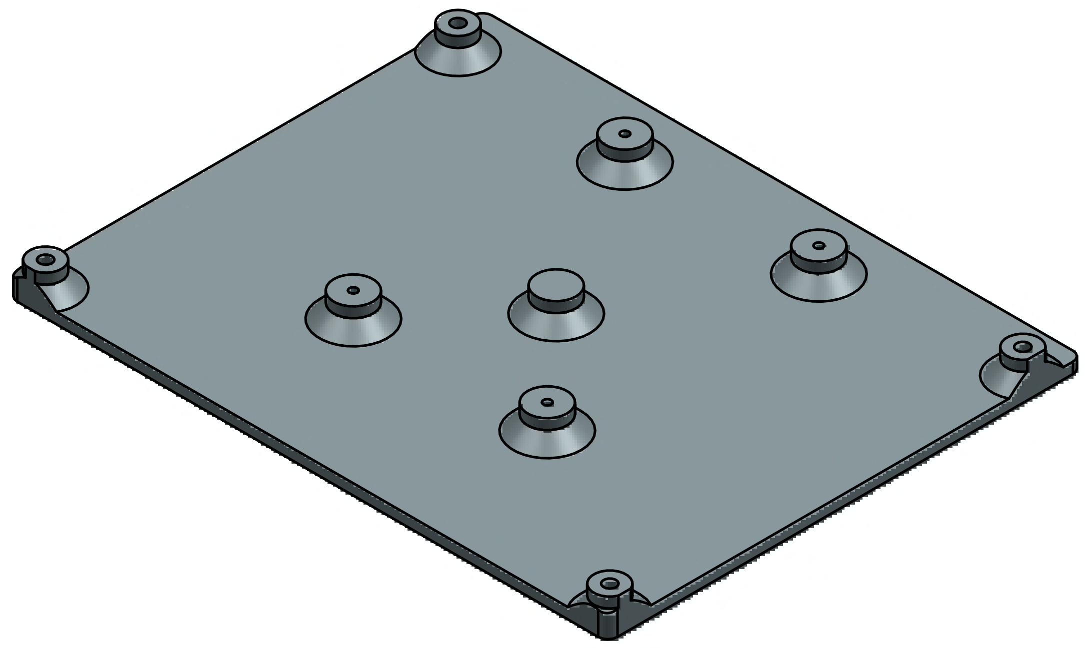




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL ABS PLASTIC	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR	
		ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 067-Touch-Screen-Cover-Front_ V1	BLADSY/ SHEET SHEET 67 OF 93

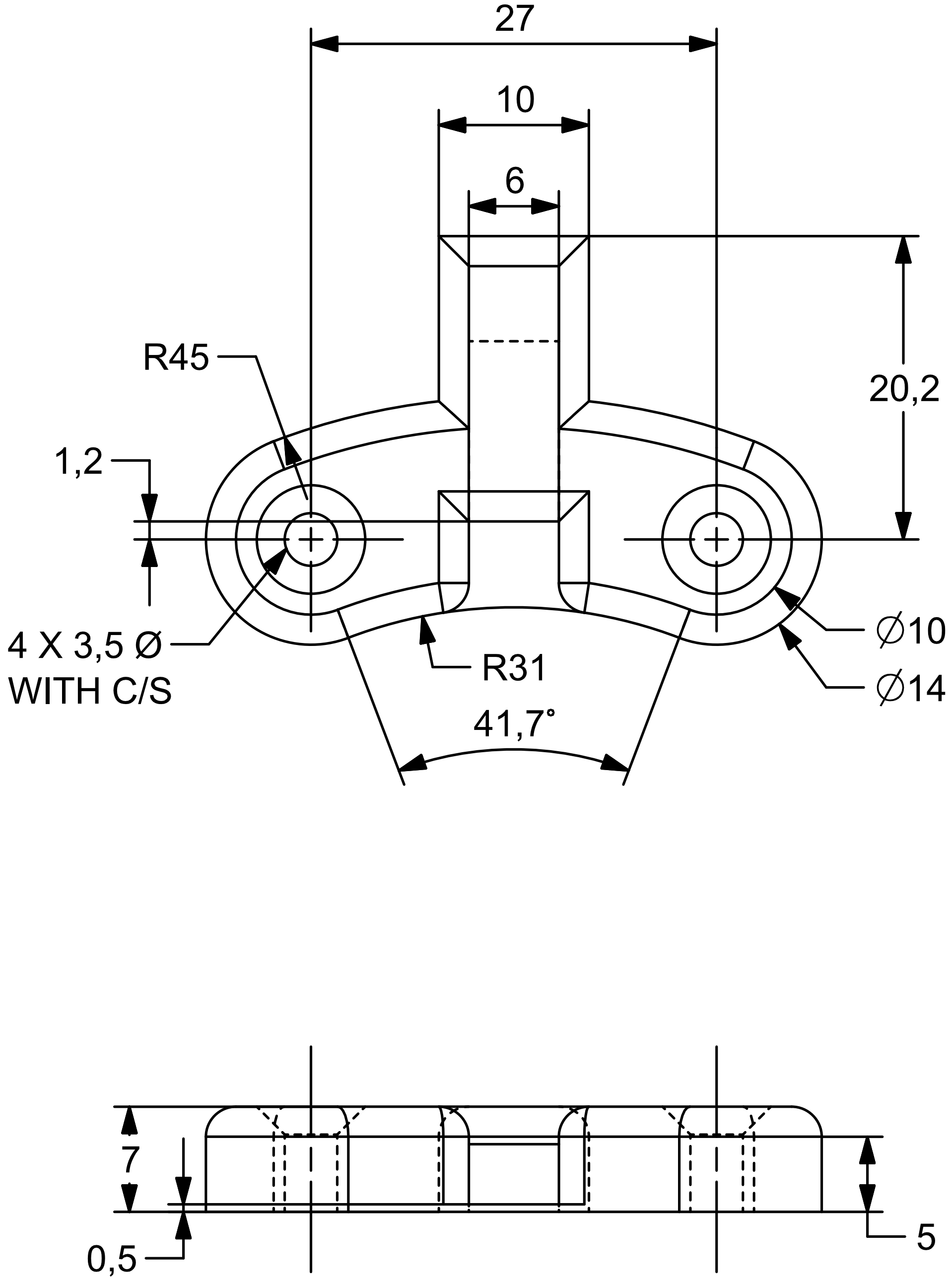
A3

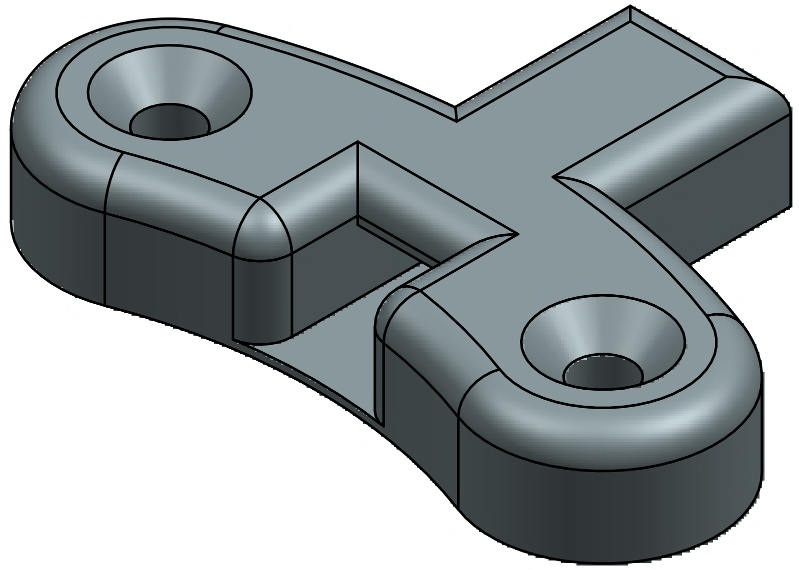




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL ABS PLASTIC	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 26/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 068-Touch-Screen-Cover-Back_V 1	BLADSY/ SHEET SHEET 68 OF 93

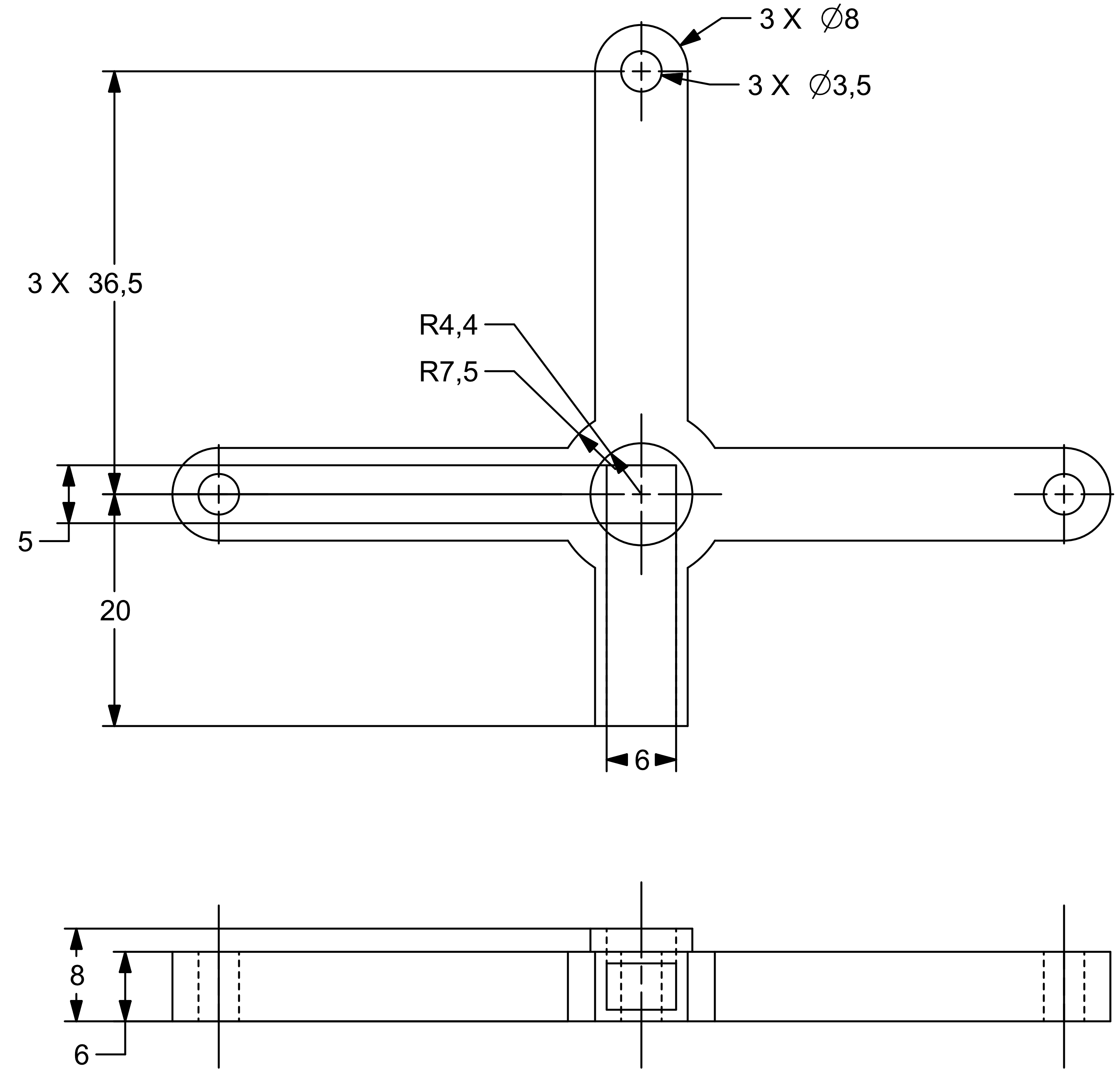
A3

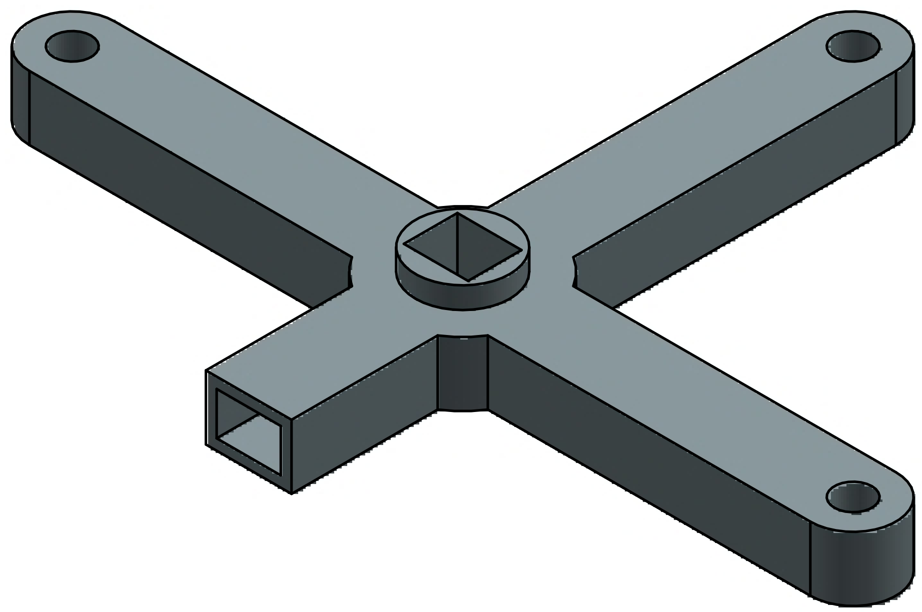




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL	
	ABS PLASTIC	PIETER MARX	29703662	MR	
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET	
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	069-Hall-Effect-Sensor-Bracket-Rotation_V1	SHEET 69 OF 93	

A3

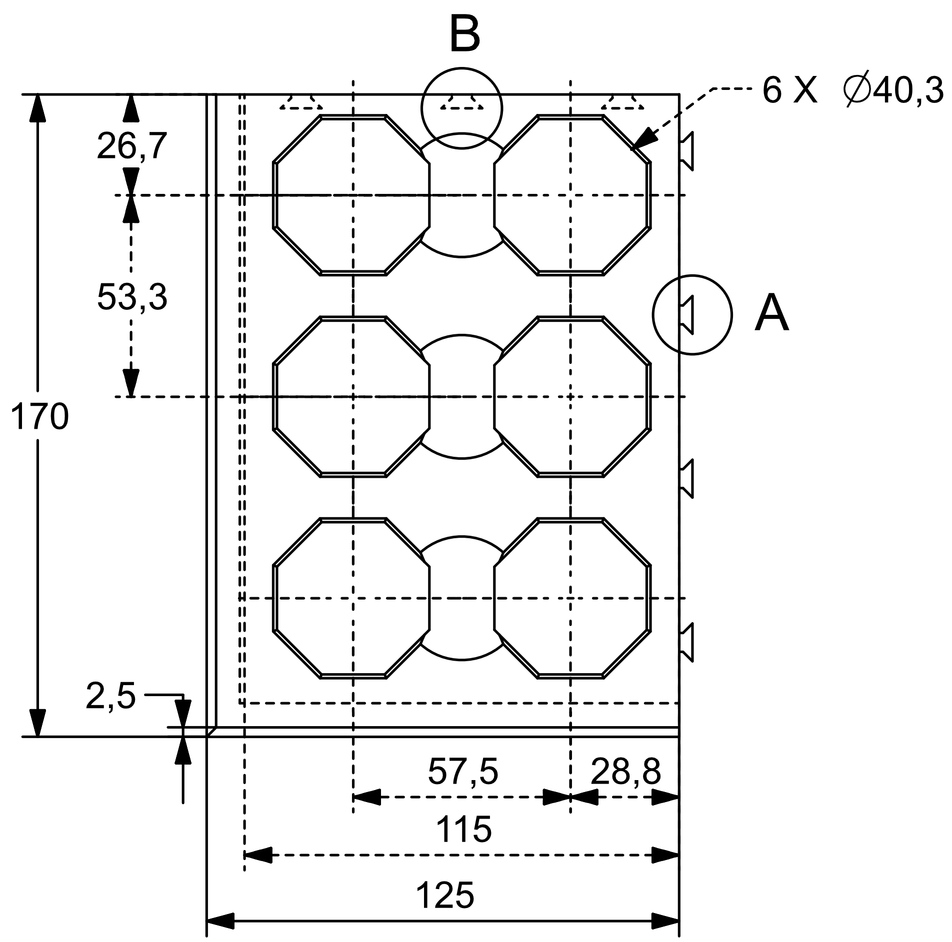


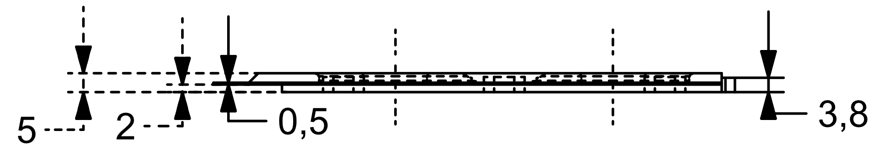


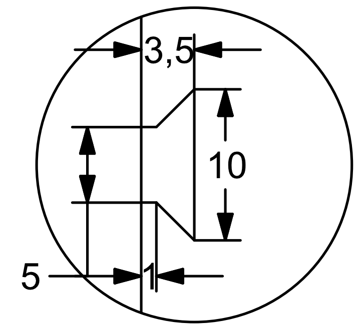
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** ABS PLASTIC 2 REQD	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	**DATUM/DATE**	**SKAAL/SCALE**	**TEKENINGNOMMER/ DRAWING NUMBER**	**BLADSY/ SHEET**
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	070-Hall-Effect-Sensor-Bracket-Tool-Post_V1	SHEET 70 OF 93

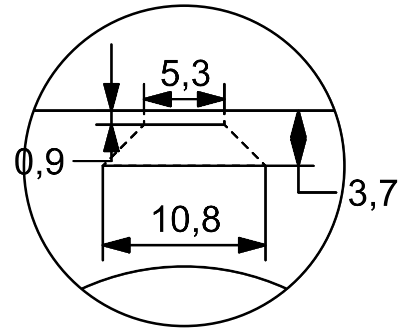
A3



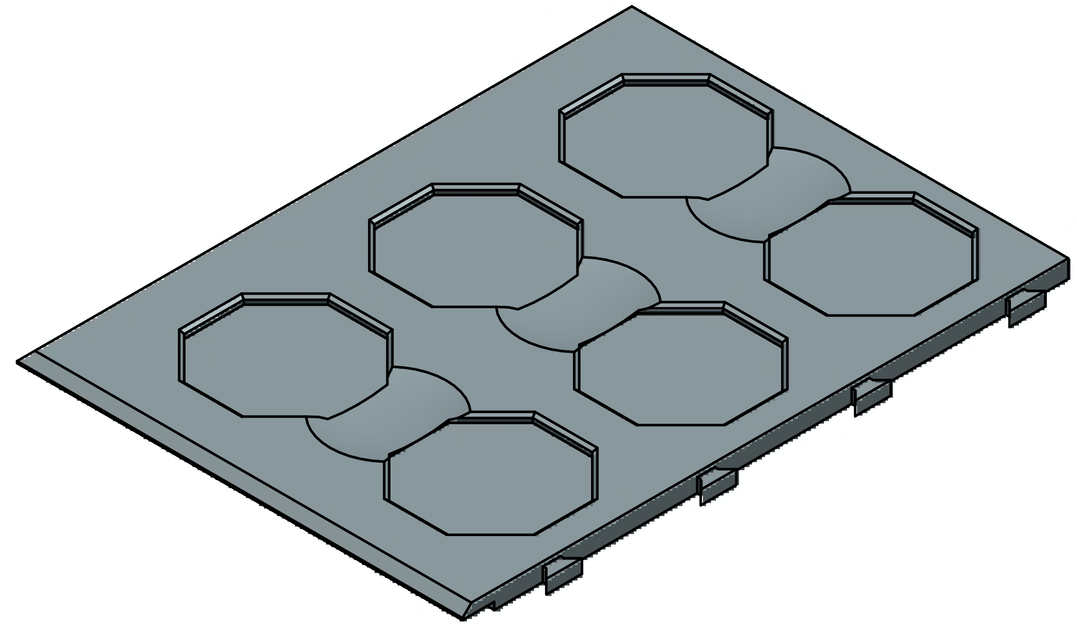




DETAIL A
SCALE 2:1



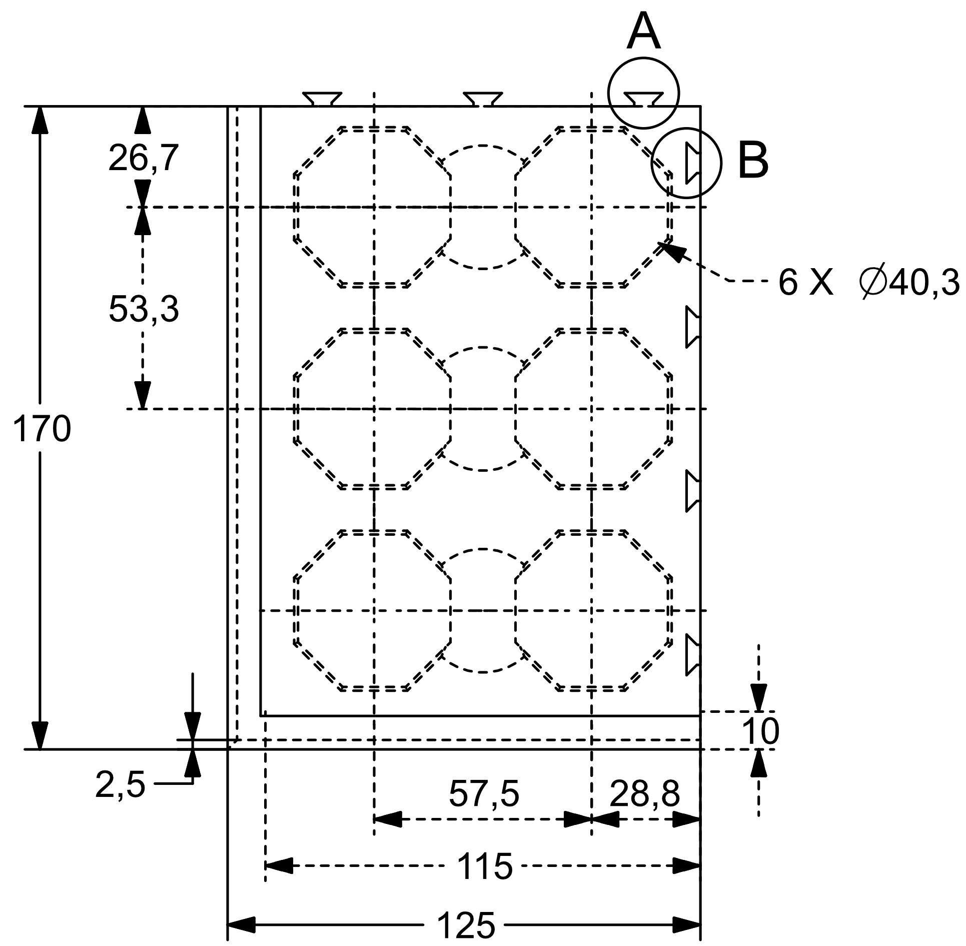
DETAIL B
SCALE 2:1

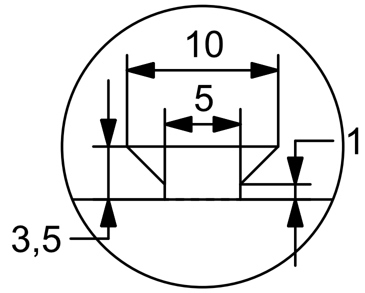


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	ABS PLASTIC 2 REQD	PIETER MARX	29703662	MR

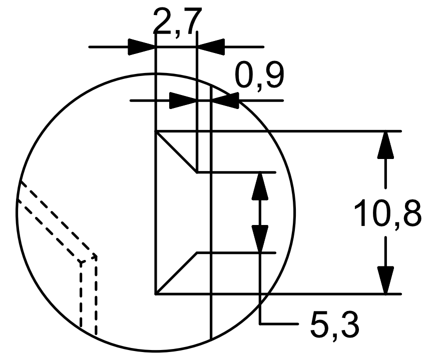
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	071-Reloading-Station-Q1_V1	SHEET 71 OF 93

A3

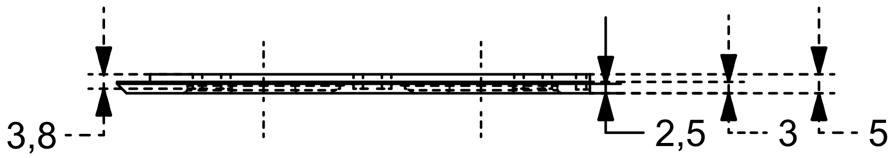


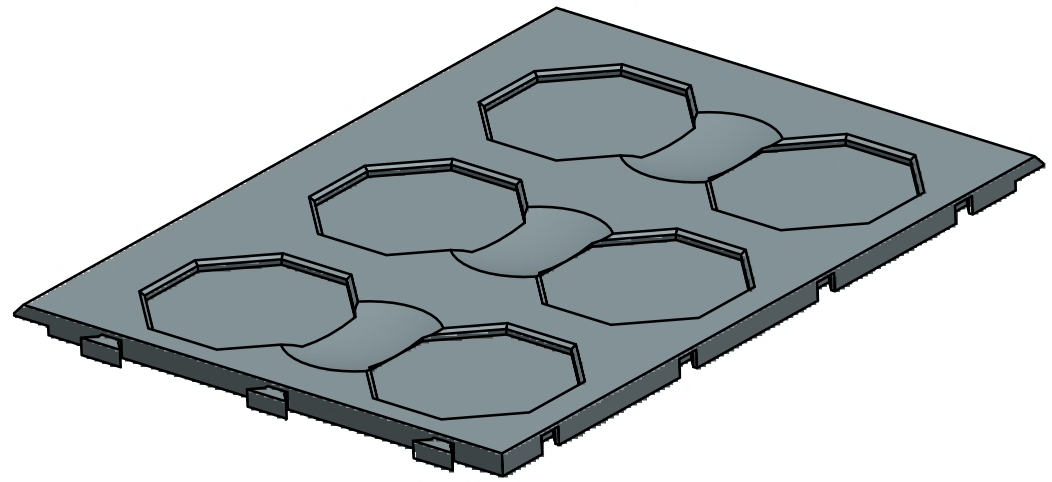


DETAIL A
SCALE 2:1



DETAIL B
SCALE 2:1

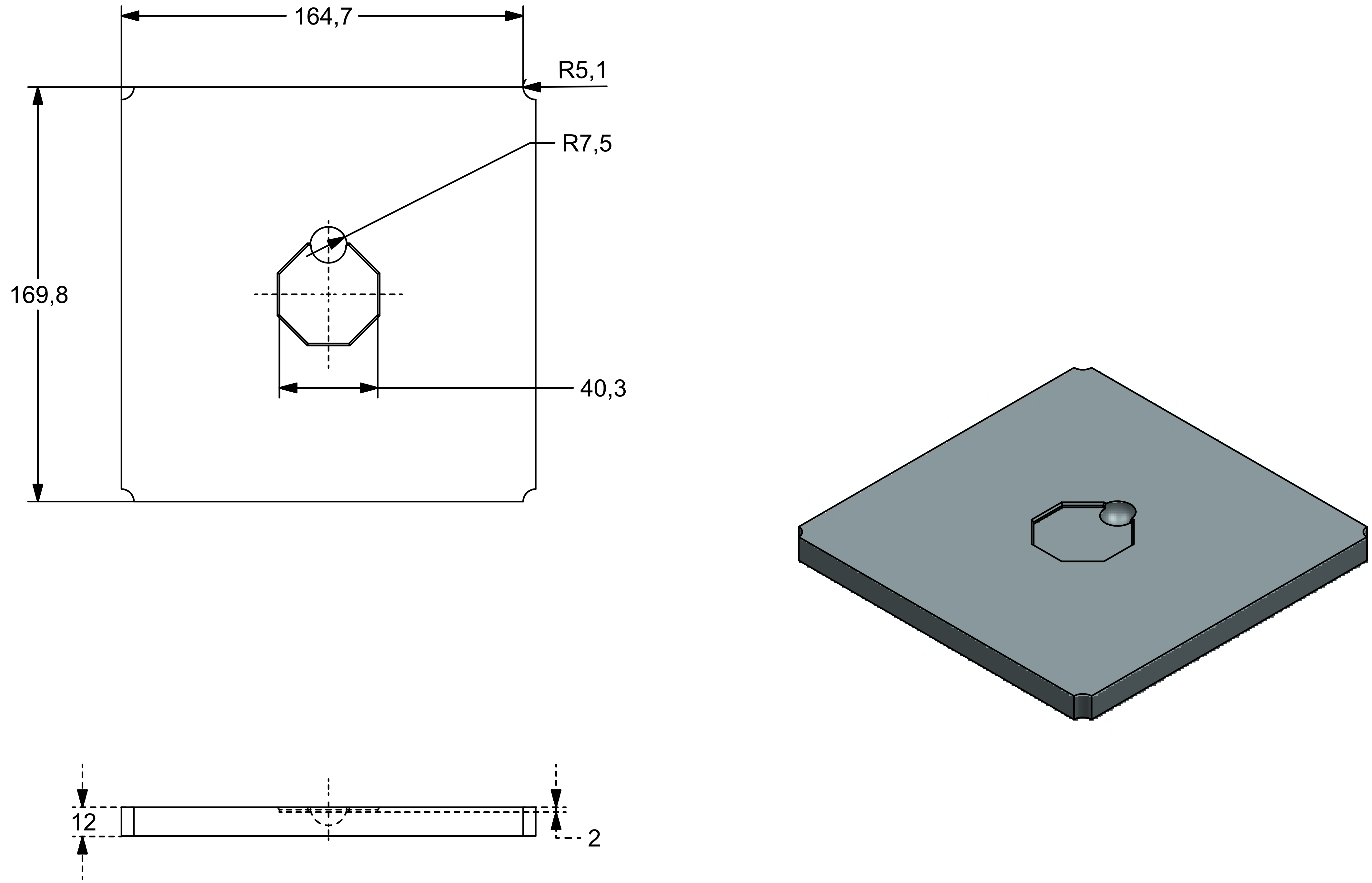




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	ABS PLASTIC 2 REQD	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	072-Reloading-Station-Q2_V1	SHEET 72 OF 93

A3



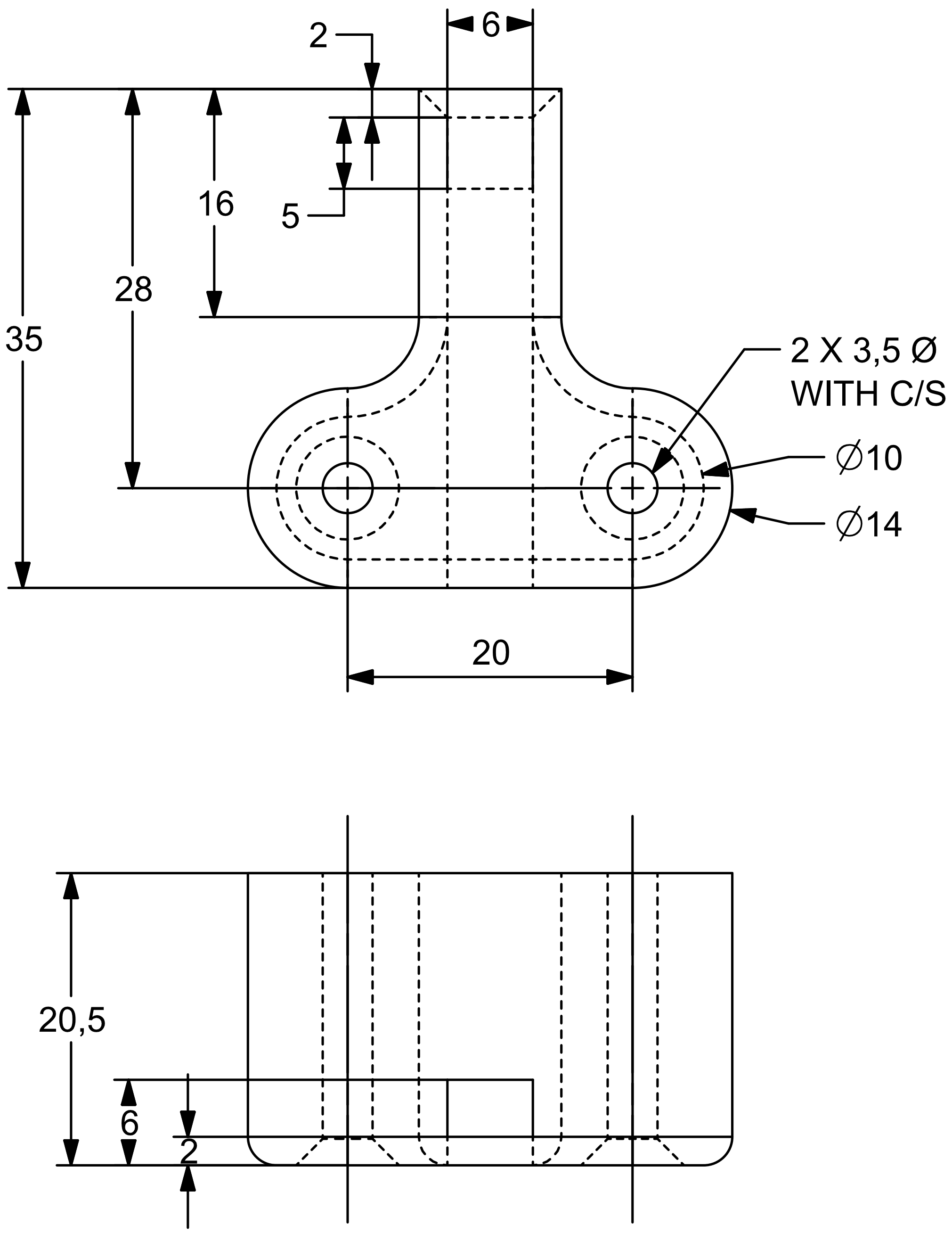
FAKULTEIT INGENIEURSWESE

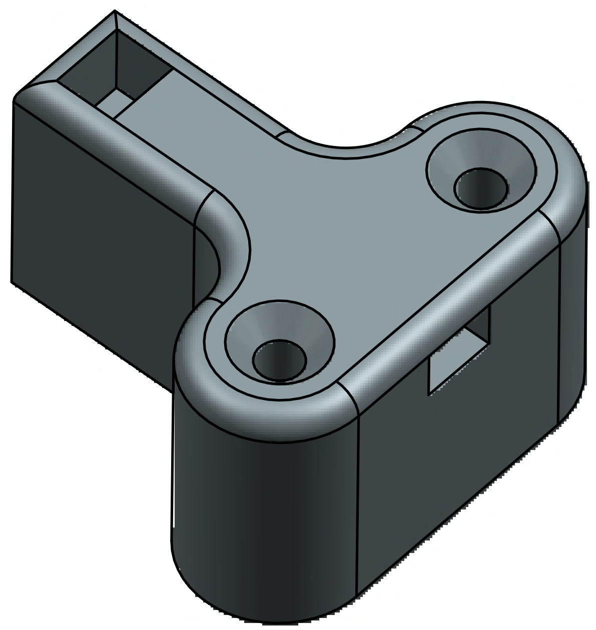
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	073-Engraving-Station-Cavity_V1	SHEET 73 OF 93

A3

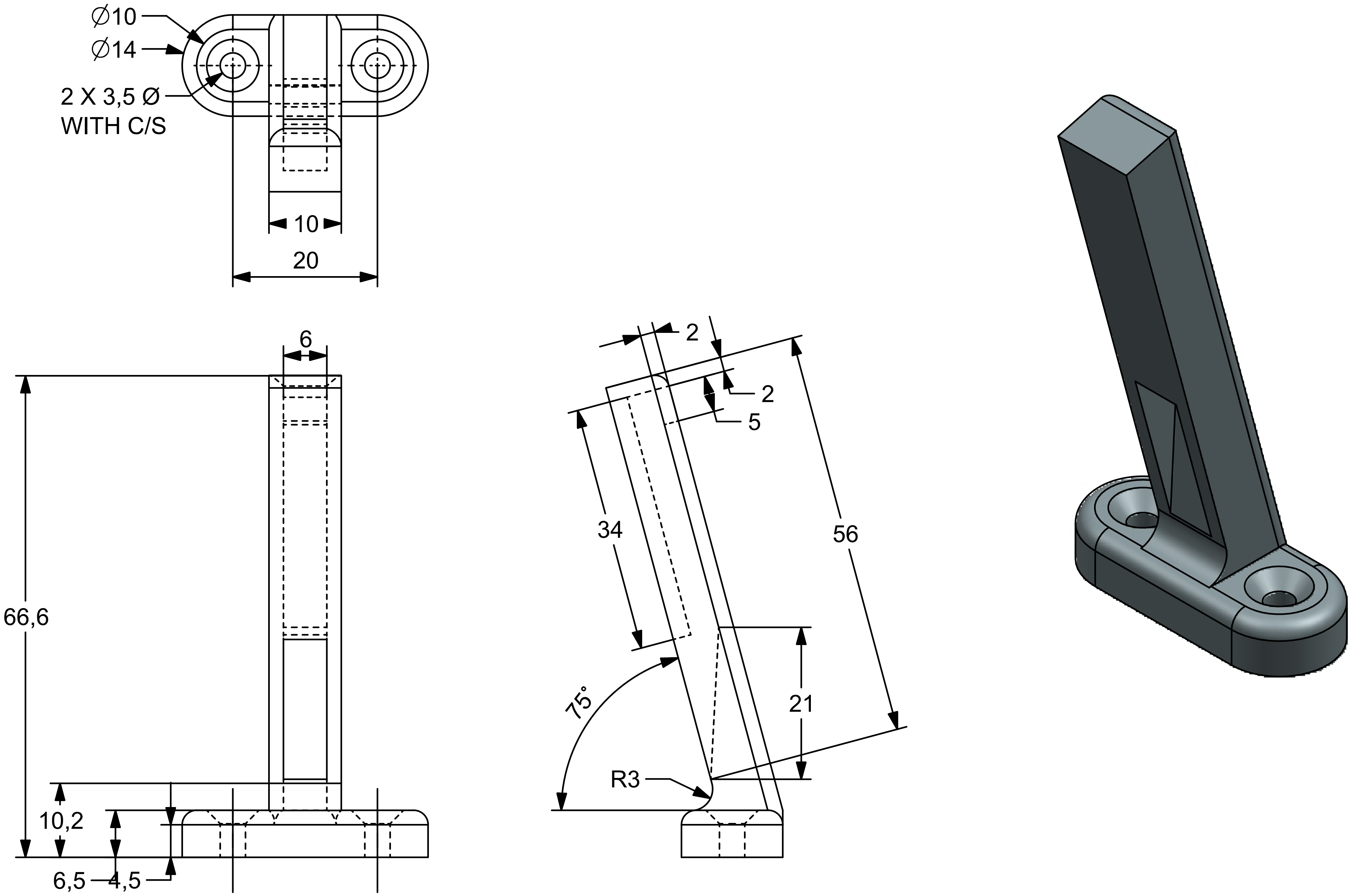




FAKULTEIT INGENIEURSWESE	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	074-Hall-Effect-Sensor-Bracket-Arm-1_V1	SHEET 74 OF 93

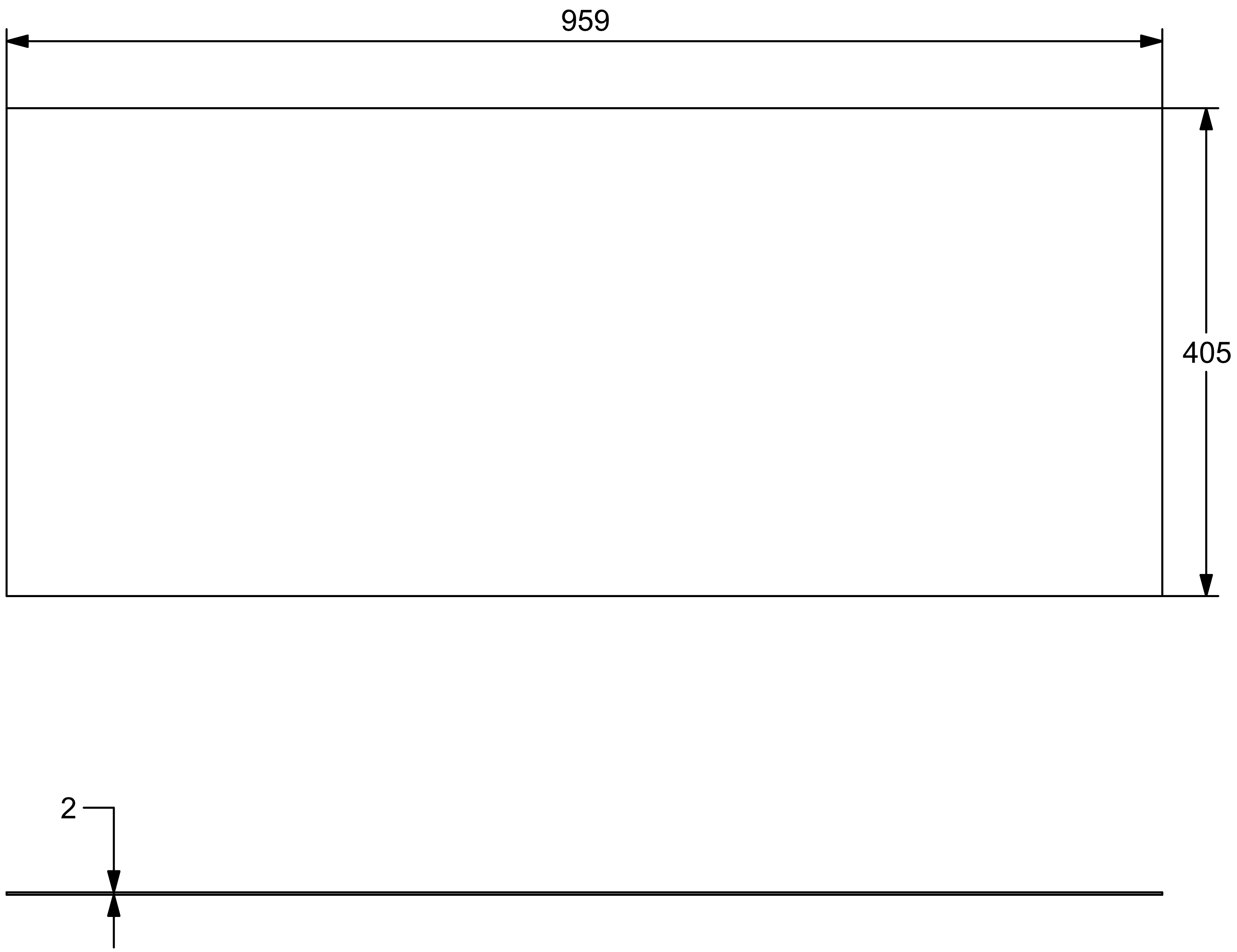
A3

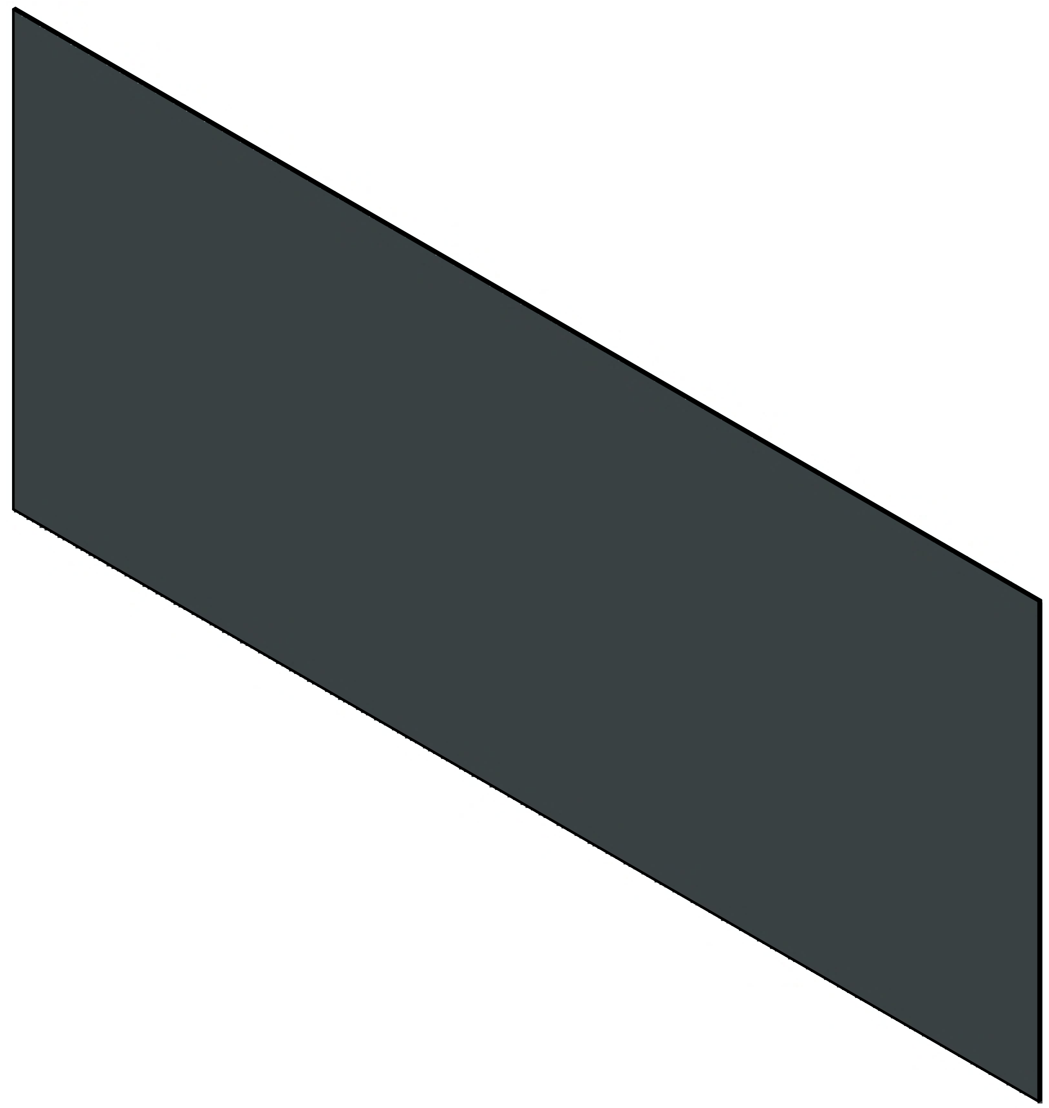


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	26/08/2020	SCALE 1:1	075-Hall-Effect-Sensor-Bracket-Arm-2_V1	SHEET 75 OF 93

A3

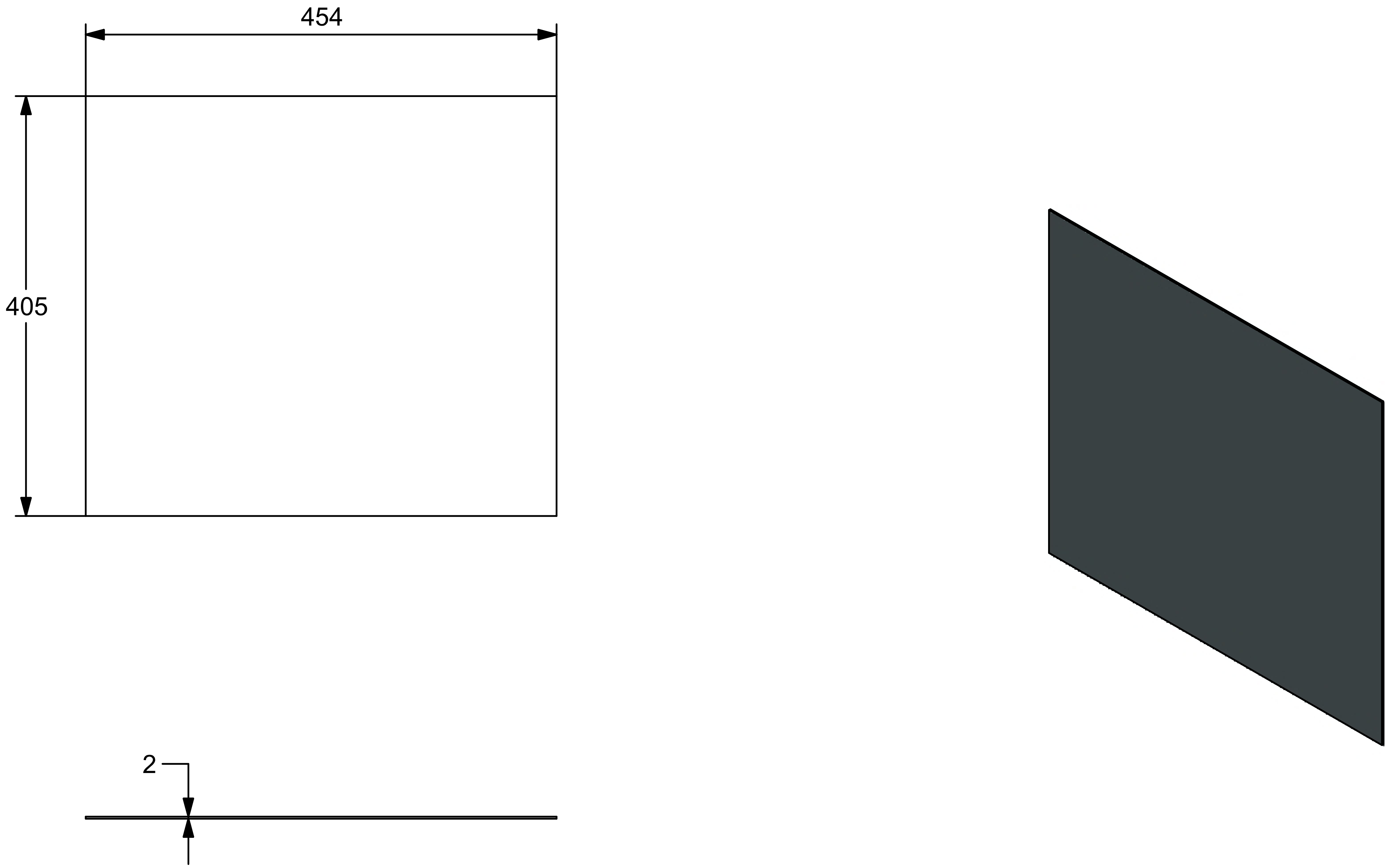




MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL	
2MM ACRYLIC	PIETER MARX	29703662	MR	
ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	076-Acrylic-Enclosure-Panel-1_V 1	SHEET 76 OF 93

FAKULTEIT INGENIEURSWESE
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

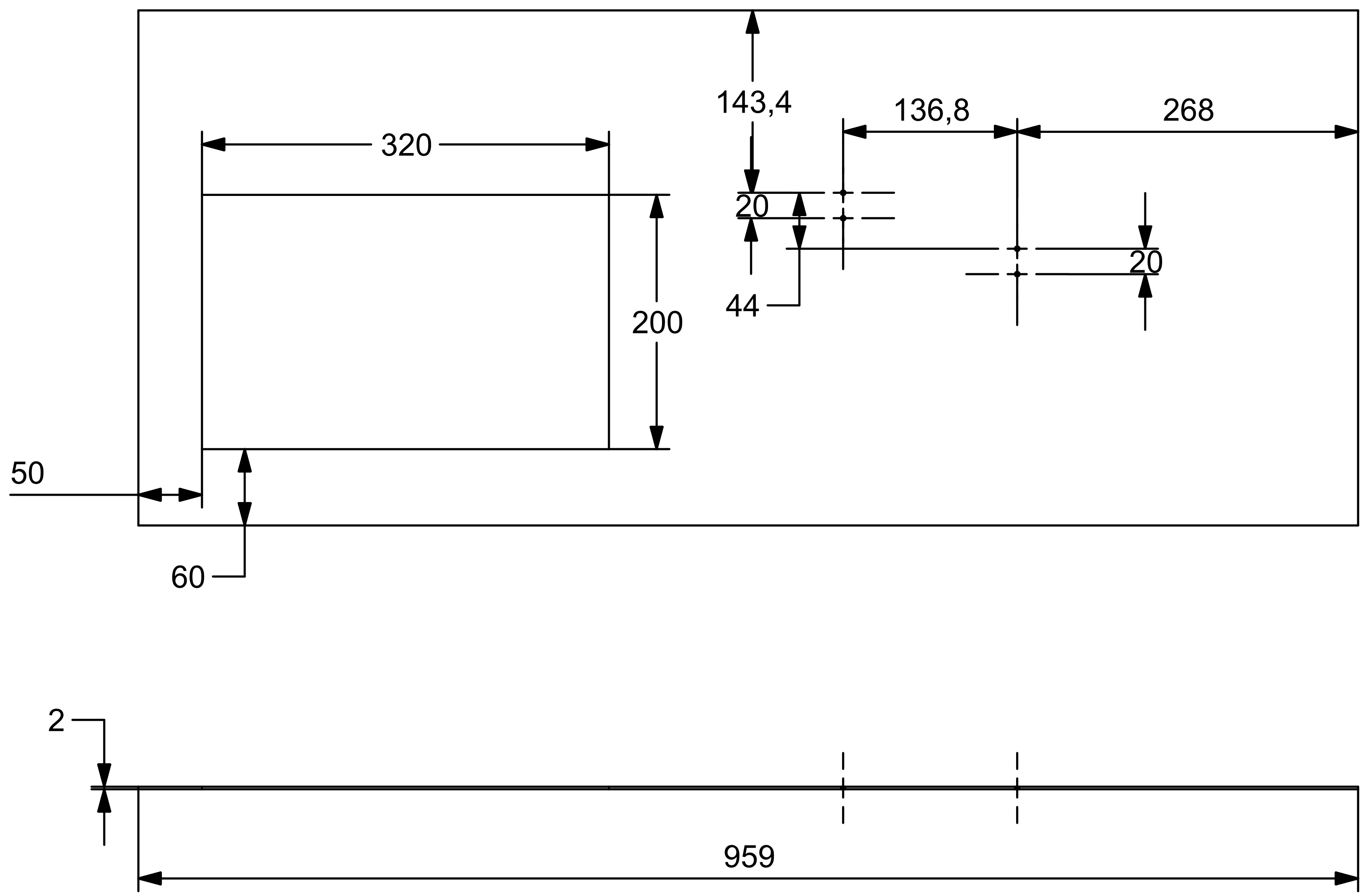
A3

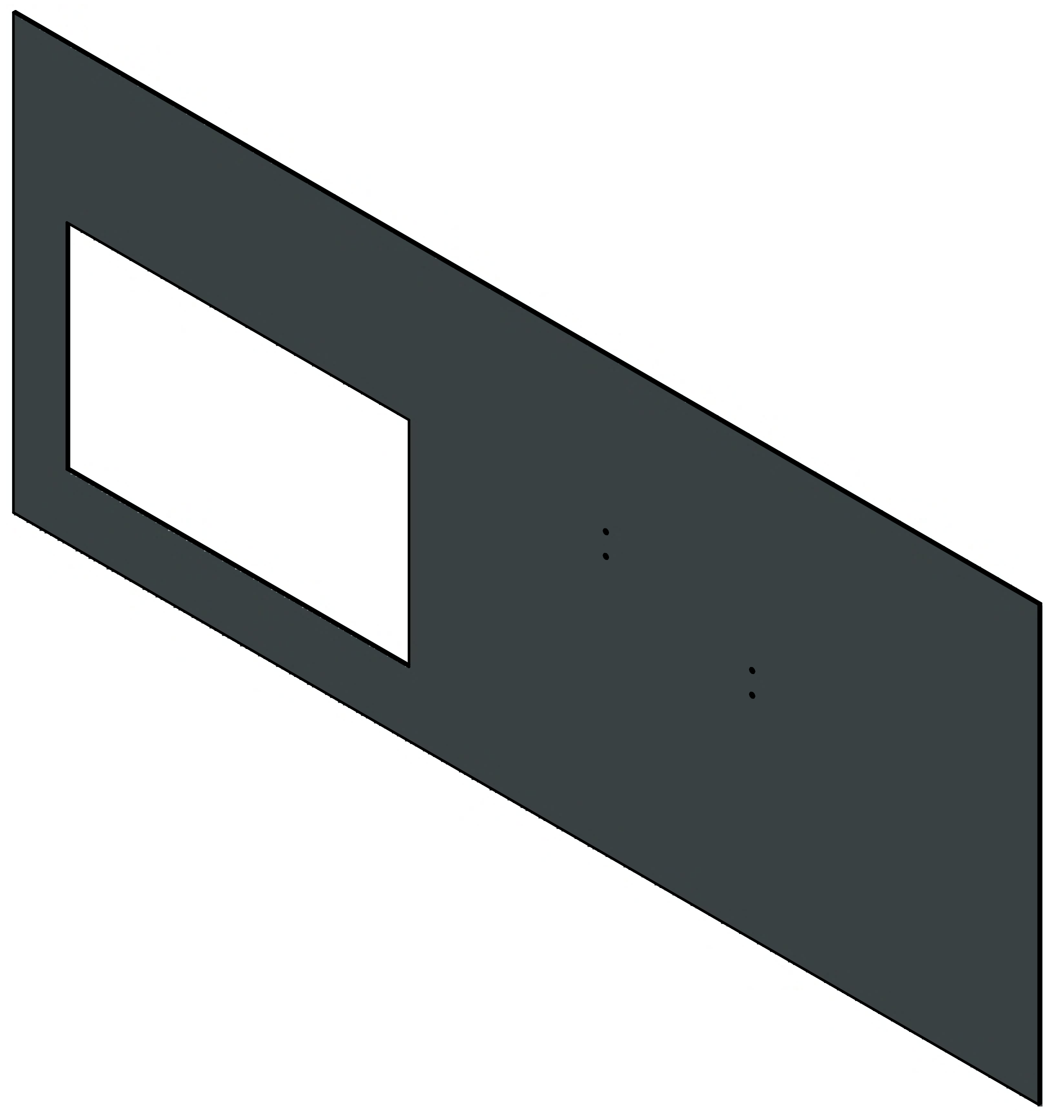


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 2MM ACRYLIC 2 REQD	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	077-Acrylic-Enclosure-Panel-2_V 1	SHEET 77 OF 93

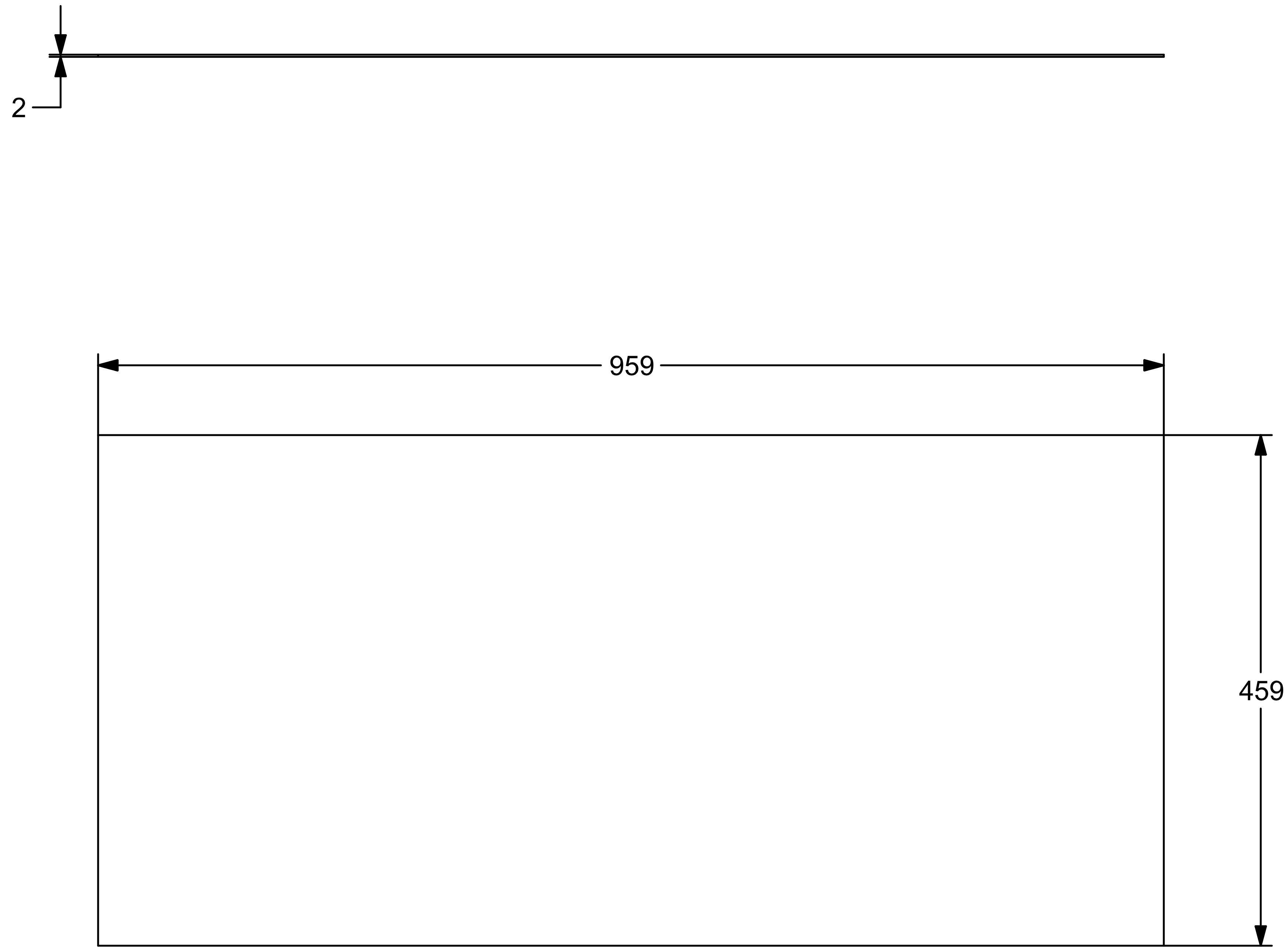
A3

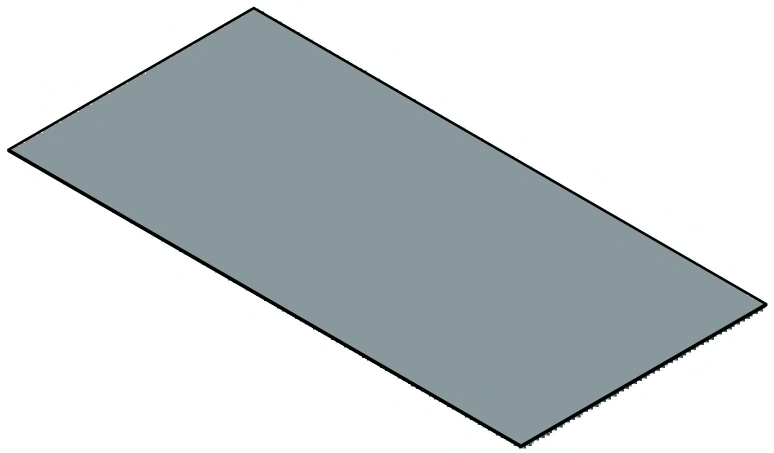




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL 2 MM ACRYLIC	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 28/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 078-Acrylic-Enclosure-Panel-3_V1	BLADSY/ SHEET SHEET 78 OF 93

A3

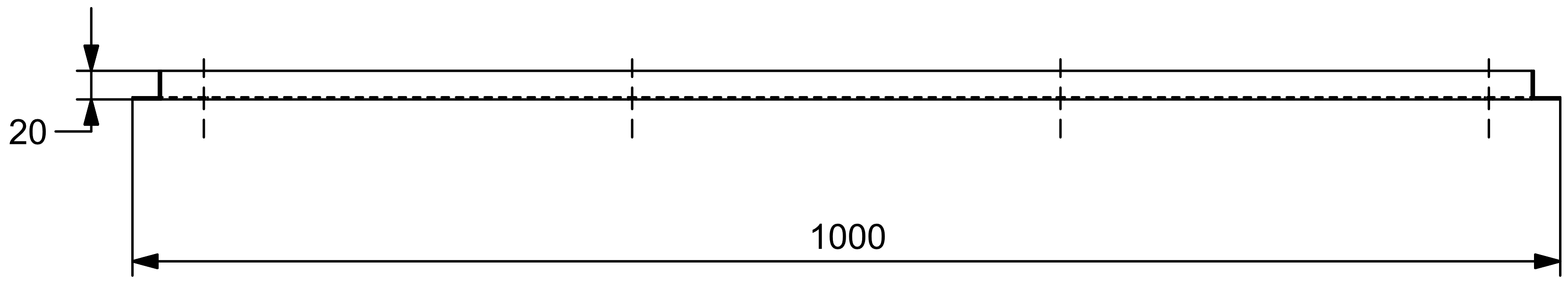


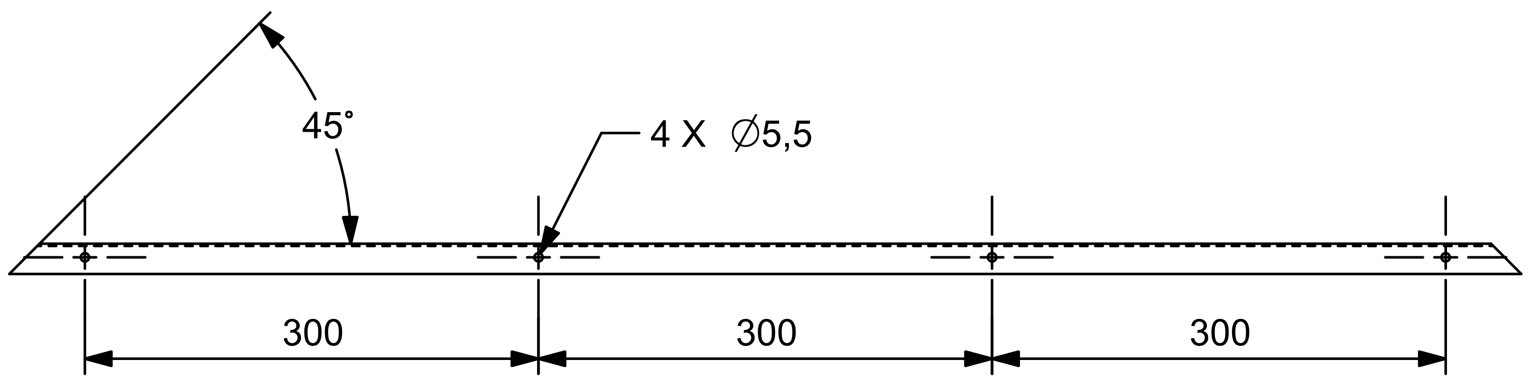


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
		2 MM ACRYLIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	079-Acrylic-Enclosure-Panel-4_V 1	SHEET 79 OF 93

A3

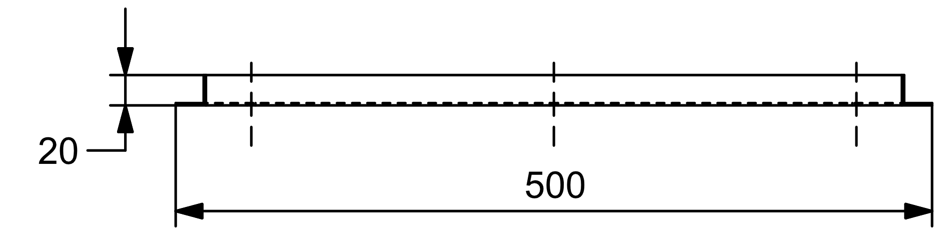


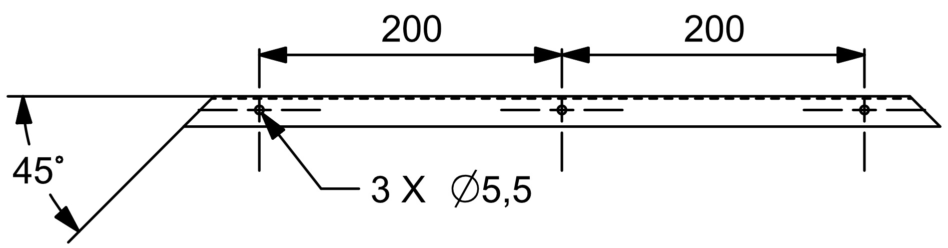


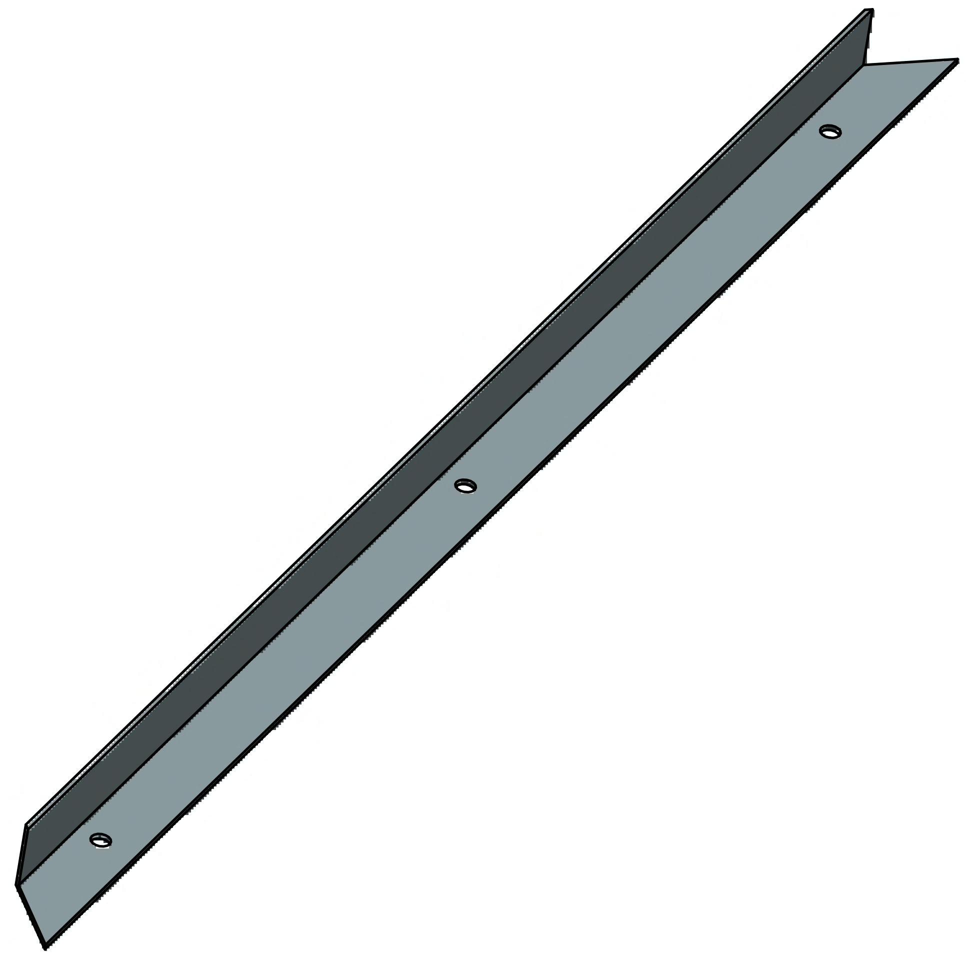
FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	20 MM ANGLE IRON	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	080-Angle-Iron-1_V1	SHEET 80 OF 93

A3

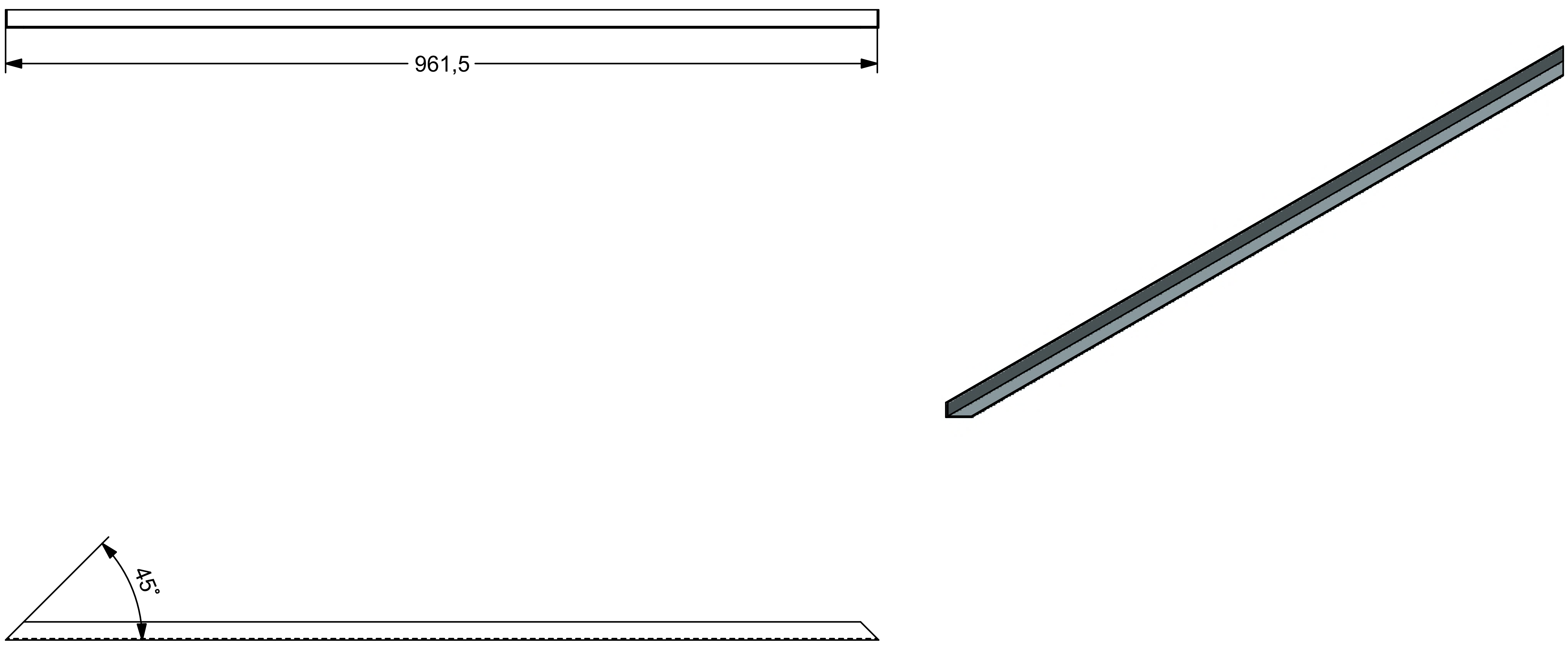






FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** 20 MM ANGLE IRON 2 REQD	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	**DATUM/DATE** 28/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 081-Angle-Iron-2_V1	**BLADSY/ SHEET** SHEET 81 OF 93

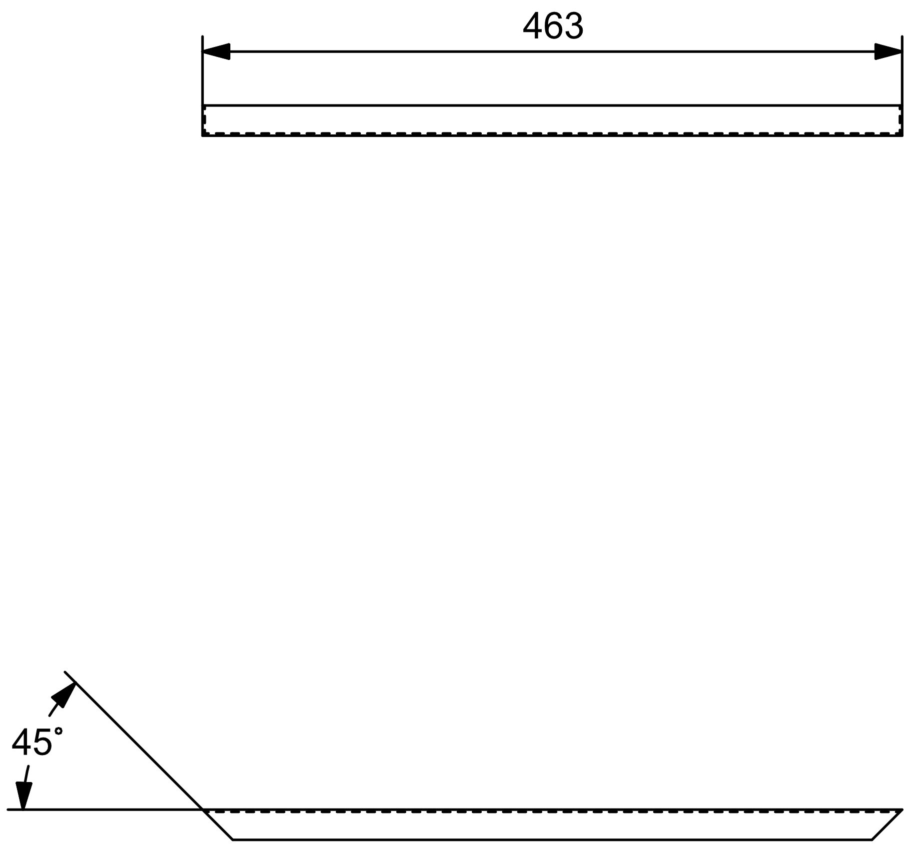
A3

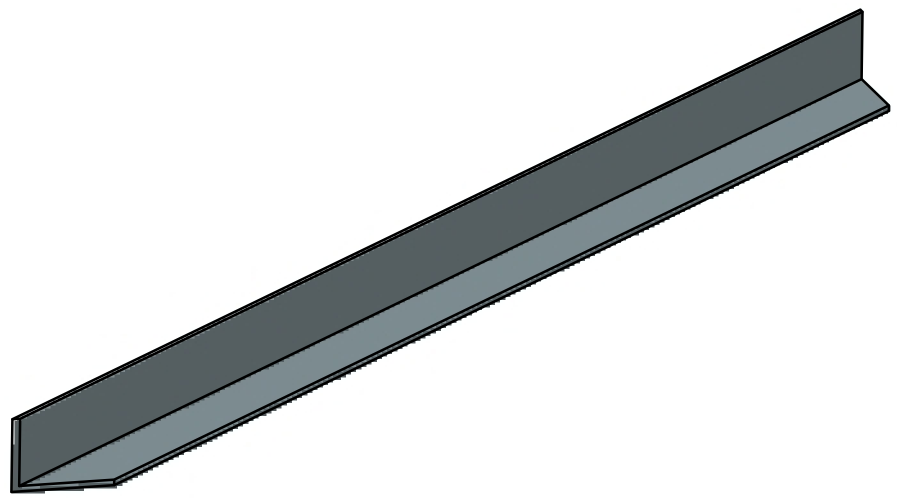


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	20 MM ANGLE IRON 2 REQD	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	082-Angle-Iron-3_V1	SHEET 82 OF 93

A3





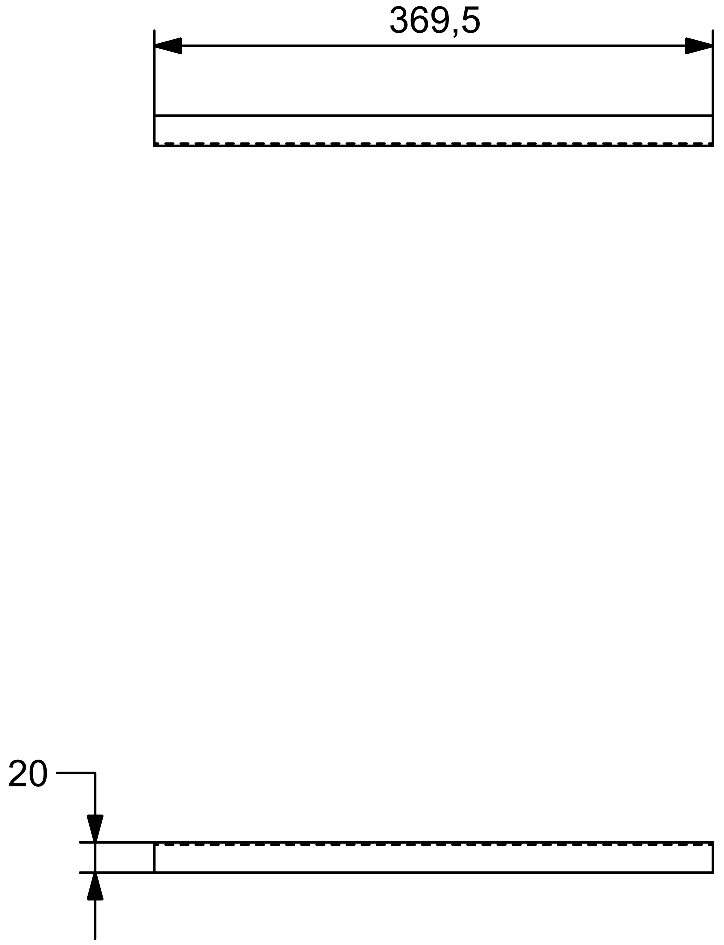
FAKULTEIT INGENIEURSWESE

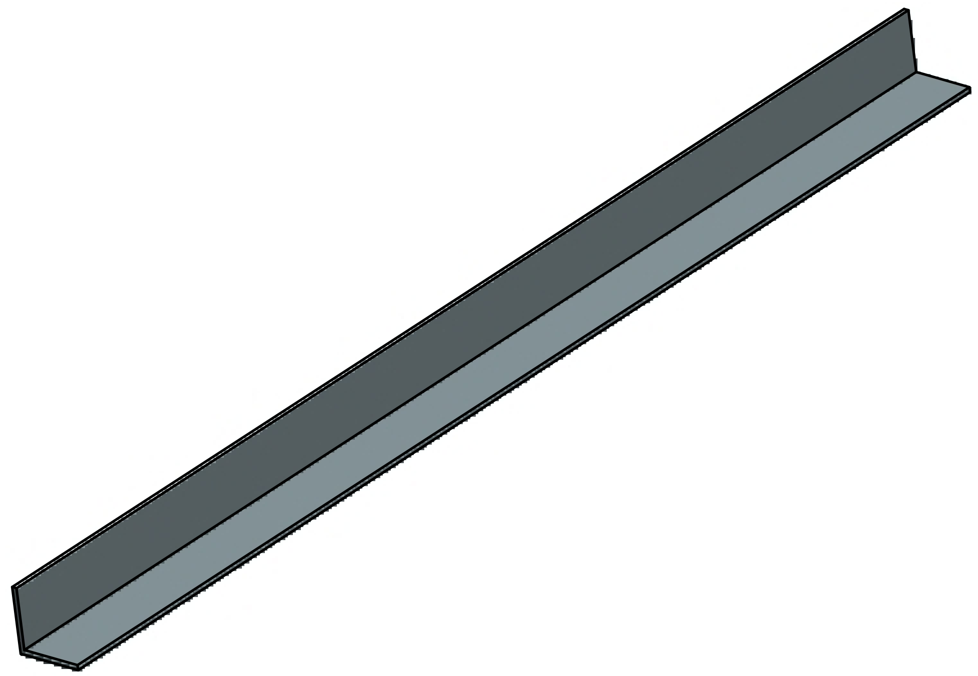
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
20 MM ANGLE IRON 2 REQD	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	083-Angle-Iron-4_V1	SHEET 83 OF 93

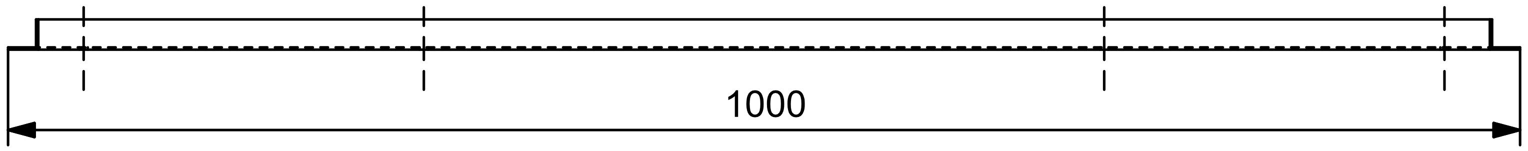
A3

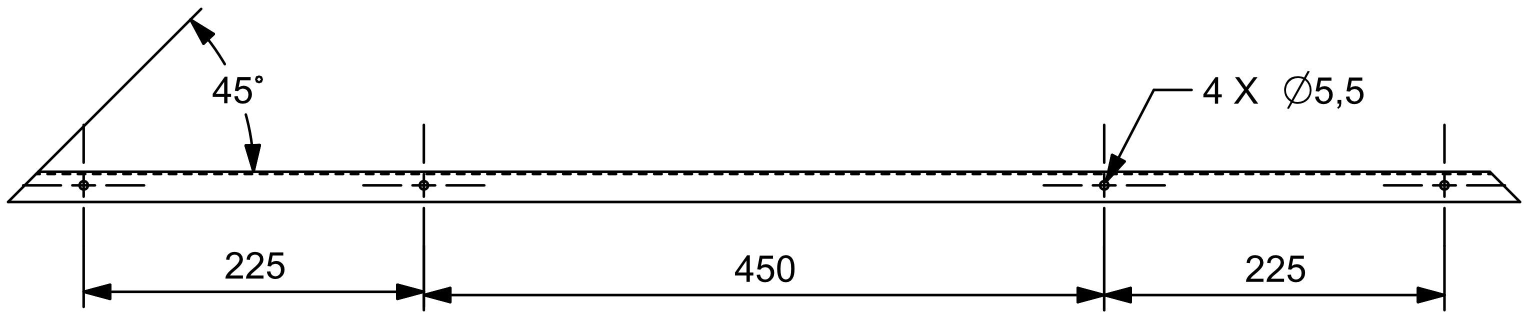


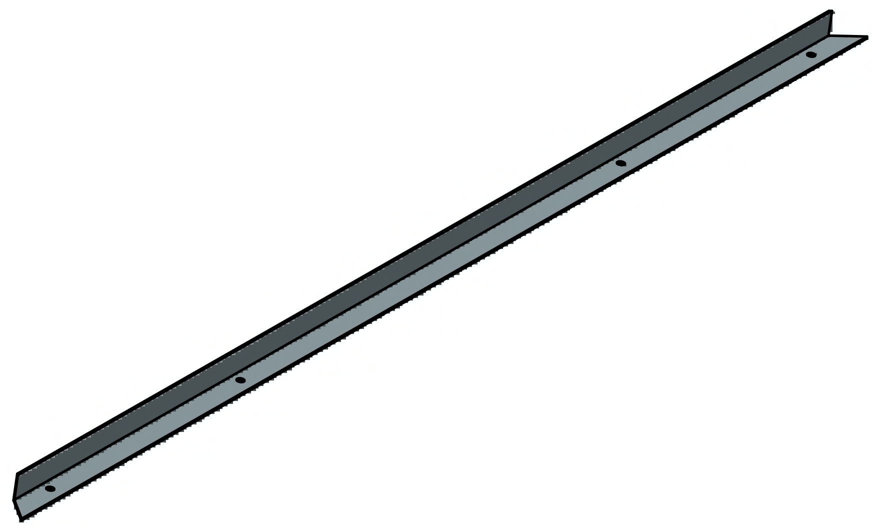


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** 20 MM ANGLE IRON 4 REQD	**NAAM/ NAME** PIETER MARX	**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR
ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	**DATUM/DATE** 28/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 084-Angle-Iron-5_V1	**BLADSY/ SHEET** SHEET 84 OF 93

A3

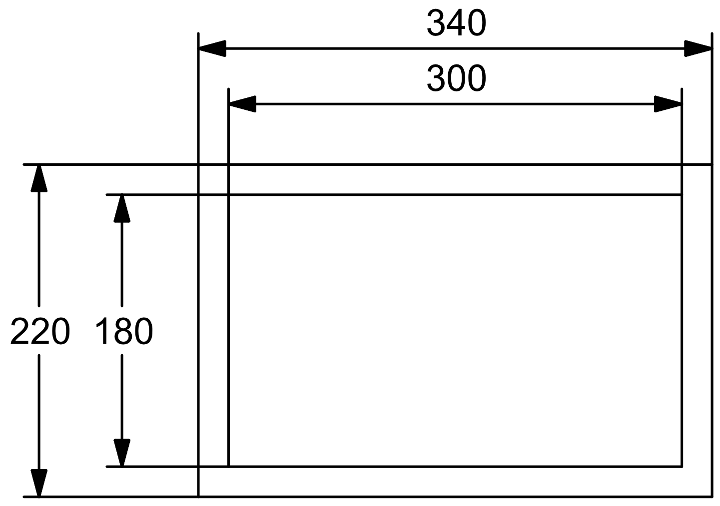


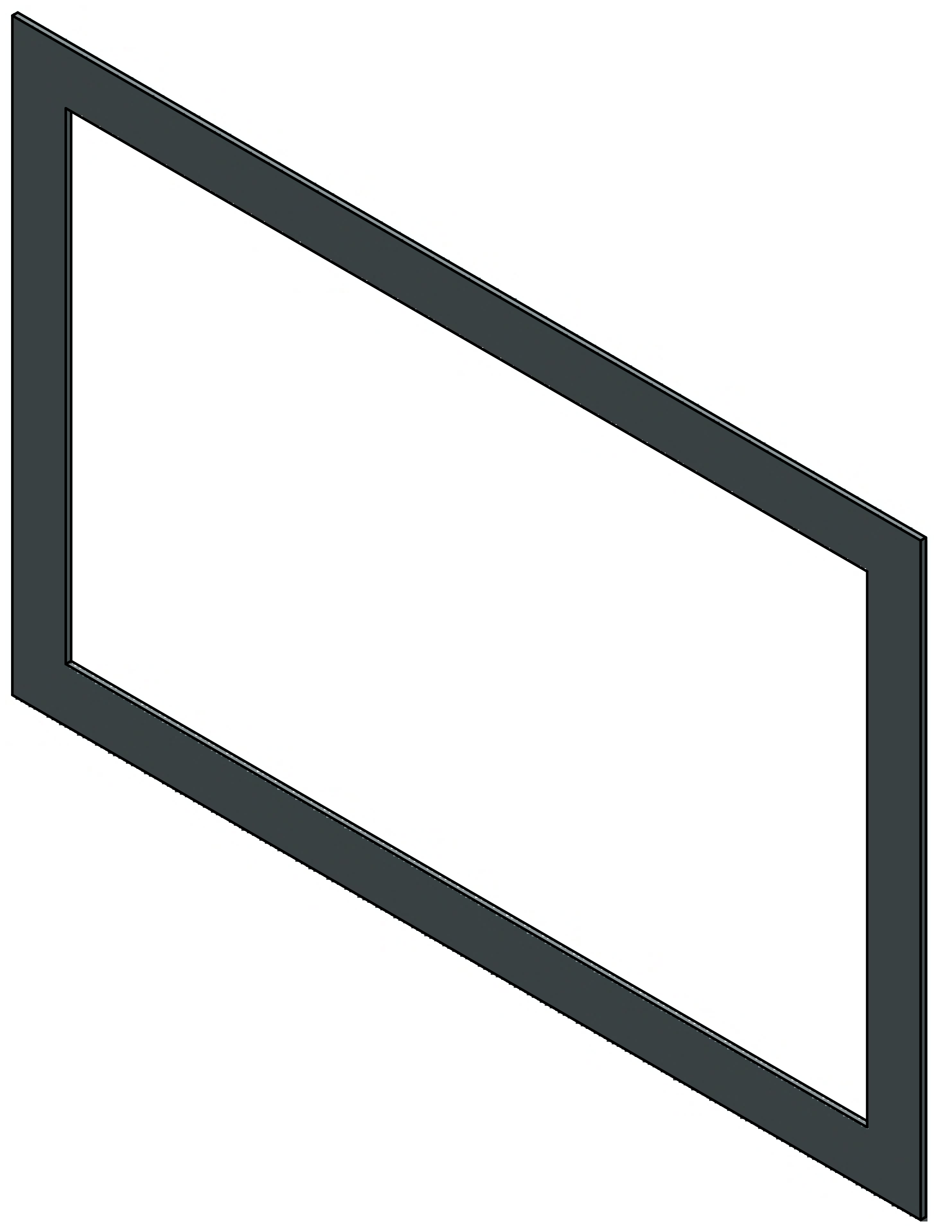




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	**MATERIAAL/MATERIAL** 20 MM ANGLE IRON	**NAAM/ NAME** PIETER MARX		**STUDENTNOMMER/ STUDENT NUMBER** 29703662	**TITEL/ TITEL** MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	**DATUM/DATE** 28/08/2020	**SKAAL/SCALE** SCALE 1:1	**TEKENINGNOMMER/ DRAWING NUMBER** 085-Angle-Iron-6_V1	**BLADSY/ SHEET** SHEET 85 OF 93

A3

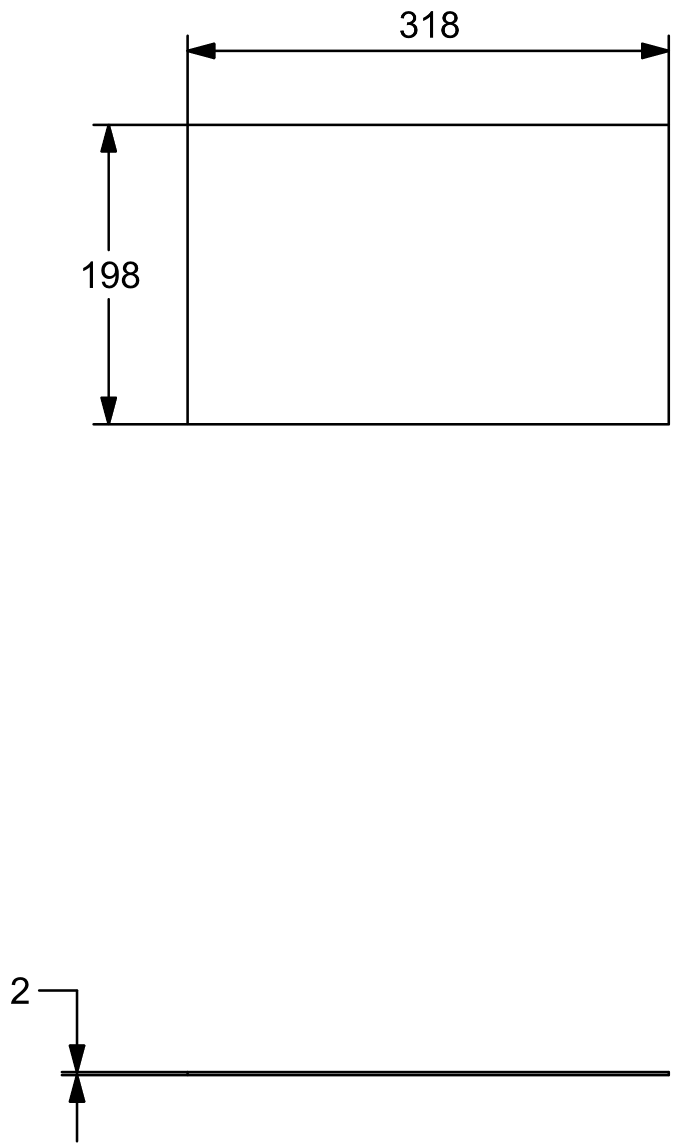




FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	2 MM ACRYLIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	086-Acrylic-Door-Frame_V1	SHEET 86 OF 93

A3



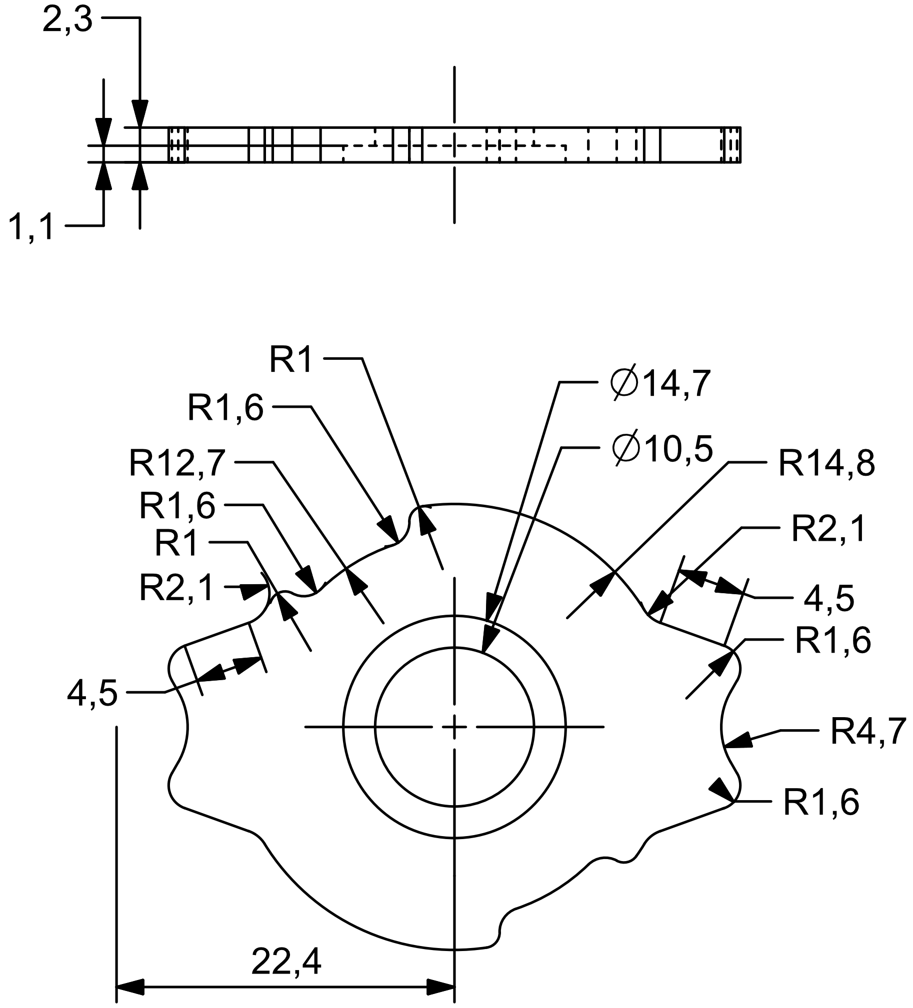
FAKULTEIT INGENIEURSWESE

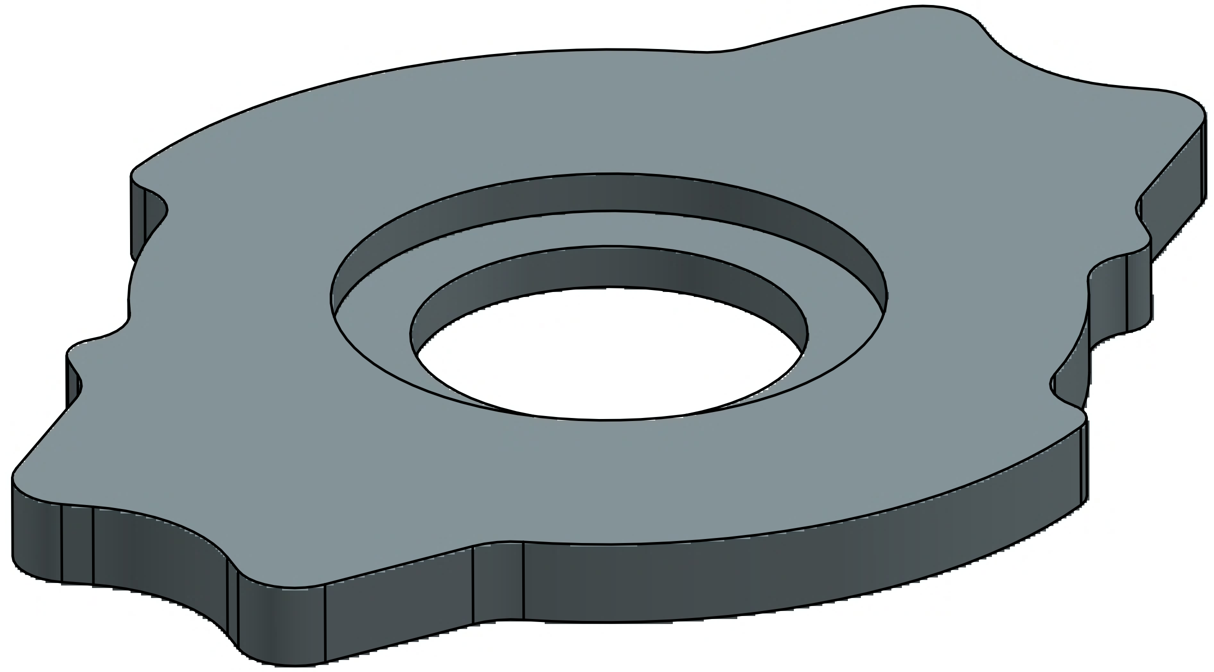
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
2 MM ACRYLIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	087-Acrylic-Door_V1	SHEET 87 OF 93

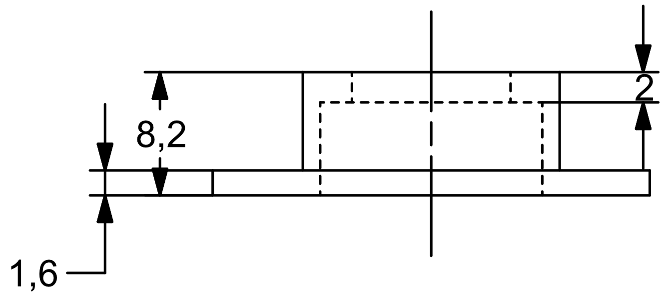
A3

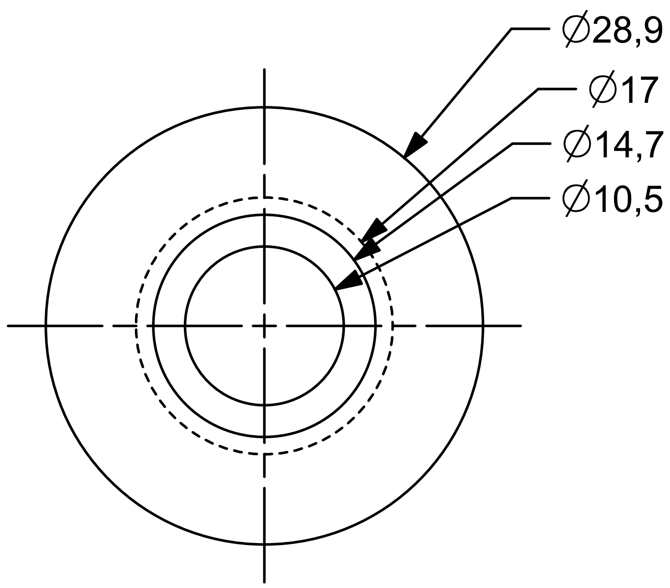


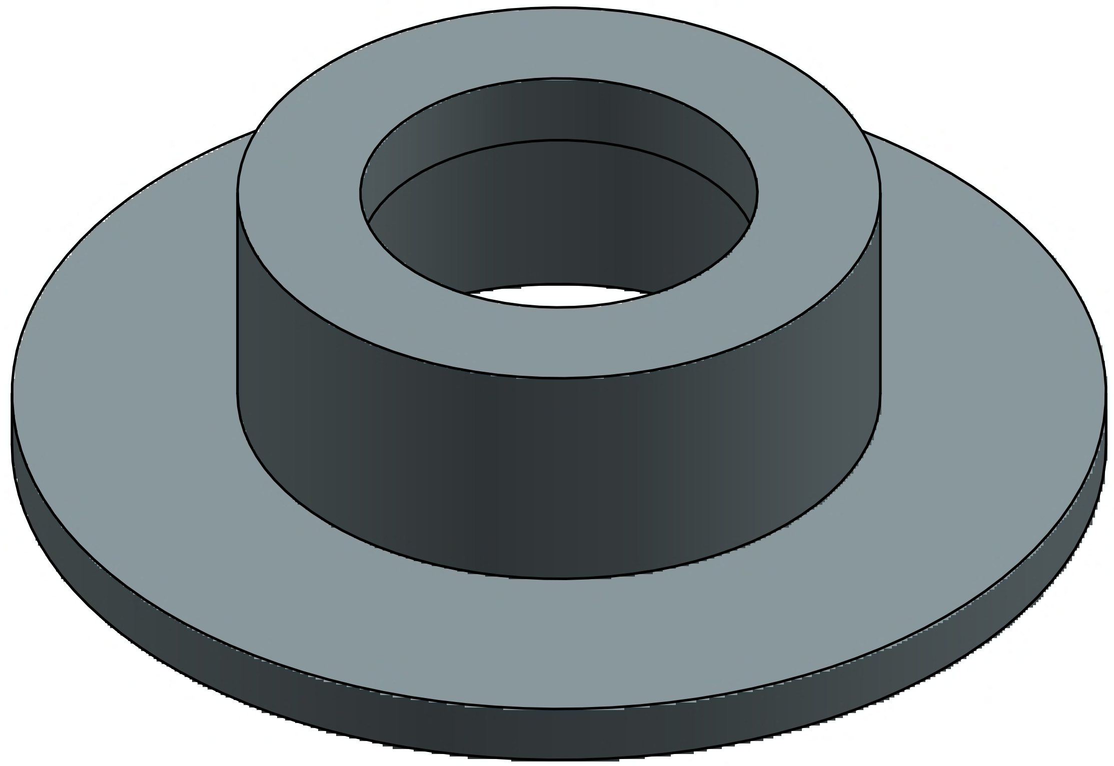


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL ABS PLASTIC	NAAM/ NAME PIETER MARX		STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
	ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 28/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 088-Bearing-Support-Top_V1	BLADSY/ SHEET SHEET 88 OF 93

A3







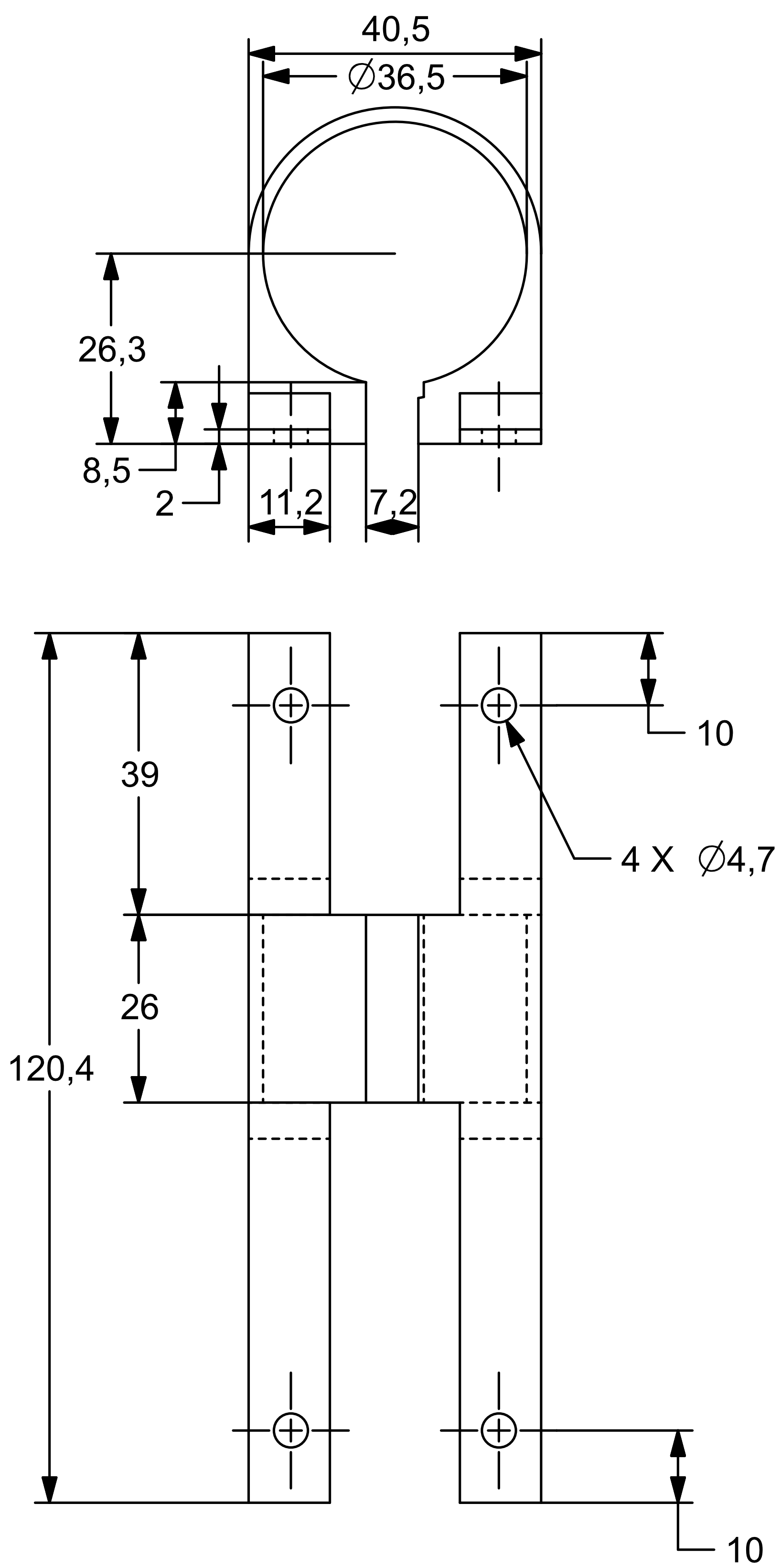
FAKULTEIT INGENIEURSWESE

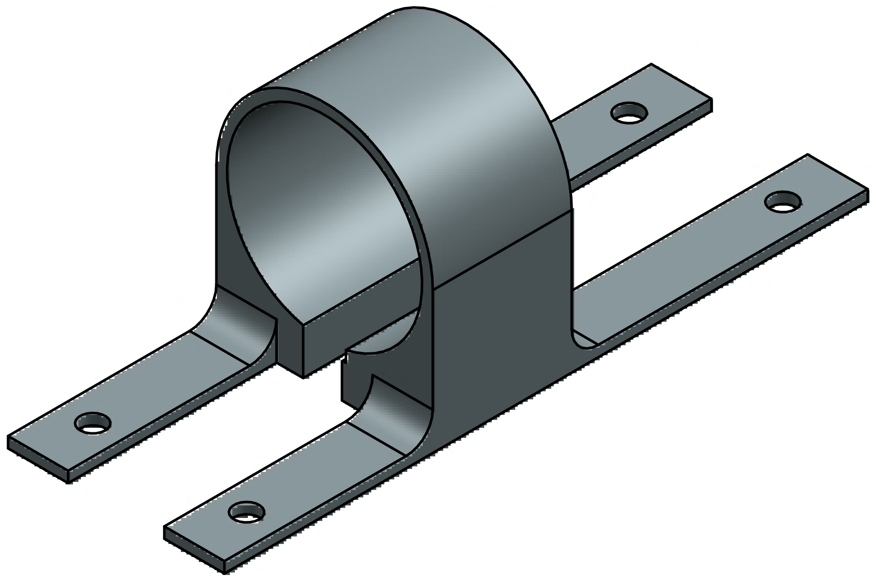
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
ABS PLASTIC	PIEWTER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	089-Bearing-Suppot-Bottom_V1	SHEET 89 OF 93

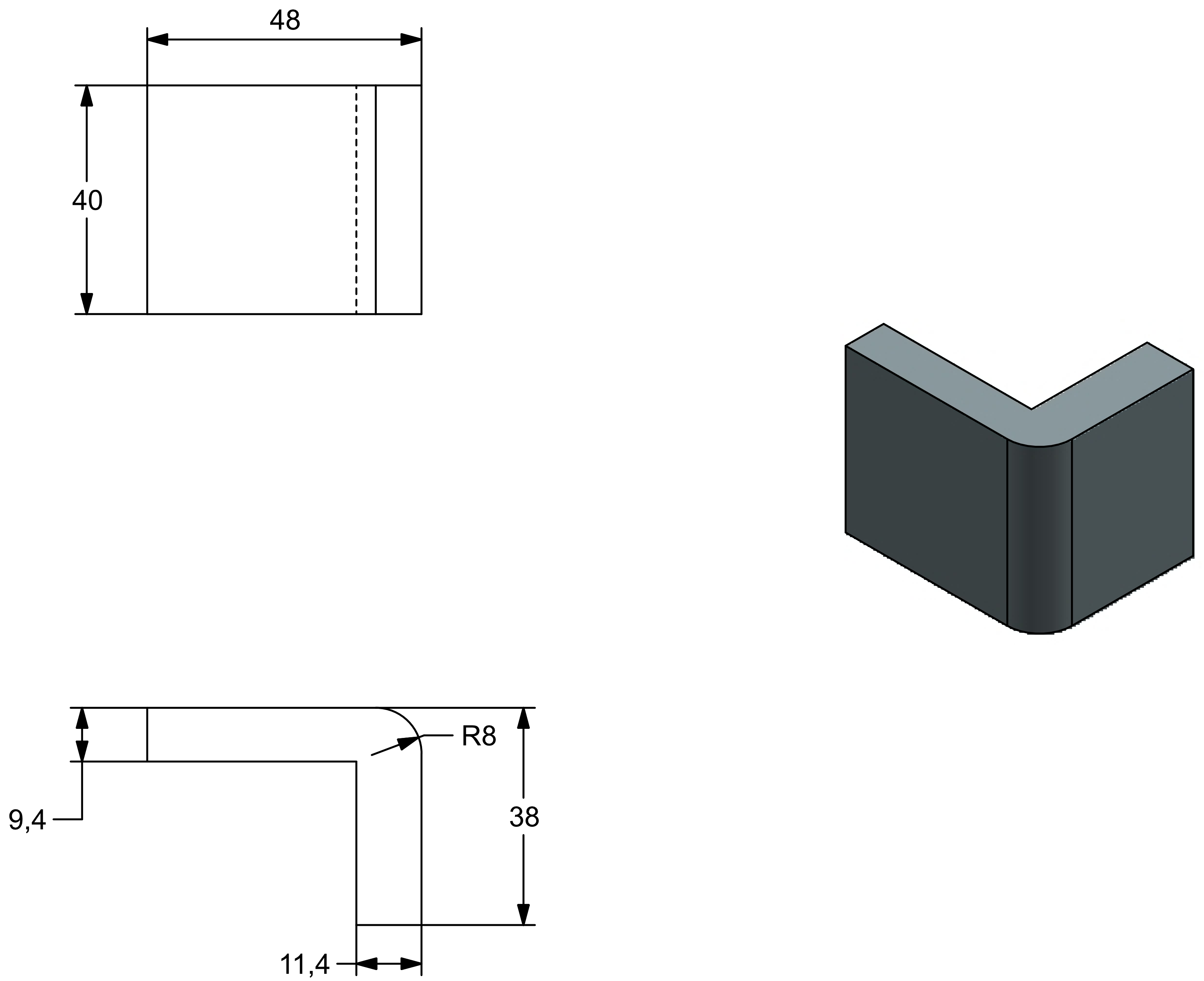
A3





FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS		MATERIAAL/MATERIAL ABS PLASTIC	NAAM/ NAME PIETER MARX	STUDENTNOMMER/ STUDENT NUMBER 29703662	TITEL/ TITEL MR
		ADDISIONELE NOTAS/ ADDITIONAL NOTES CLIENT WILL PROVIDE AND MACHINE THE PART	DATUM/DATE 28/08/2020	SKAAL/SCALE SCALE 1:1	TEKENINGNOMMER/ DRAWING NUMBER 090-Vacuum-Pump-Bracket_V1
					BLADSY/ SHEET SHEET 90 OF 93

A3



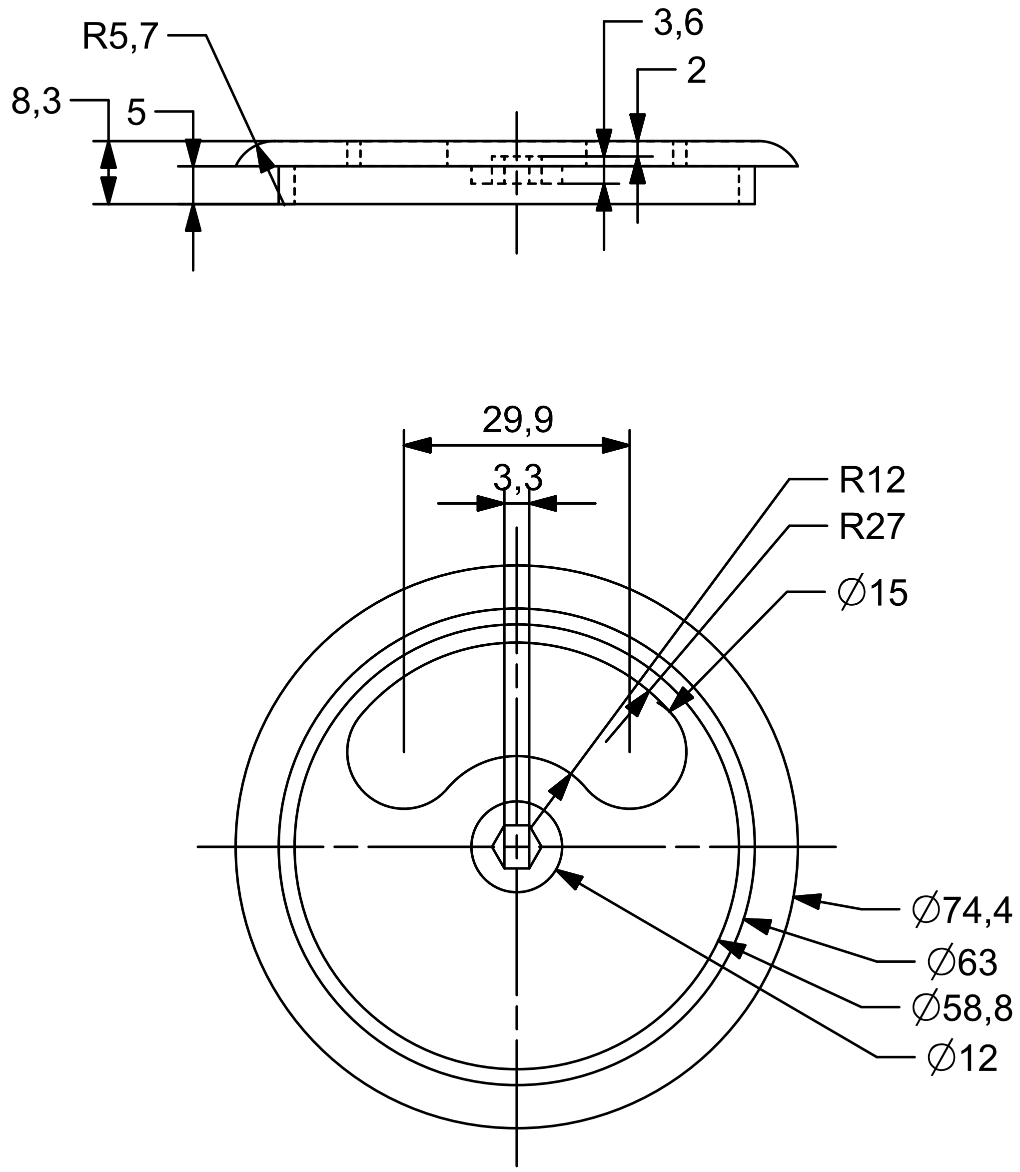
FAKULTEIT INGENIEURSWESE

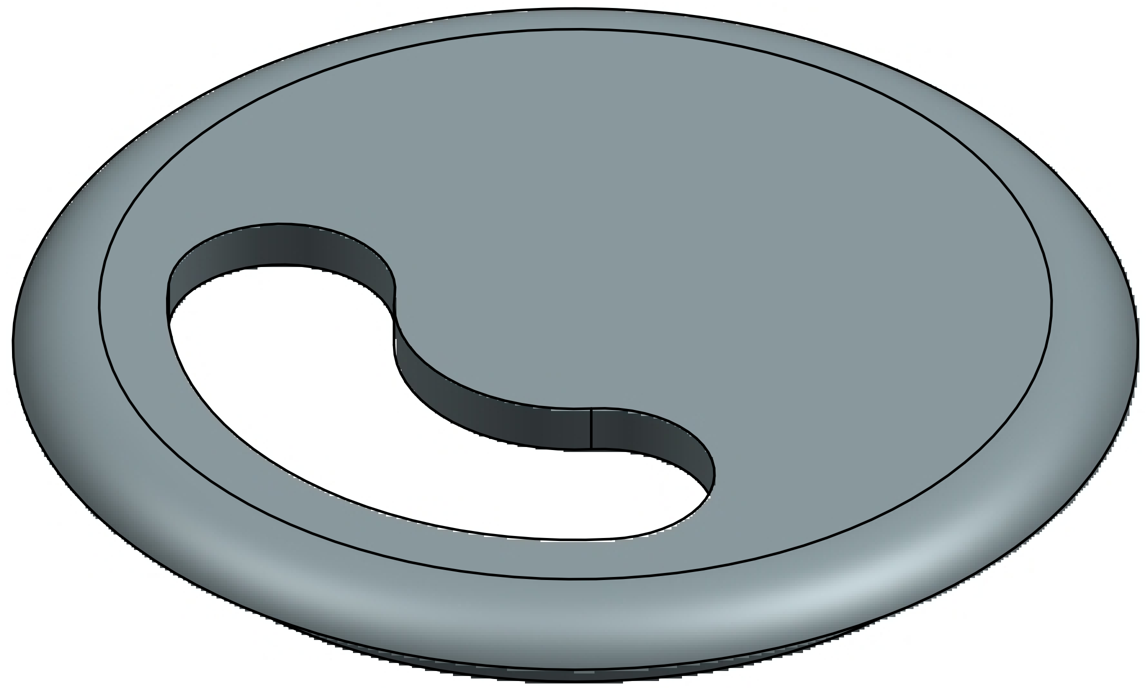
NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOMKAMPUS

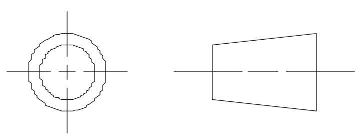
MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	091-Vacuum-Pump-Bracket-Support_V1	SHEET 91 OF 93

A3



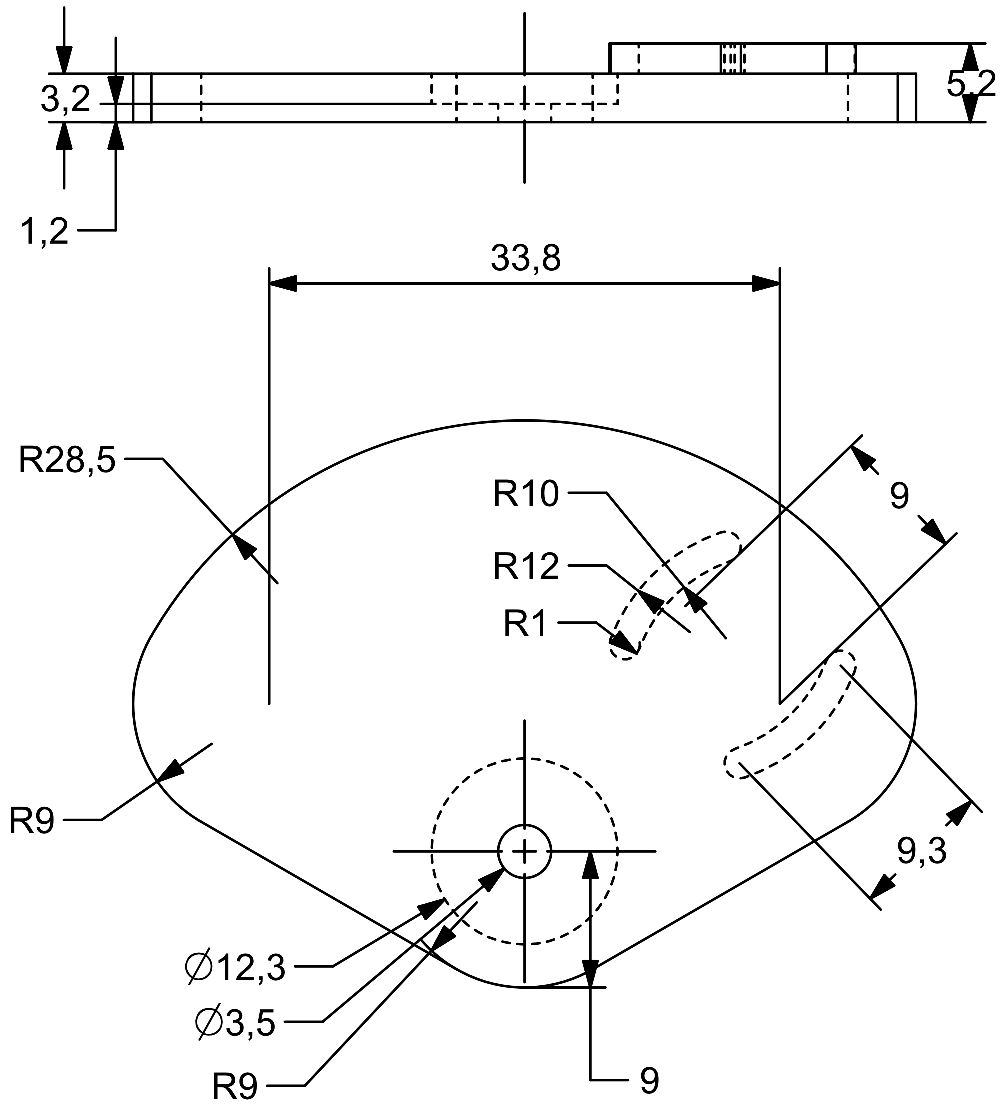


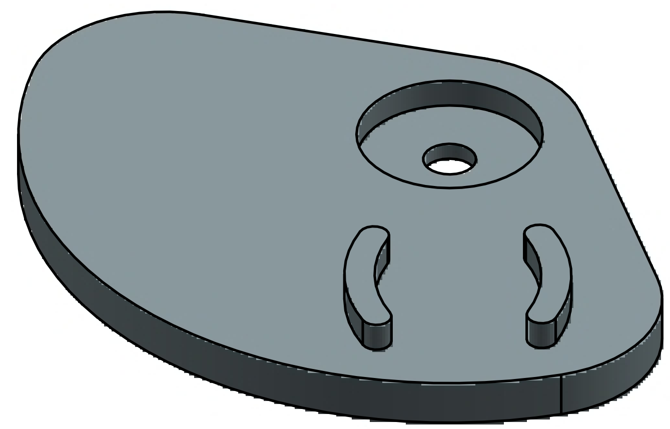


FAKULTEIT INGENIEURSWESE NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
	ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	092-Grommet-Face_V1	SHEET 92 OF 93

A3





FAKULTEIT INGENIEURSWESE	MATERIAAL/MATERIAL	NAAM/ NAME	STUDENTNOMMER/ STUDENT NUMBER	TITEL/ TITEL
NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT POTCHEFSTROOMKAMPUS	ABS PLASTIC	PIETER MARX	29703662	MR

ADDISIONELE NOTAS/ ADDITIONAL NOTES	DATUM/DATE	SKAAL/SCALE	TEKENINGNOMMER/ DRAWING NUMBER	BLADSY/ SHEET
CLIENT WILL PROVIDE AND MACHINE THE PART	28/08/2020	SCALE 1:1	093-Grommet-Slider_V1	SHEET 93 OF 93

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