4-DOF Robotic Arm For Industrial Automation

A Final Year Project Report

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ABSTRACT

This Project involves the design and development of a 4-DOF hybrid Kinematic Machine for industrial innovation. The key points about it are its light weight, high speed and high precision. This is achieved using lightweight high-performance materials like carbon fiber and aluminum to keep the inertia low and in turn making the motion more precise and faster. This arm is design to perform pick and place operation in process of packaging and motorcycle assembly.

The project starts with finalizing and fixing the design parameters. After that the manipulator is modeled on CAD software like SolidWorks. Finite Element Analyses is done to assess the arms material and structural integrity. After getting satisfactory results were obtained, the project preceded to the next step; manufacturing.

The arm was manufactured keeping in mind the goal to keep the cost low. Aluminum plates were casted and the required parts were machined. CNC was used to get the finishing and accuracies required. After that the robot was assembled. The structure showed the motion expected and predicted. Motors were locked into the position.

The project resulted into a fully functional robotic arm giving 4 Degrees of Freedom which can be programmed specifically to the needs of the industry. The robotic arm has huge potential in different industries like manufacturing, logistics and automotive. It provides automation, reduced risk and higher efficiency inn workspaces. This project provides a fundamental ground for further research in the field of robots for industrial automation.

In conclusion, this project successfully designed and developed a fully functioning robotic arm capable of performing operations with high accuracy and precision. This use of the robot in industry makes it exciting for further development. Future work could be done in the field of in robotic arm gripper, that opens a whole new world of opportunities to exercise the prowess of this robotic arm.

ACKNOWLEDGMENTS

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Lastly, we would express our thanks to everyone who has directly or indirectly helped us in this project, you support made us stronger and helped us get through the tough time. It gives us pleasure to say that your effort has played a vital role in making this idea into a reality, and we are grateful for your contributions.

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ABBREVIATIONS

DOF	Degree of Freedom
CF	Carbon Fiber
SDG	Sustainability Development Goal
FMCG	Fast moving Consumer Good

CHAPTER 1: INTRODUCTION

In the recent years, robotics has emerged as one of the most pivotal fields for development and advancement in the industry, a lot of investment is being done and interest is shown in this regard. Robotic arms have a lot of applicability and can help ease life of humans around it. This thesis focuses on the design, development and implementation of a 4 Degree of Freedom Robotic Arm.

1.1 Problem Statement:

> "The Absence of high-speed, lightweight robotic arms hinders efficiency and automation in Pakistan's FMCG industry. This project aims to design a low-cost 4-DOF robotic arm to meet this need and boost local industrial productivity and reduce inefficiencies."

We aim to provide an efficient and a cost-effective solution to the advancement of indigenous manufacturing of robots, which will aid to reduce imports in the manufacturing sector of Pakistan and help the local sector grow.

1.2 Motivation:

The world is now advancing and moving further towards an automated industry. Pakistan is also following this trend and is also capitalizing on the innovation and automation brought by robots to tackle the existing industrial challenges. This technology is becoming crucial aspect to performing sensitive, difficult and precise task in various sectors, including manufacturing, logistics, automotive etc. By espousal of development, Pakistan aims to boost productivity, embrace sustainability, and unlock new growth opportunities.

The motivation behind this project was to bring a change and revolutionize the robotic industry, making it self-sufficient in order to reduce the need for imports and be able to provide advanced technology to the industry of Pakistan. We aim to develop a machine that can help automate and streamline the assembly and packaging process in FMCG industry thus reducing inefficiencies. Moreover, producing these machines in house in Pakistan will empower the industry by reducing its impots. The avenue and availability of low cost, easily available robotic arms will help in achieving this goal.

Nowadays, all the development and innovation is mostly centered towards Sustainability Development Goal (SDG). It is important for a new machine to contribute towards the betterment of humans and nature. This project also maps and contributes to the SDG no 9, 11 and 12.

Figure 1: Sustainability Development Goal

1.3 Concept:

This thesis puts emphasis on a fixed 4 Degree Of Freedom Robotic Arm that operates at high speed and high precision. The unique thing about it is the placement of the actuators on the base, reducing its inertia and increasing the maneuverability. This model can have further upgrades (Interchangeable end-effectors) to accommodate different uses in the industry. Materials such as carbon fiber and aluminum are used in order to reduce weight and maintain strength.

1.4 Objective Of The Project:

The objective that we want to achieve through this project is designing and manufacturing of a 4 DOF high acceleration and low inertia robotic arm that can be deployed in the FMCG industry to perform high precision pick and place operations. This will in turn help in blooming of indigenous robot manufacturing by Pakistan and usage of modern technology by industry in Pakistan.

1.4.1 Deliverable:

Building upon the primary objective, the deliverables set for the project are as follow:

- Analytical Design and CAD Model:

Designing the structure of the robotic arm that supports our deliverable weight of 1kg.

- Analysis of the design:

Using analysis software to get a proof of load bearing capacity of different components used.

- Prototype and Testing:

Procuring raw material, machining parts according to the 3D model and assembling to get a working prototype.

- Simulation and Optimization:

Implementing and testing the electrical system deployed to optimize the performance of the robotic arm.

CHAPTER 2: LITERATURE REVIEW

2.1 Robotic manipulators for automation:

Throughout the history of mankind, humans have been trying to move towards developing solutions that make life easy for themselves. One such important development is the development of systems that eliminate redundant tasks, increase efficiencies, and save time for other valuable operations. The development of the robotic manipulators is an important technology that has been pioneer of automation in industries. These robots, robotic manipulators, and robotic arms carry out the redundant, time consuming, and often unsafe tasks, so that the resources are managed more efficiently.

2.2 Industrial implication of robotic manipulators:

Through multiple iterations, these devices have been improved to be more accurate and faster, hence reducing the production time and increasing profit in industries. This is one of the primary reasons, more and more industries these days are employing these manipulators for automating their production processes. The automotive production and assembly plants were one of the first major industries that employed such robotic arms. Initially, these were used for the purpose of picking, holding and placing large heavy parts so the workers could bolt or weld the parts in place. These days, the robotic arms are capable of high precision bolting and welding of the components as well, hence further reducing production time and increasing the accuracy of the units produced.

Multiple other industries have also employed robotic systems for automation such as consumer products, food packaging and even electronics.

2.3 Types of Robotic Manipulators:

Multiple variants of robotic manipulators have been developed for highly specific operations. These differences can be due to the requirements of speed, precision, torque, workspace or a combination of these.

2.3.1 Conventional Robotic Arms:

These robotic arms are the most common ones seen in industries. In automotive industries, large robotic arms are used for picking, holding and bolting or welding large parts like the doors, engine, windshields.

One of the major drawbacks of these robotic arms is the fact that in this configuration, all the actuators are attached at the individual joints. This means that the motor at the first joint has to move the load of the links as well as the load of the other motors. This reduces the maximum achievable speed of this type of robotic arms.

Figure 2: Conventional Robotic Arm

2.3.2 Delta Robots:

Delta robots are also known as spider robots due to their three or four lightweight arms. These robots stand out for their unique design: parallelograms linked by universal joints at the base enable independent arm movement while maintaining constant orientation of the end effector, unlike other parallel robots like Stewart platforms. This translates to impressive speed (up to 200 cycles per minute) and precision. Their compact footprint and lightweight design further enhance their appeal, while simple programming thanks to the parallelogram linkages simplifies operation. However, payload capacity remains moderate compared to traditional robots, and their workspace is typically confined to a dome-shaped region below the base.

Figure 3: Delta Robot

2.3.3 Scara Robots:

SCARA robots, short for Selective Compliance Assembly Robot Arm, excel in high-repeatability tasks thanks to their unique design. These robots have two parallel arms mounted on a base, allowing movement in a single plane with speed and precision. The key feature is their "selective compliance": rigidity in the vertical Z-axis combined with motion in the XY plane. This enables tasks like inserting components into tight spaces without binding. While payload capacity is moderate compared to larger

Figure 4: Scara Robot

robots, SCARA robots shine in high-speed applications with cycle times as low as 0.3 seconds. However, their workspace is limited to a cylindrical area around the base, and they may not be suitable for tasks requiring complex manipulation or large payloads. Despite these limitations, SCARA robots remain popular due to their speed, precision, and affordability, making them valuable players in various industrial automation applications. They are constantly evolving, incorporating vision systems and advanced controllers, ensuring their continued relevance in the future of automated manufacturing.

2.4 Choice of Actuators:

Various different types and sizes of motors and motor drivers are used for different applications in robotic arms. In such applications where high speed, precise motion and high torque is required, either stepper motors or servo motors are employed.

2.4.1 Servo Motors:

Servo motors work on a closed loop feed back system, hence they are able to correct and adjust their positions very swiftly, which accounts for their high accuracy. Every servo motor also consists of an encoder, which gives the data about the position of the shaft to the motor driver, which makes adjustments accordingly. The speed of the motor is controlled by the frequency of the pulses, and the position is controlled by the number of pulses.

Within the PLC, the gearbox ratio and the actuator ratios are entered into a scaling algorithm so that when the PLC commands the servo to move a specific distance at a specific velocity, the drive system will be able to calculate the specific frequency and stop the servo after the encoder reports back the correct number of rotations.

2.4.2 Stepper Motors:

A stepper motor operates by using a magnetic field to turn electricity into movement, but it contains more magnetic poles compared to standard motors. These motors break down a full rotation into multiple equal parts. When one magnetic pole receives power, the motor shaft advances by one segment, known as a 'step,' which is why it's called a stepper motor. If we power the poles in order and quickly, the movement looks like a continuous rotation.

A unique feature of the stepper motor is the holding torque at zero speed or when the link is to be kept stationary at a specific position.

2.4.3 Selected Motor for 4 DOF Robotic Arm:

A bipolar stepper motor with two phases is employed as the actuator. This brushless DC motor translates electrical pulses from a microcontroller (Arduino) into precise angular displacements of the shaft.

Specifically, the NEMA 34 bipolar stepper motor is used in this application. It offers a step angle of 1.8 degrees. This means it requires 200 steps to complete one full revolution. Additionally, its impressive holding torque of 7.07 Nm makes it well-suited for this task.

Figure 5: NEMA 34-bipolar stepper motor

2.5 Materials used in robotic arms:

Robotic arm bodies require a diverse material selection to meet varying performance demands. Key considerations include:

Steel offers exceptional load-bearing capacity, making it ideal for the base, joints, and linkages. Its high strength allows for operation in demanding environments and manipulation of heavy payloads.

Aluminum provides a favorable strength-to-weight ratio and ease of machining, enabling strategic application in non-load-bearing segments and covers. This weight reduction enhances agility and maneuverability in applications where such attributes are crucial.

Titanium exhibits outstanding stiffness-to-weight ratio, making it the preferred material for high-performance robots operating in aerospace and other demanding fields where minimal weight and exceptional strength are paramount. However, its premium cost necessitates its use in specialized scenarios.

Carbon Fiber Reinforced Plastic (CFRP) offers a unique combination of strength, lightweight properties, and impressive corrosion resistance. Its increasing adoption caters to applications demanding agility and weight reduction, such as medical robots.

CHAPTER 3: METHODOLOGY

The methodology is primarily divided into 2 parts, addressing areas of projects:

- Design Approach
- Prototyping
- Control System

3.1 Design Approach

After conclusive literature review, designing of the robotic arm was initiated keeping in mind the industry requirement and the parameters being target (written in section 3.1.1). The arm exercises 4 DOF motion. Initially software's like SolidWorks and Ansys were used for this purpose. Following steps shows the design from start to finish.

- Setting of design parameters
- Modeling and Simulation of the parts
- Market Analysis

The payload (1kg) and maximum reach (1800mm) constraints were fixed to proceed with the design.

3.1.1 Setting of Design Parameters:

Before making machine is important the design parameters are set to get a direction for the end product. For this robot the major design parameters that were required were as follow:

Table 1:(a) Design Parameters

Degrees of Freedom (Actuators Used)	4
Revolute joints	4
Prismatic Joint	0
Nominal Payload	0.5 kg
Maximum Payload	1 kg
Workspace	1800 mm
Robot Height	780 mm

The specification of motion imparted on each axis also holds a firm position to be an instrumental component to designing. The amount of motion allowed in each axis is as follows:

Table 2:(b) Design Parameters

Axis 1	±180°
Axis 2	±56°
Axis 3	±32°
Axis 4	360°

3.1.2 Modeling and Simulation of the parts:

After setting the design parameters, modeling of the robot was started on SolidWorks. An iterative approach was taken to model the arm. And later modifications were imparted upon calculation and assessment of the profiles. After reaching a conclusive model, simulations were done on SolidWorks and Ansys to ensure the safety of the system and that it was built well enough to cater to all the loads that it will face in the real world. The important components of the robots comprising each axis are shown below:

3.1.2.1 Axis 1:

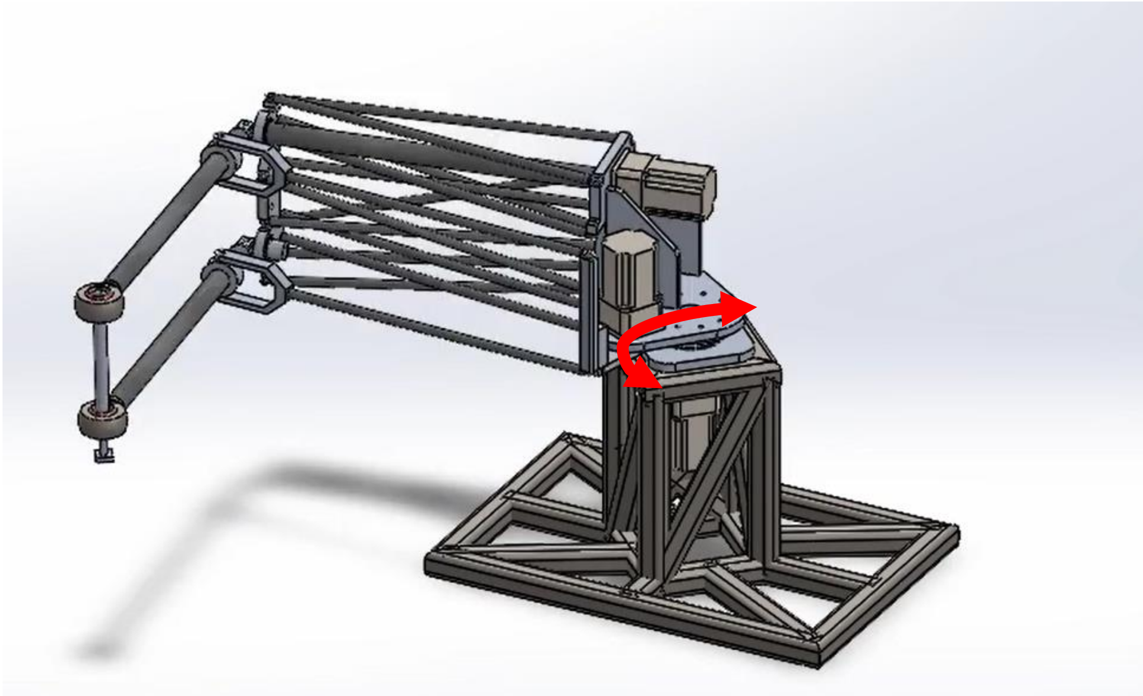

Figure 6: Motion of Axis 1

The first axis is situated at the base of the motor. It is responsible for the rotation of the entire arm. The major component of this axis is listed below:

Base Assembly:

The base assembly comprises of the base plate, turn-table, and clutch release bearing. The purpose of this assembly is to give the robot a sturdy base so that the load of the entire system can be bared and grounded properly. It helps provide smooth first axis motion.

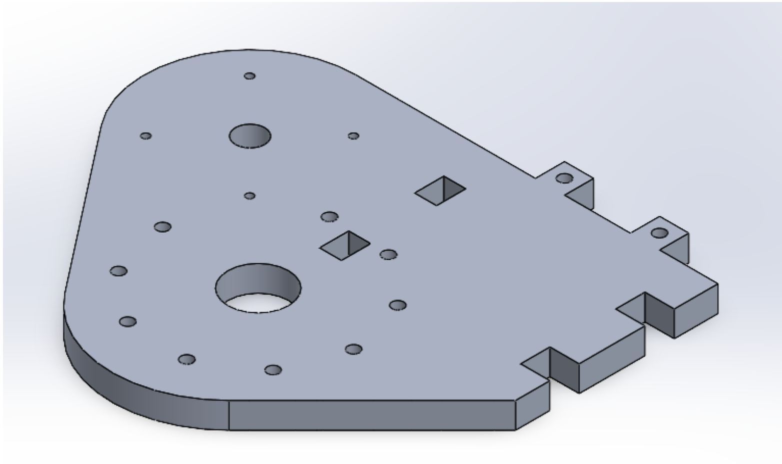

Figure 7: Base Plate

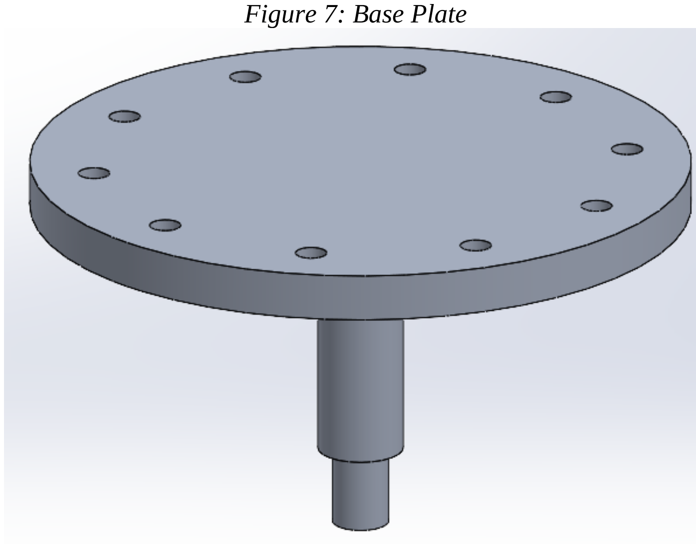

Figure 8: Turn-Table Shaft

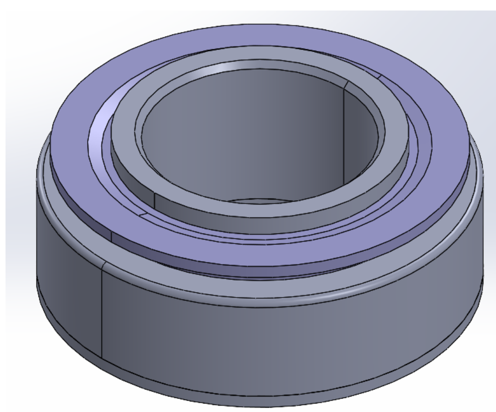

Figure 9: Clutch Release Bearing

Front Plate:

Front plate supports the motors that provide motion to third axis, it also is a mounting position for all the static carbon fiber rod that are supposed to keep the system rigid so that the bending force does not affect the rotating components. It was initially designed and later modified into this shape by considering the amount of support needed from the structure.

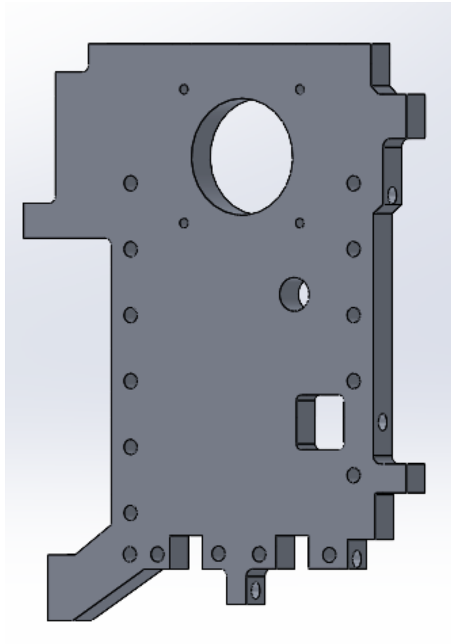

Figure 10: Front Plate

Side Plate:

Side plates are supports just like gussets that support and strengthens the connection between the front plate and base plate.

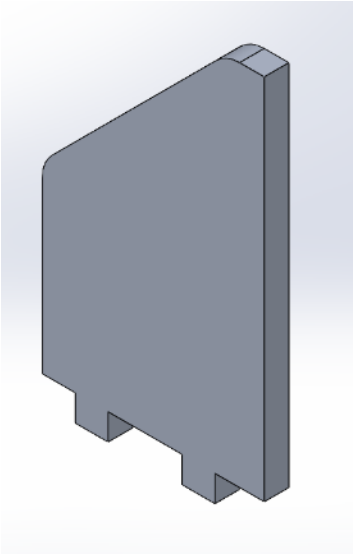

Figure 11: Side Plate

3.1.2.2 Axis 2:

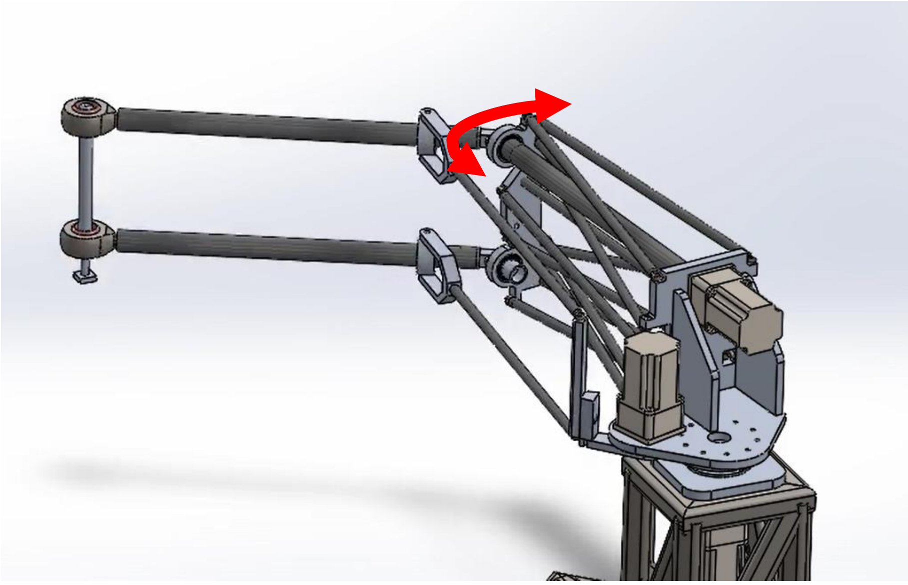

Figure 12: Motion of Axis 2

Axis 2 is the back-and-forth motion of the end effector; it is provided by the motor placed on the base plate. Motion is transferred by the L-shaped link that pushes and pulls the rods.

Y-Clamp:

The robot arm consists of 2 Y-Clamps. It holds the 30 mm CF rods and gives pull/push motion to the end effector. It is connected to the L-shaped link via an 18 mm CF rod.

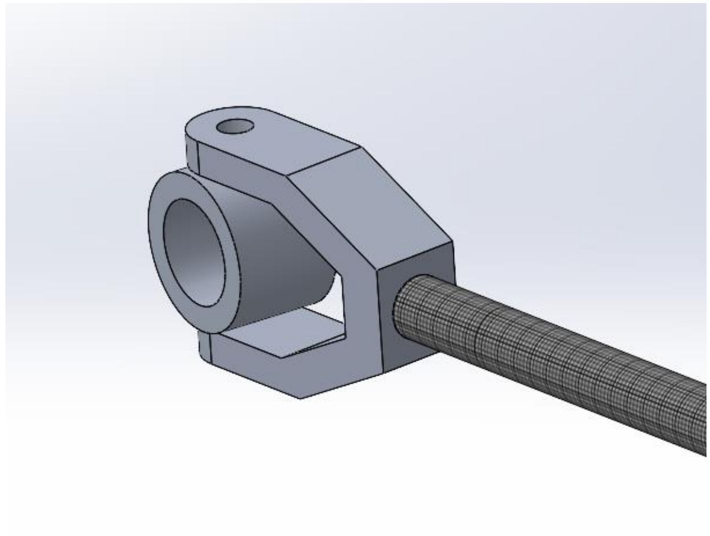

Figure 13: Y-Clamp

L-Shaped Link:

This link is responsible to transfer the motion of the motor to the 18 mm CF rods that connect with the Y-Clamp. To make it easy to manufacture, it was made into three parts and then fastened.

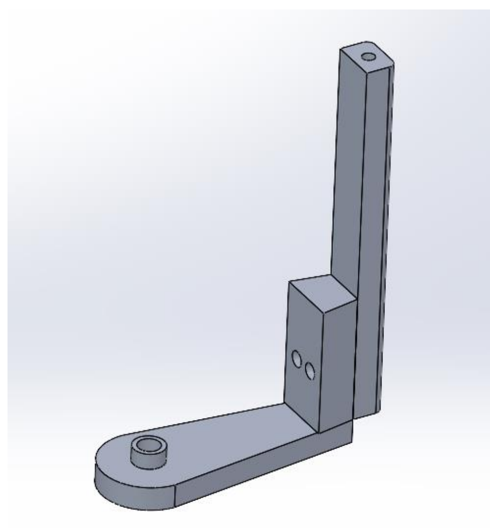

Figure 14: L-Shaped Link

3.1.2.3 Axis 3:

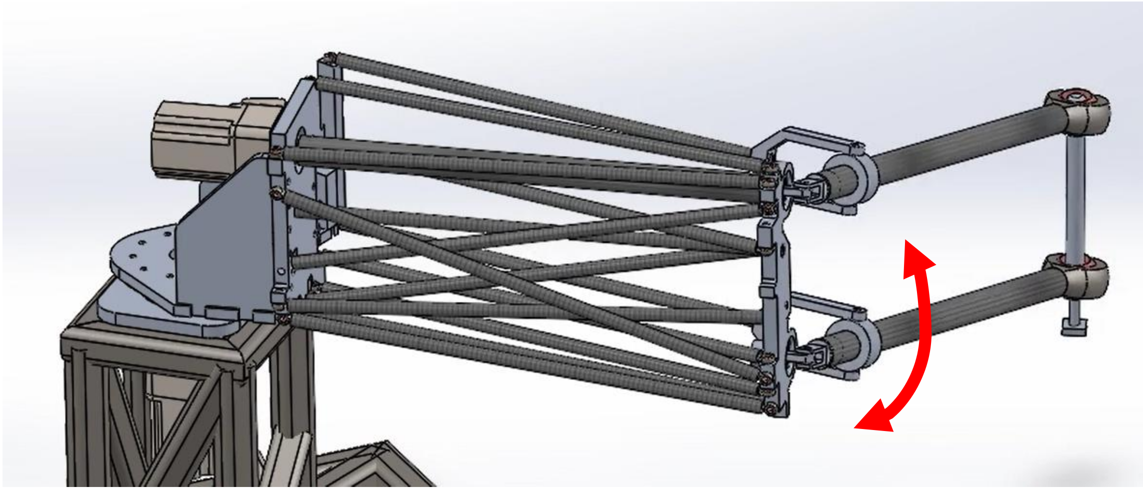

Figure 15: Motion of Axis 3

This axis provides up and down motion to the end-effector. The motor that actuates the motion is placed on the Front plate and the motion is transferred via a 40 mm CF rod. The important component of this axis is showed under.

Mid Plate:

It is one of the most crucial components of the robotic arm that helps hold the structure rigid. It also aids in the both the motion of axis 2 and 3. 18 mm CF rods which were mounted on the front plate from one side are mounted to the mid plate on the other end to ensure structural integrity.

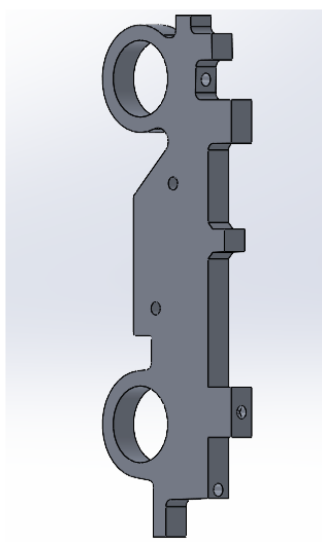

Figure 16: Mid plate

Bearings:

Ball bearings are pressed fitted into the mid plate in order to help sustain the radial load that the system will be experiencing. These are important components as they help in providing smooth motion and also keeping the system safe.

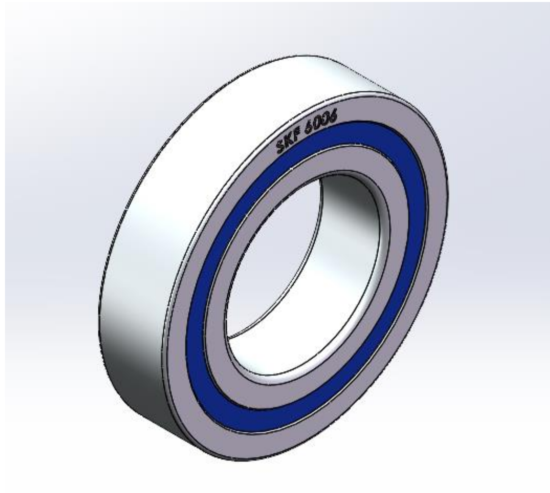

Figure 17: Ball Bearing

Joint:

This is the joint that connects the 40 mm CF rod to the 30 mm CF rod. One end is connected to the motor and the other end of the second rod is connected to the end effector. The metal part of the joint is the seat where the bearing is meshed and assembly is fixed.

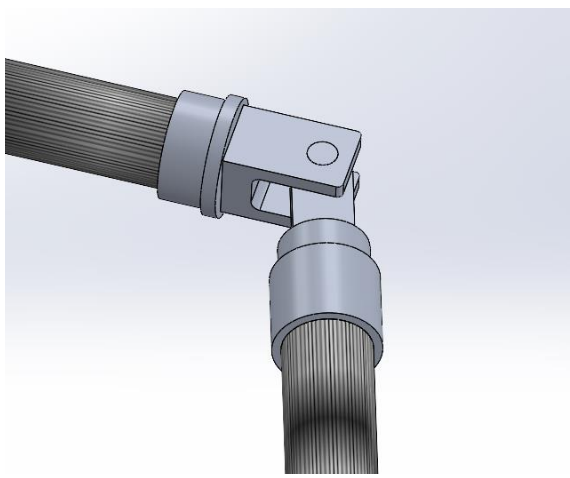

Figure 18: Joint between 40 mm and 30 mm CF rod

3.1.2.4 Axis 4:

Axis 4 provides the final motion of the end effector. It comprises of a MG 95 servo motor, that is mounted directly on the 3D printed frame of the end effector. It helps to rotate the object picked via the end effector, to change its orientation. The rod ends between the end effector and the mid plate are designed in a parallelogram shape such that they keep 4^{th} Axis frame straight.

Frame:

The frame is 3D printed from PLA. It is connected to the carbon fiber via rod ends and provides a mounting area for the motor.

MG 995 motor:

MG 995 is a high-performance servo motor used in axis 4 as the actuator with a stall torque of 12 kg/cm. it is responsible to change the orientation of the object picked up by the end effector.

Figure 19: MG 995 Servo Motor

3.1.2.5 Vacuum Gripper:

The End effector is using a vacuum gripper to perform the pick and place operation. The main working principle is quite simple. A plastic vacuum nipple is connected with a pneumatic pipe that is further connected with a T joint where at one end we have connected a 12 V DC pump that creates vacuum and on the other end of T we have connected a pressure relief valve that is controlled by Arduino signals. When the End Effector reaches its target location the relief valve opens and the payload is dropped. The pump runs continuously creating the vacuum when ever plastic nipple is placed over surface of our target object it creates vacuum and gets stuck with the surface due to differences in pressures inside and outside the plastic nipple. The vacuum cup can create a pressure difference of 100KPA that is equivalent to 1 atm.

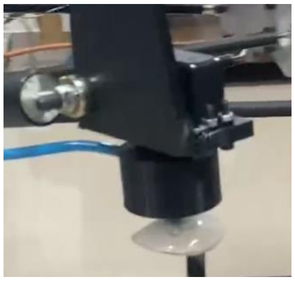

Figure 20: Vacuum Gripper

The diameter of the plastic vacuum nipple (assuming it's circular) is 50 mm, we can calculate its area (AA) using the formula for the area of a circle:

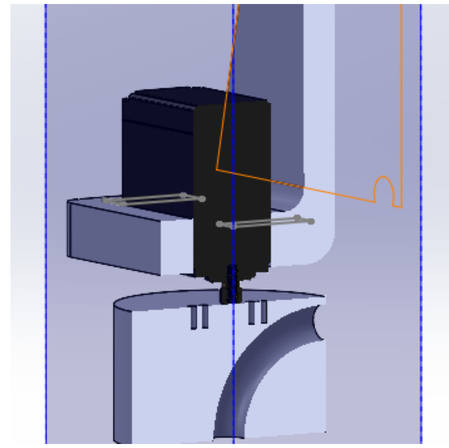

Figure 210: Section View of Model

$A=\pi\times r2A=\pi\times r2$

Where:

- AA is the area of the circle,
- $\pi\pi$ is a mathematical constant (approximately 3.14159),
- rr is the radius of the circle.

Given that the diameter (dd) is 50 mm, the radius (rr) would be half of that, so $r=d2=50$ mm2=25 mm$r=2d=250$mm=25mm.

Now, we can calculate the area:

$A=\pi\times(25$ mm)2$A=\pi\times(25$mm)2
$A=3.14159\times(625$ mm2)$A=3.14159\times(625$mm2)
$A\approx1963.5$ mm2$A\approx1963.5$mm2

Figure 221: Vacuum Gripper with Load

So, the area of contact (AA) between the vacuum cup and the object would be approximately 1963.5 mm21963.5mm2.

Using this value, we can recalculate the force exerted by the vacuum gripper:

$F=100000$ Pa×0.0019635 m2$F=100000$Pa×0.0019635m2 $F\approx196.35$ N$F\approx196.35$N
So, with a pressure difference of 100 kPa and a circular vacuum nipple with a diameter of 50 mm, the vacuum gripper could theoretically lift a weight of up to approximately 196.35 Newtons, or roughly 20 kg.
The weight we lifted from this suction pressure was 5.2 Kg since the surface texture play a vital role in it.
The Tubing and the Vacuum plastic nipples are mounted in a 3D printed part that firmly holds both while avoiding any bending in the pipe.

3.2 Prototyping
After the design phase, FEA was used to verify the design according to the materials used and the rated load requirement. Following analysis, the manufacturing phase was

initiated. Numerous manufacturing techniques including pattern making, casting, surfacing, permanent and non-permanent fastening, and CNC machining were used throughout the prototyping process. A detailed account is given below:

3.2.1 Pattern Making

The first part of the manufacturing process was to make wooden patterns of the plates at the 1st axis of rotation. Wooden patterns according to the CAD model were made from plywood sheets. 1:1 scale drawing were used to get accurate measurements for the patterns. 3% shrinkage allowance and 3mm machining allowance was left according to the shrinkage properties of aluminum.

Figure 23: Casting Molds

3.2.2 Casting

Sand Casting was the process following pattern making. Industrial quality aluminum (6061 Grade) was procured. Its properties are as given in the following table:

Table 3: Material Properties of aluminium

Density	2700 kg/m3
Melting Point	588°C
Yield Strength	276 MPa
Shear Strength	207 MPa

The aluminum was heated to its melting temperature of 588° using an open pit gas furnace. After casting, the surface was examined for any defects and was found not to have any major defects.

Figure 24: Casted Aluminium

3.2.3 Facing

After inspection, the first step was to get the plates surfaced. A carbide tool on the milling machine to surface the plates. The machines were finished according to the final required measurements.

Figure 25: Facing of plate

3.2.4 CNC Machining

The plates were then machined using CNC in order to get accurate profiles and precise holes at desired locations. The G-Code for CNC machining is attached later.

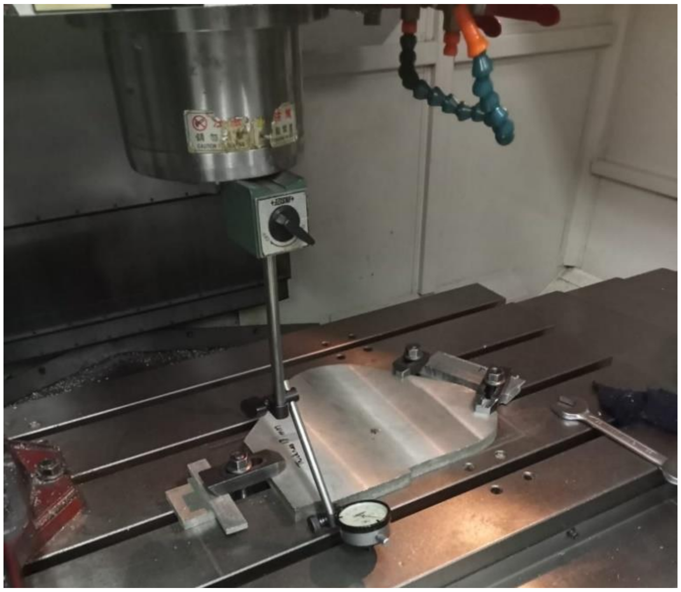

Figure 26: CNC Machining of plates.

3.2.5 Motor Clamp

In order to transfer the motion from the actuator to the base plate, an assembly was formed that held the motor in place and transferred the weight to the ground. A C-Clamp was fabricated with slots in both x and y directions so that the motor, shaft, and the base plate could be aligned.

3.2.6 Base Assembly

A 16-gauge, 1.5 x 1.5 in, square pipe was used to ground the motor mount and bending moment of the robotic transferring all of the weight to a MS plate acting as the base.

3.2.7 Carbon Fiber Tubes

CF rods of sizes 18 x 16 mm, 30 x 26 mm and 40 x 36 mm are used in the model as links. Carbon fiber was selected as the material of choice due to its exceptional strength and lightweight nature.

Figure 27: Carbon Fiber Tubes

3.2.8 Rigid Truss Structure:

The carbon fiber fitted with one bush on either side. To have the CF tubes in such a way that once fastened from both sides, they can be tightened to compress and attain rigidity in the structure, we used a left tapped bush and a right tapped bush. This helped us achieve a structure which could be tightened or loosened by turning the rod. So in this truss structure we have 3 rods in tensile loading and 9 rods in compressive loading and this was achieved by the help using left hand and right hand taping on both sides of rods. While the rods in tensile loading have only Right hand taping on both sides.

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3.2.9 Bill of Materials:

Item	Quantity	Cost
Carbon Fiber Tubes (18x16)	8	27,300
Carbon Fiber Tubes (40x36)	1	10,200
Carbon Fiber Tubes (30x26)	2	16,400
Carbon Fiber Tubes (18x16)	4	15,200
NEMA 34 Stepper Motors	3	-
Ball Bearings	3	1,200
Aluminum Material	-	8,000
MG995 Servo	1	800
Vaccuum Pump 12V	1	900
MS Round Plate	-	4,200
MS Shaft	1	1,700
Ground Base (MS Pipes and Sheet)	1	8,200
Square Pipe (MS)	8	1,200
MS Bearing Housing	1	1,950
Carbide End Mills	2	5,500
PLA Spool	1	2,500
M8 Bolts and Nuts	36	1,600
M8 Tap Left Hand	2	700
M8 Hex Head Bolts	14	1,230
M6 Bolts and Nuts	8	1,120
Rod Ends M8	22	11000
Aluminum Scrap	#	16,200
Aluminum Rod 55mm	1	1,350
Aluminum Rod 40mm	1	1,100
Aluminum Rod 16mm	1	650
Aluminum Machining	2	3,500
Cutting Disk	2	300
Welding Rod	40	400
Pneumatic Piping	1	250
T Joint	1	150
Jummper wires	3	1,380
CT 70B (Angular Contact Bearing)	1	1,600
Arduino Mega	1	8,200
Electric Cables (Red and Black)	10	4,200
Spray Paint	2	900
Printing A3 Drawings	8	1200

Casting Dies-Plywood	1	1,600
Miscellaneous		2,900
12 V supply	1	900
Pressure Relief Valve	1	200
Motor Coupling	2	1,400
Carbide Drill Bit	1	1,200
Total		170,480

CHAPTER 4: RESULTS AND DISCUSSIONS

In this section we will discuss the results achieved by the 4 Degree of Freedom Robotic Arm. As previously mentioned, the purpose for the development of the robotic arm is to achieve high speed and low inertia pick and place operation in the Fast-Moving Consumer Goods industry. We discuss the results in subsequent subsections:

Comparison with previous year's iteration:

Some major optimizations and improvements from the previous iterations of the attempt of the in-house manufacturing of the 4DOF robotic arm can be seen here and are discussed in following sub-sections:

Figure 28 Previous Prototype (2023)

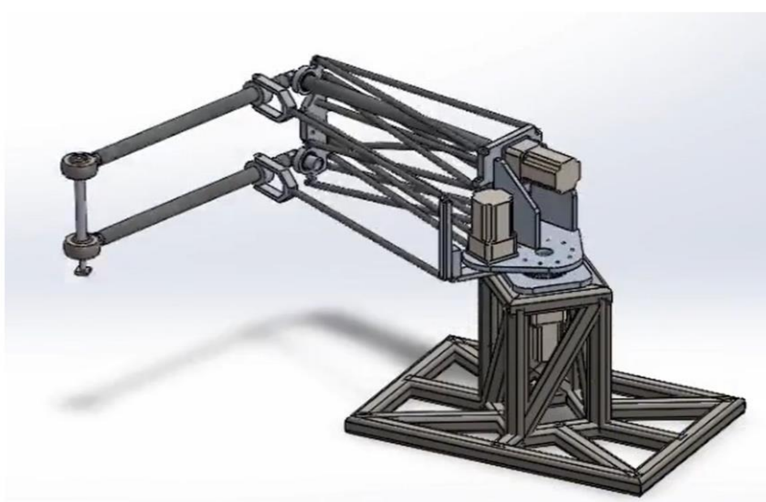

Figure 29: Revised and Improved Design (2024)

Figure 30: Working Prototype (2024)

Structural Integrity:

We can see from the visual comparison that this iteration of the robotic arm is more structurally stable than previous year’s design. This is due the use of proper geometrization of the carbon fiber tubes which are able to hold the weight of the mid plate and keep it static with respect to the front plate of the robotic arm. This provides rigidity and structural integrity to the entire structure and helps the end effector to move to the desired location as smoothly as possible without compromising the structure. This ensures that the robotic arm will have better reliability than the previous model.

Rigid Base:

A large emphasis is placed on making the base of the robotic arm as rigid as possible in order to sustain the bending load due to the extended linkages of the robotic arm. A large base is manufactured, with dimensions of 2.5x1.5 feet so that the center of mass of the robotic arm remains within the base at all positions. This eliminates the possibility of the robotic arm toppling under static conditions. Furthermore, links below the base ensure that the robotic arm does not topple in dynamic motion as well.

Figure 31: Working Prototype (2024)

Importance of angular contact ball bearing:

One of the biggest improvements to the robotic arm can be seen due to the implementation of the angular contact ball bearing at the base, which is able to support both the axial load as well as the radial load of the structure. As can be seen in the prototype and after testing at multiple RPMs, the bearing was able to withstand the loading while keeping the motor shaft and the base plate concentric to ensure smooth operation.

Combining the gripper with the robotic arm:

The deliverable set for the maximum weight that the robotic arm should be able to pick and place was set to be 1 kg. With the implementation of a pneumatic end effector with suction cups, the robotic arm was observed to be able to pick up loads of about 1.8 kg and keep the motion smooth and fast. This result was achieved due to the suction capabilities of the pump as well as the structural stability of the robotic arm.

Figure 32 Object Pick and Place

Motor Positions:

Effective and planned motor placements in the base plates ensured that we were able to achieve the desired motion with linkages, using 4 bar mechanism and crank coupler mechanism. Changing the motor placement from all the motors facing downwards and only pushing and pulling the linkages in the previous design, we were able to achieve the back and forth, as well as the up and down motion of the end effector. The horizontal motor provided the necessary upwards and downwards motion to the end effector and the vertical stepper motor provided the necessary back and forth motion within the prescribed range. After a few modifications and testing, we were also able to modify the range of the angles in which the motors and linkages could move.

Achieving Low Inertia and High Speed:

After careful, multiple, controlled testing, we were able to verify that the robotic arm was able to achieve its target goal by being extremely light weight at the end effector, and extremely swift in its process. The robotic arm was able to achieve speeds as high as 300 RPM with the help of the 8.5 Nm stepper motors and the extremely light weight of the carbon fiber tubes.

Cost Effectiveness:

The entire manufacturing and assembly of the robotic arm was completed within under 0.3 million PKR which is well below the cost of the imported robotic arms implemented for similar purposes, which ranges from 0.8 million to 1.8 million PKR. In this way, one of the biggest deliverables of the project was achieved. All the materials are readily available and easy to manufacture which can greatly reduce the cost impact of the automation initiatives being carried out in industries.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Conclusion:

The biggest conclusion that we can derive from this entire project is that Pakistan has the capability for the in-house manufacturing of high-speed kinematic machines and this can be done at a massively reduced cost as compared to similar robotic arms that are imported and implemented in the industry.

Future Prospect and Recommendations:

This project has much further to go, a lot of ground to cover and higher heights to reach. For it to be a fully functioning solution it is needed to be equipped with a very precise and dynamic control system, that guides the robot to change its parameters when it loadings and surrounding changes. When that is done it will prove to be a very powerful equipment, that can add much to the automation of the processes.

Further, the fields of artificial intelligence can also be integrated into the robot by the means of image detection. This will make the robot more versatile to different tasks and also increase the quality of work it does.

The project has a lot of room for optimization, be it structural optimization or modification in the workspace.

Implementation of Object Detection:

AI is the talk of the town when it comes to automation. The biggest advantage of AI is that it can be implemented in almost all of our processes to increase efficiency and productivity. This project is no exception to that advancement. One of the future prospects and improvements to the robotic arm is the implementation of object detection to increase the accuracy and reduce uncertainties in the working of the robotic arm. Using an overhead camera, we can use a tensorflow modelto train the robotic arm with data of our products and the environment it will function in. This training data can then help to improve the accuracy by making the robotic arm intelligent and providing it with the capability to observe and detect the objects it needs to pick up in real time and place them in the desired locations. Furthermore, integrating object detection into the robotic arm opens up possibilities for advanced applications, such as sorting and categorizing items based on their attributes. For instance, the arm could distinguish between different types of products or identify defective items for removal from the production line. This level of automation can significantly improve quality control processes and overall production efficiency.

Swappable End-Effectors:

Another future optimization that can be implemented on the project is the use of a swappable end effector module. Just like in CNC machines where we can select a variety of cutting tools, we can have multiple end effector shapes, sizes and lengths, for various purposes. A pneumatic gripper to be used for picking up flat surfaces, a claw for picking up irregularly shaped objects, a magnetic solenoid end effector for use with metallic containers or products, a soft gripper for picking up sensitive and fragile objects like medicine bottles, the possibilities and applications are limitless. This can make the robotic arm more versatile and easier to implement in a variety of industries. Furthermore, the ability to swap end effectors easily can lead to quicker reconfiguration of the robotic arm for different tasks. For example, if the arm needs to switch from handling flat surfaces to delicate items, it can simply swap out the gripper without requiring significant downtime for reprogramming or adjustments. Moreover, having swappable end effectors can also extend the lifespan of the robotic arm by allowing it to adapt to changing production needs or advancements in technology. As new types of end effectors are developed, they can be easily integrated into the existing system, keeping the arm up-to-date and relevant in various industries.

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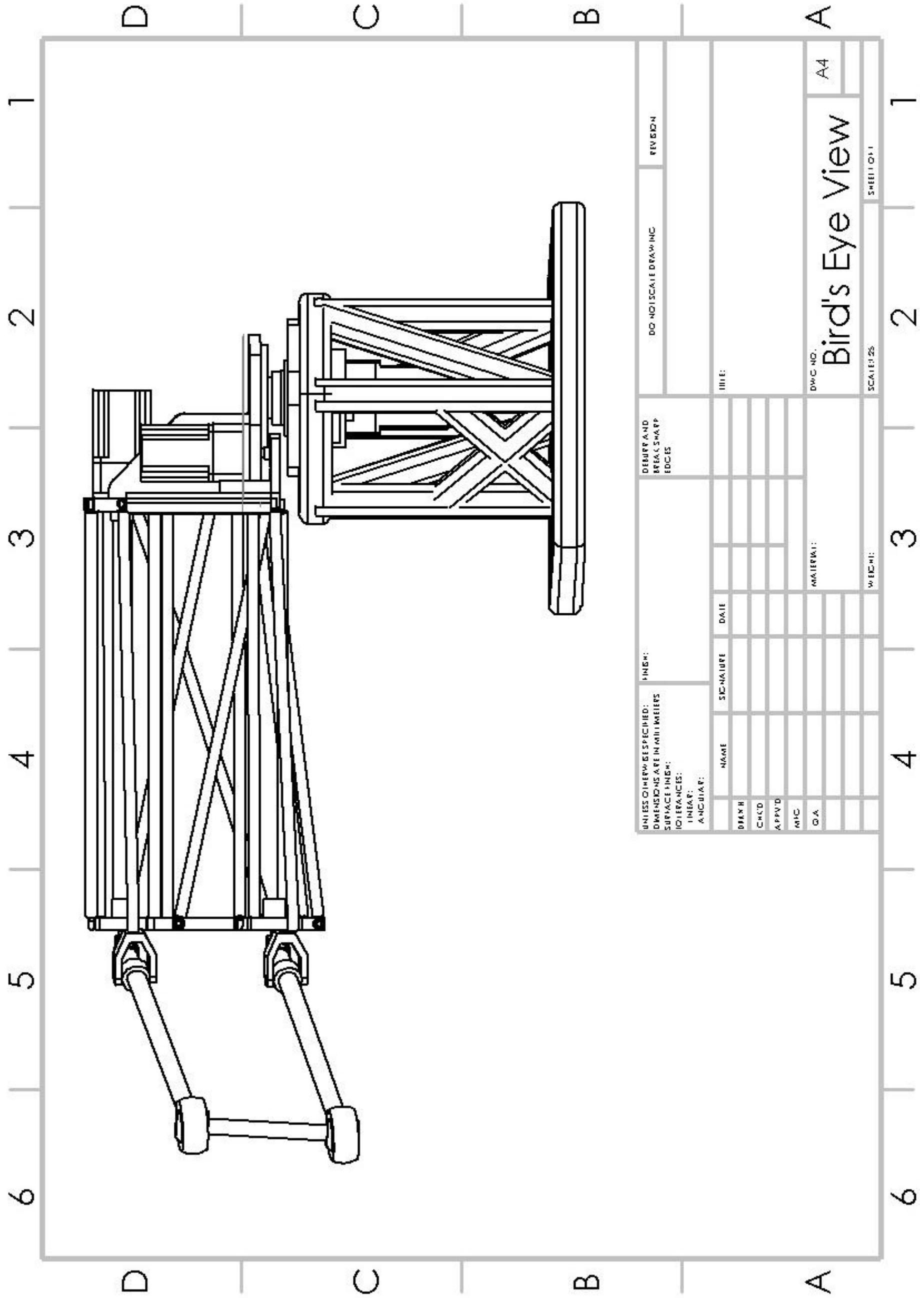
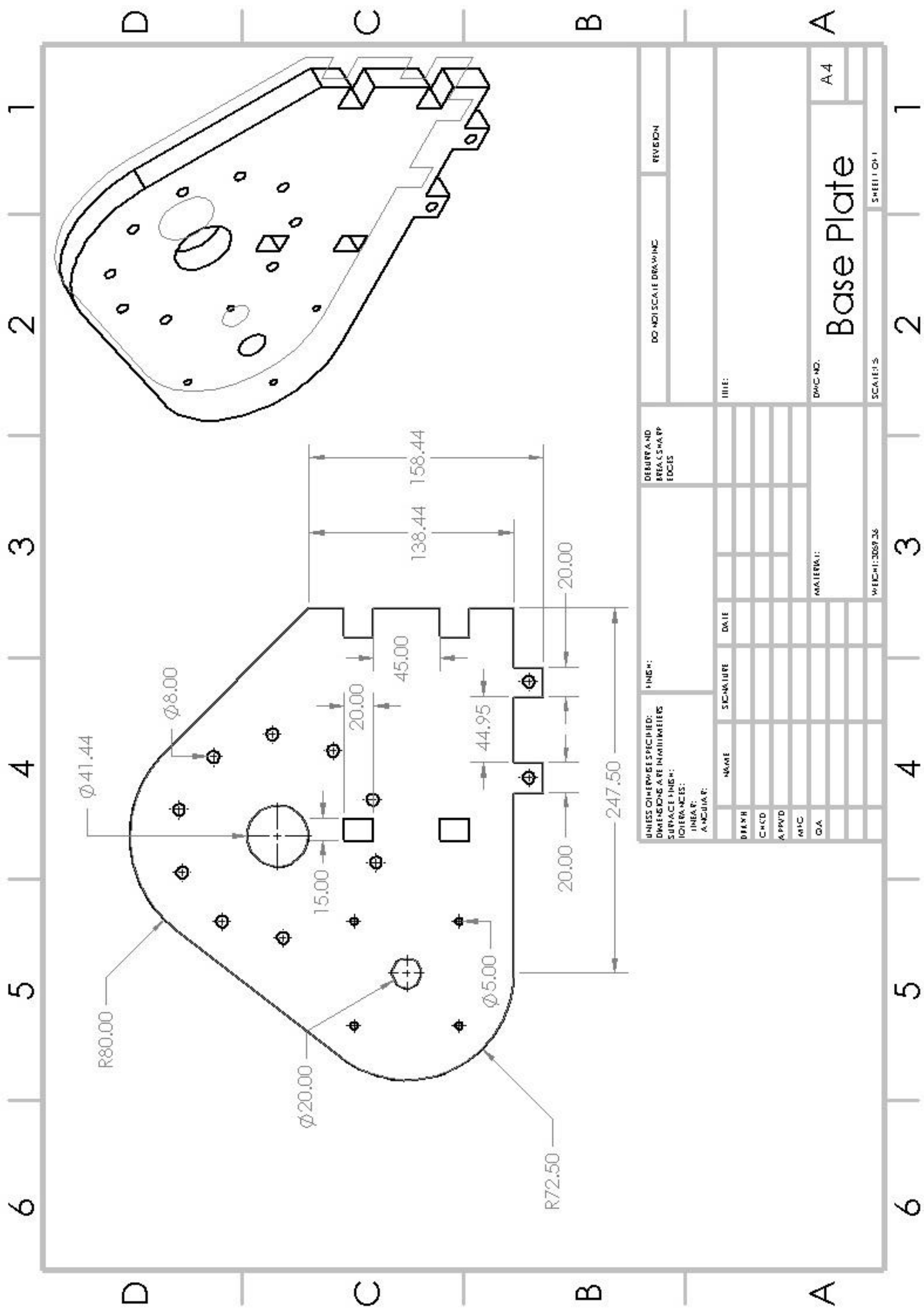
APPENDIX I: ENGINEERING DRAWINGS:

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45.00
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44.95
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20.00
20.00
247.50
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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
NAME
SIGNATURE
DATE
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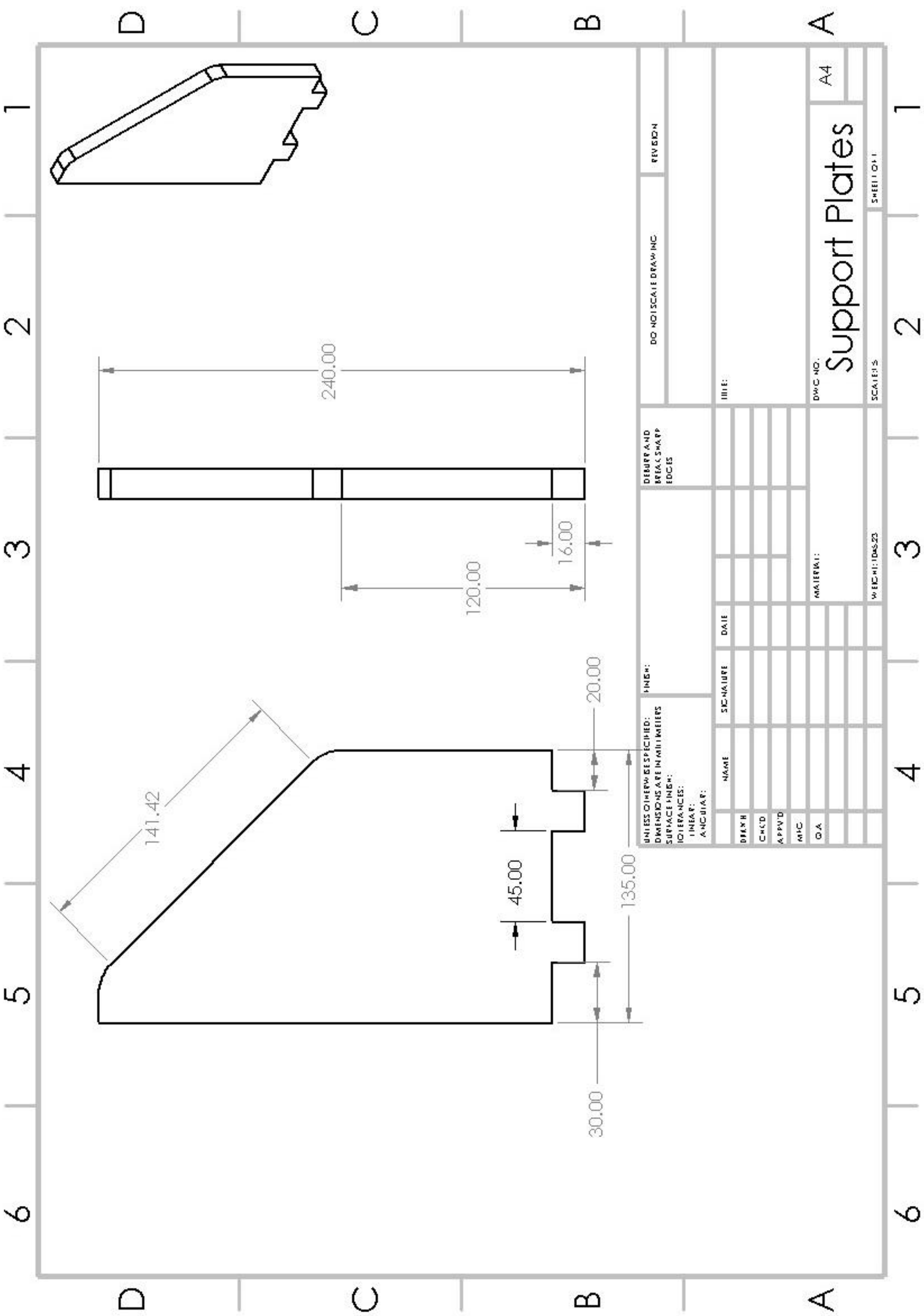
CHK'D
APPV'D
MFG
Q.A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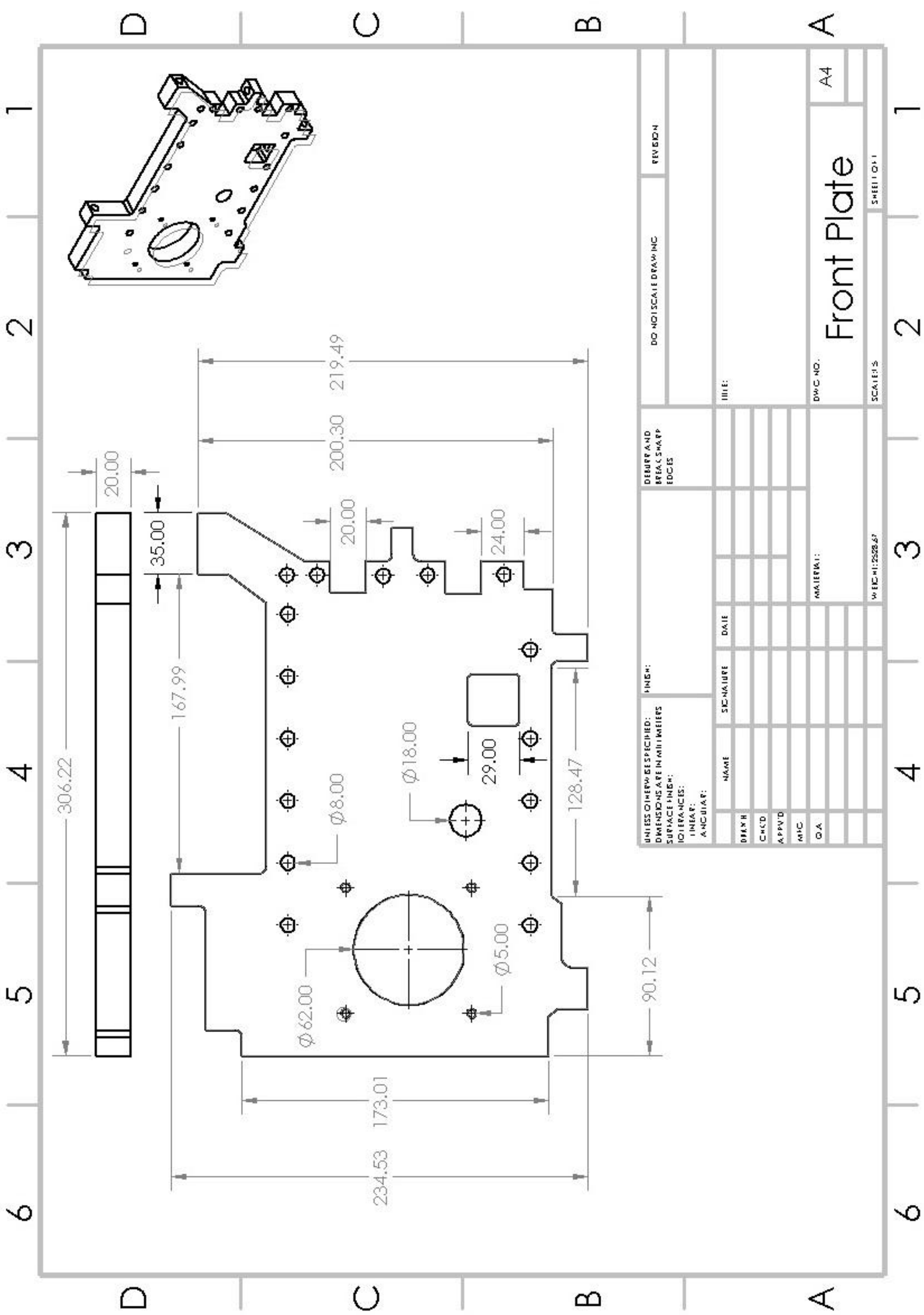
30.00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20.00
24.00
Ø18.00
29.00
Ø8.00
128.47
Ø62.00
Ø5.00
90.12
173.01
234.53
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WEIGHT:
FINISH:
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UNLESS OTHERWISE SPECIFIED:
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ANGULAR:
NAME
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MFG
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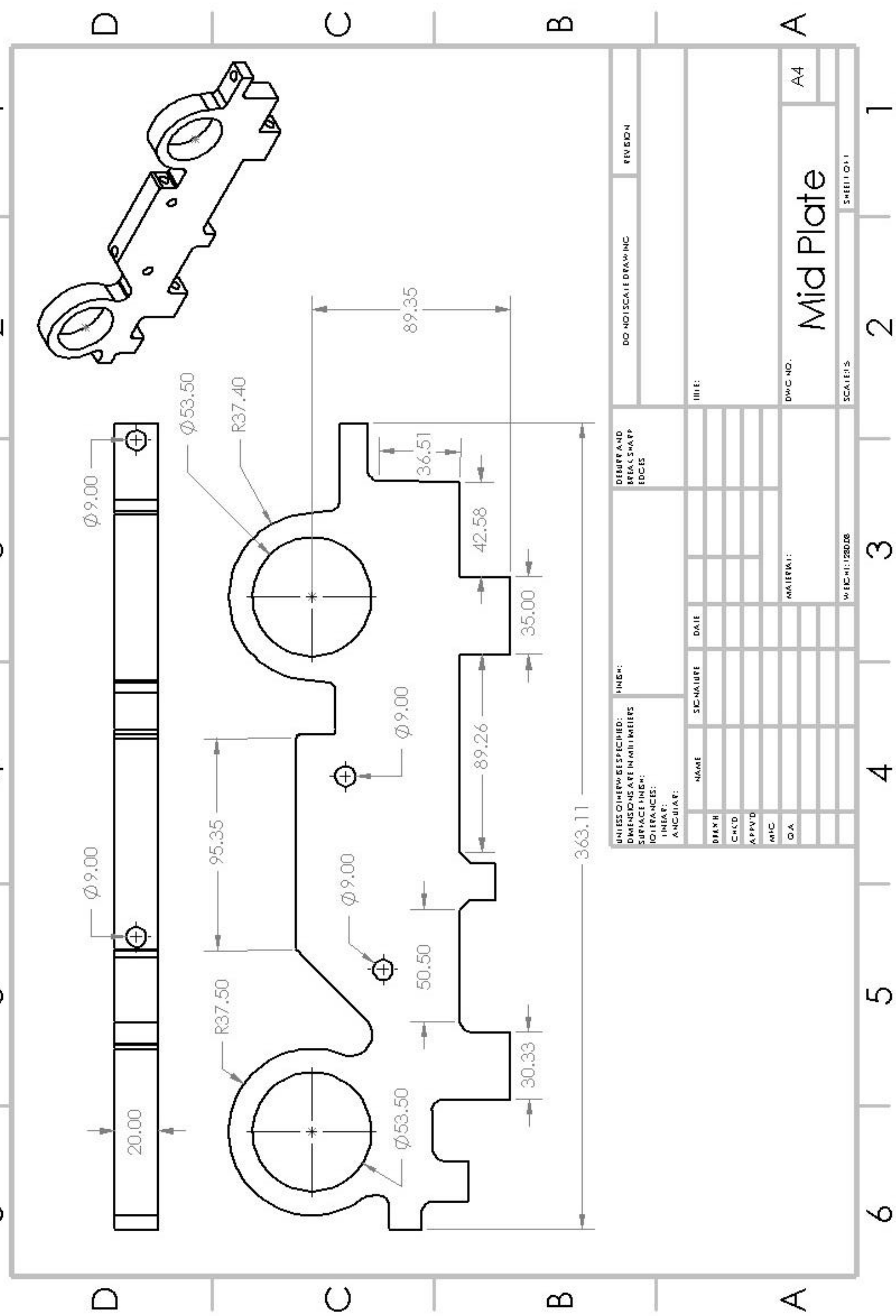
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REVISION
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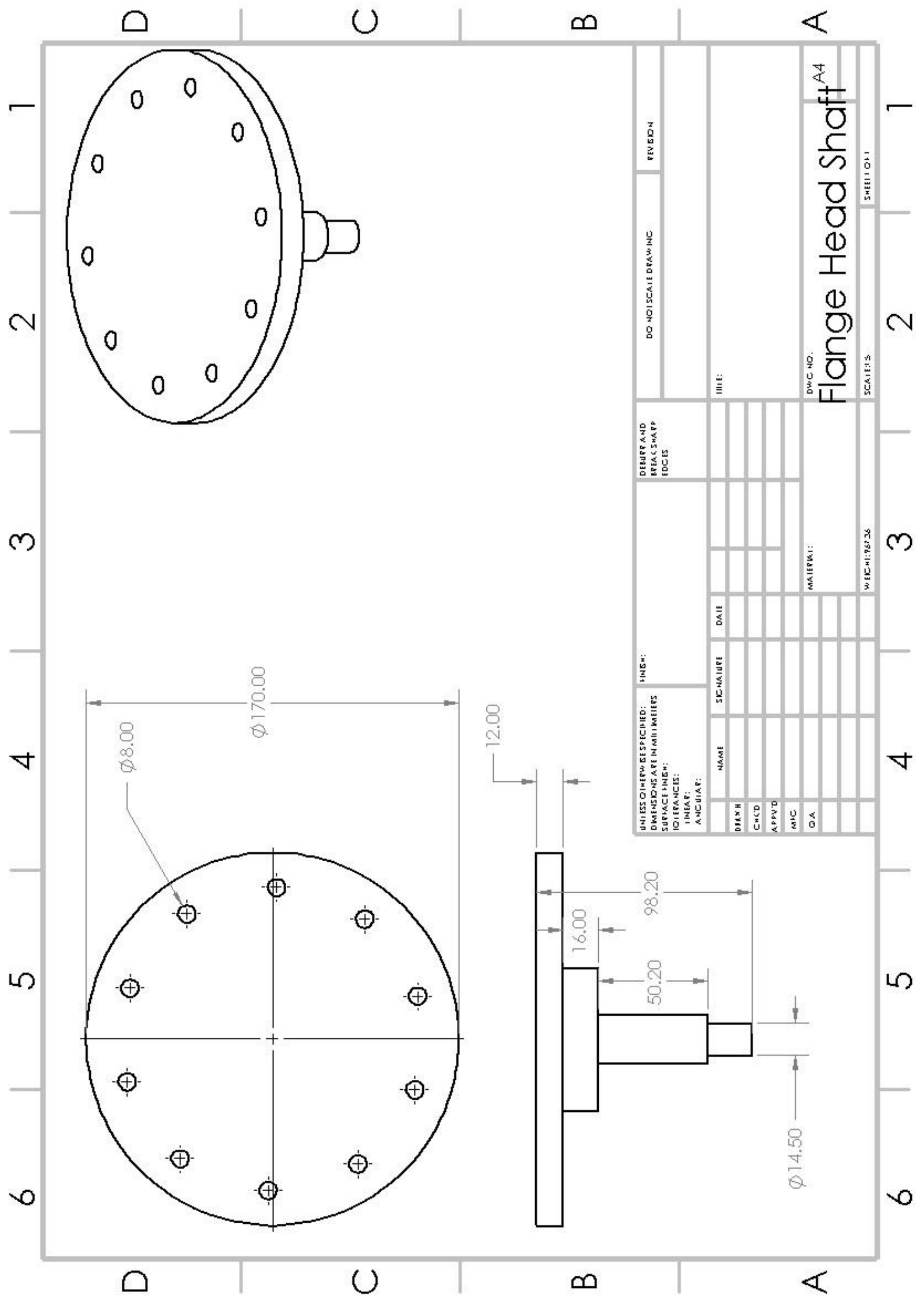
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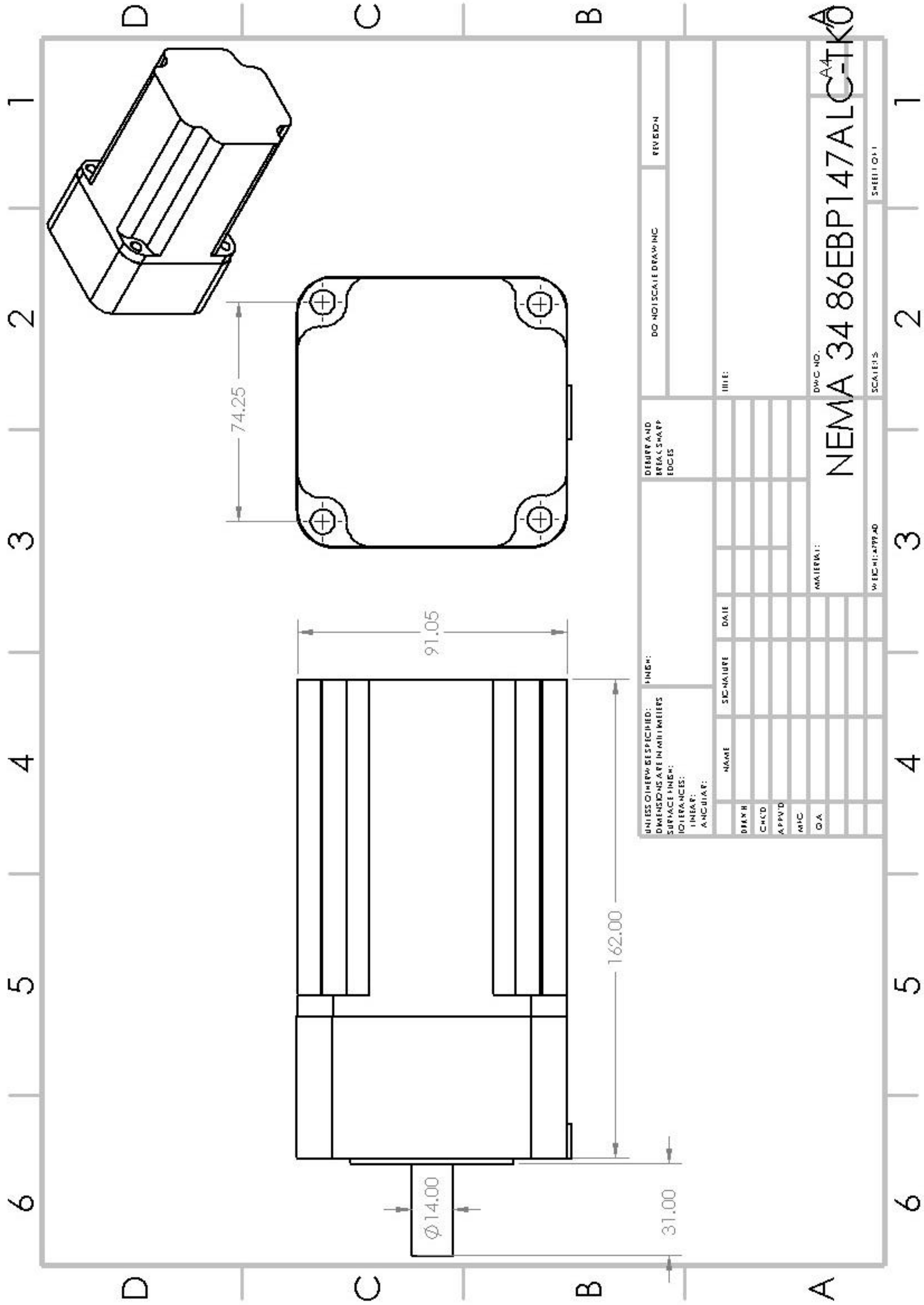
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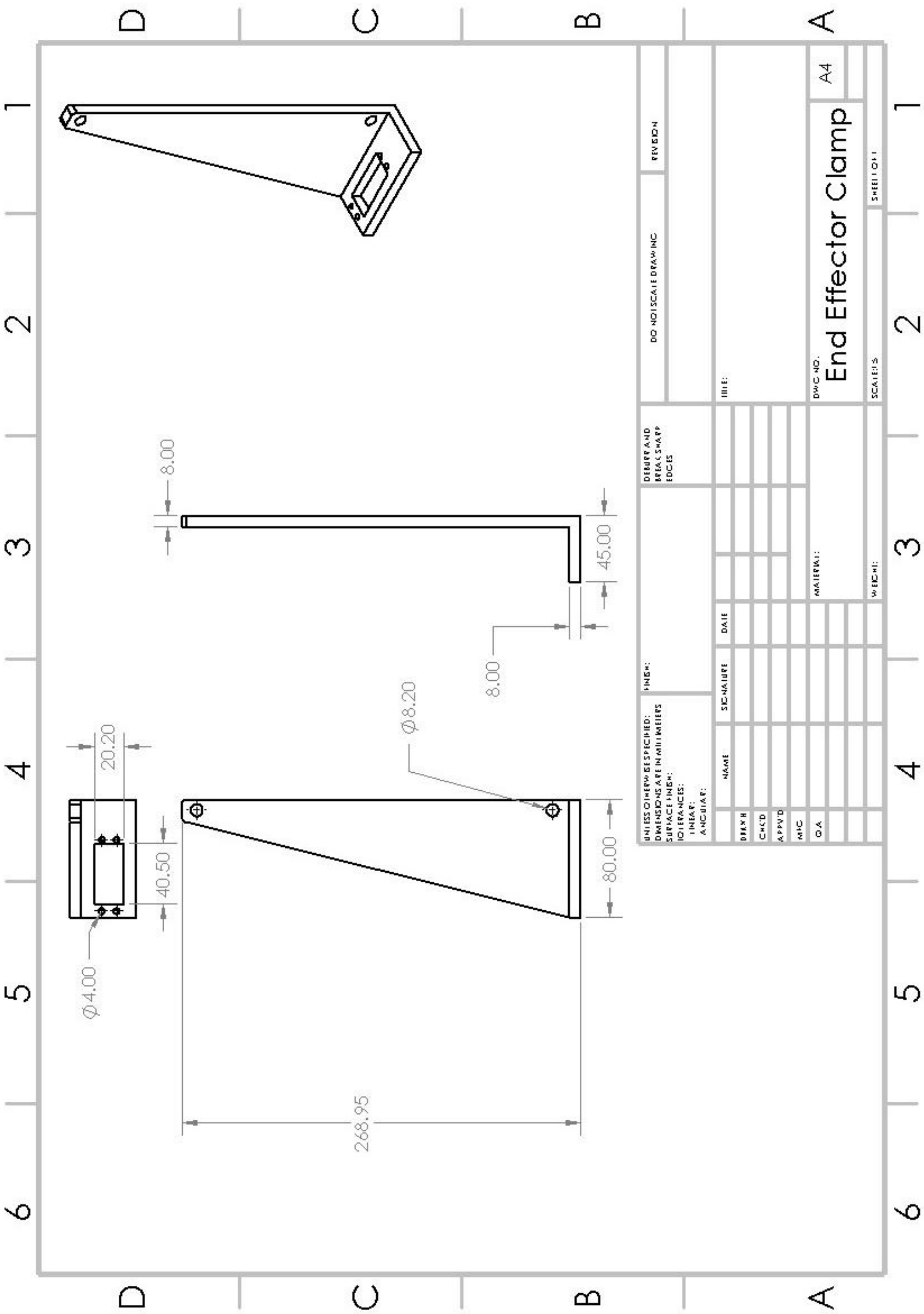

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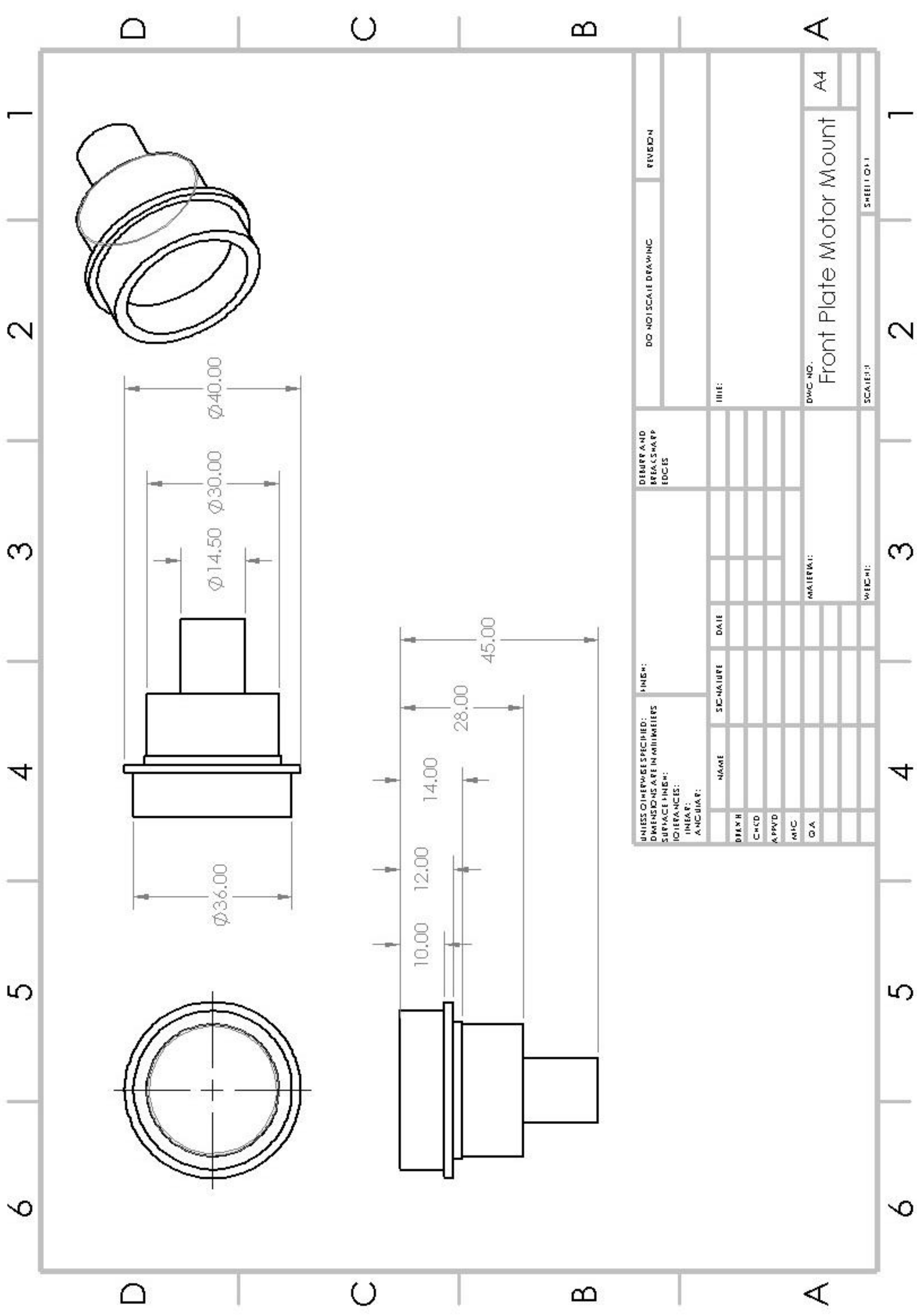
20.20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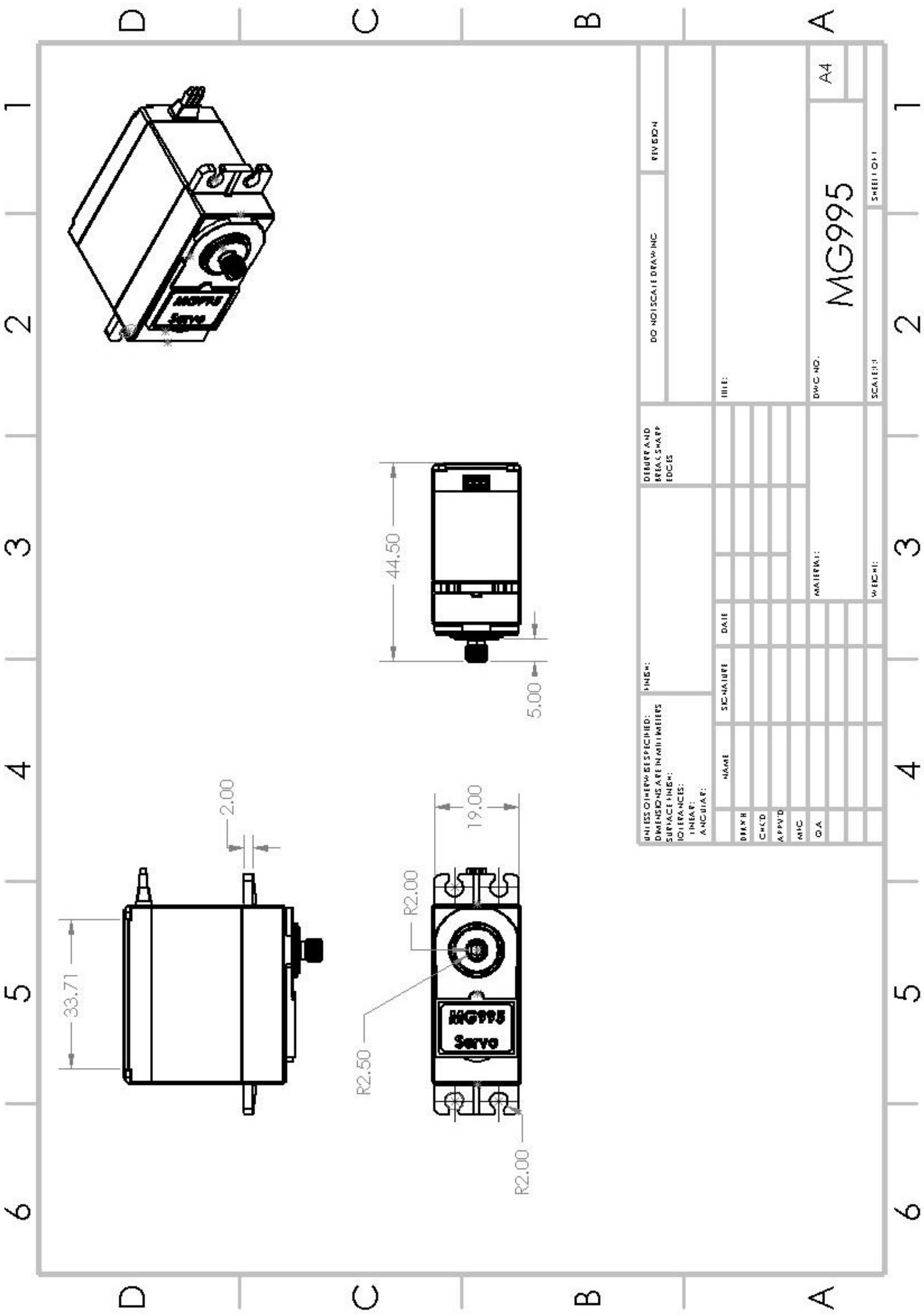
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Servo
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R2.00
R2.50
R2.00
UNLESS OTHERWISE SPECIFIED:
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LINEAR:
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SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
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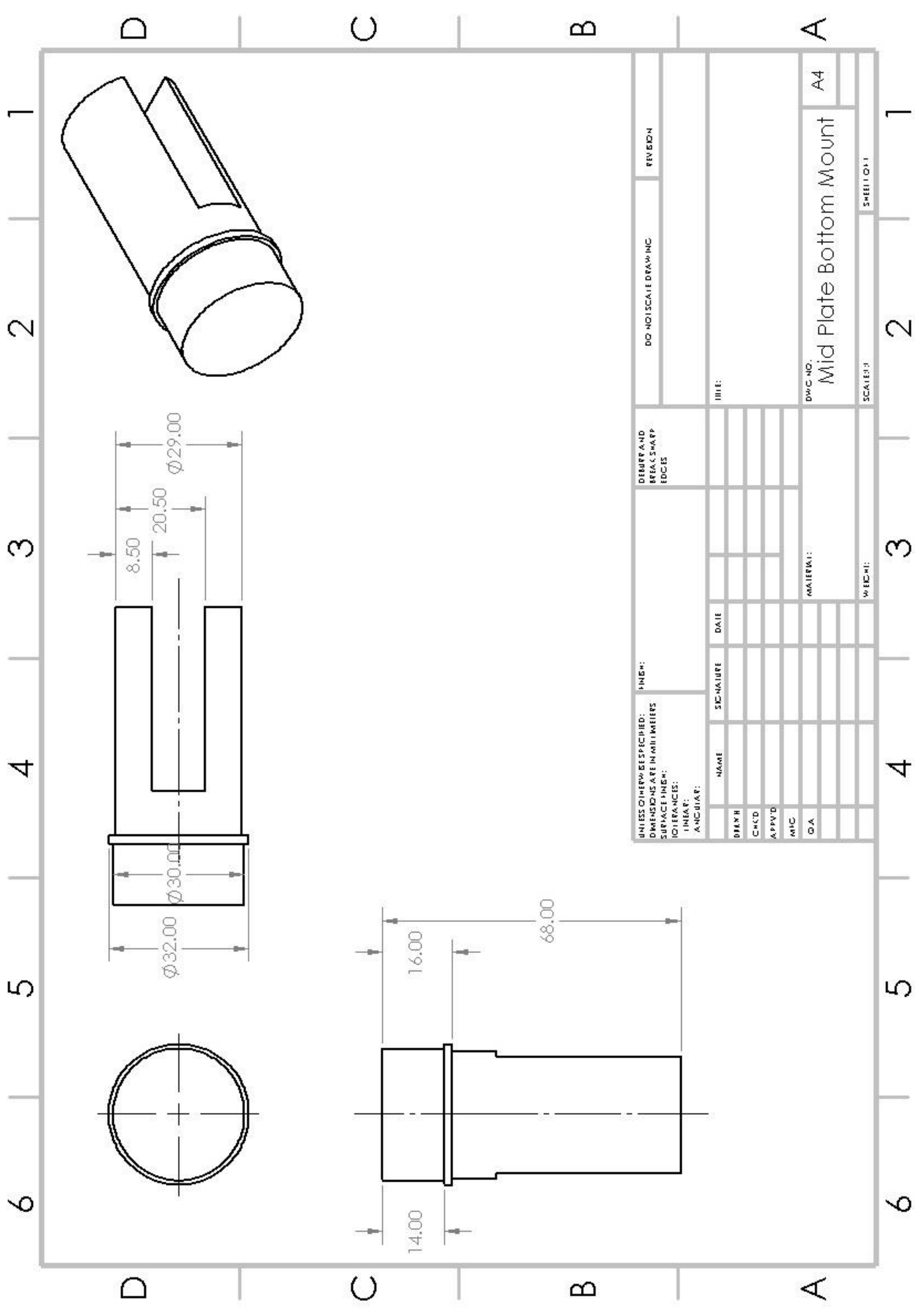
Mid Plate Bottom Mount
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Ø30.00
Ø32.00
16.00
68.00
14.00
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REVISION
DEBURR AND BREAK SHARP EDGES
FINISH:
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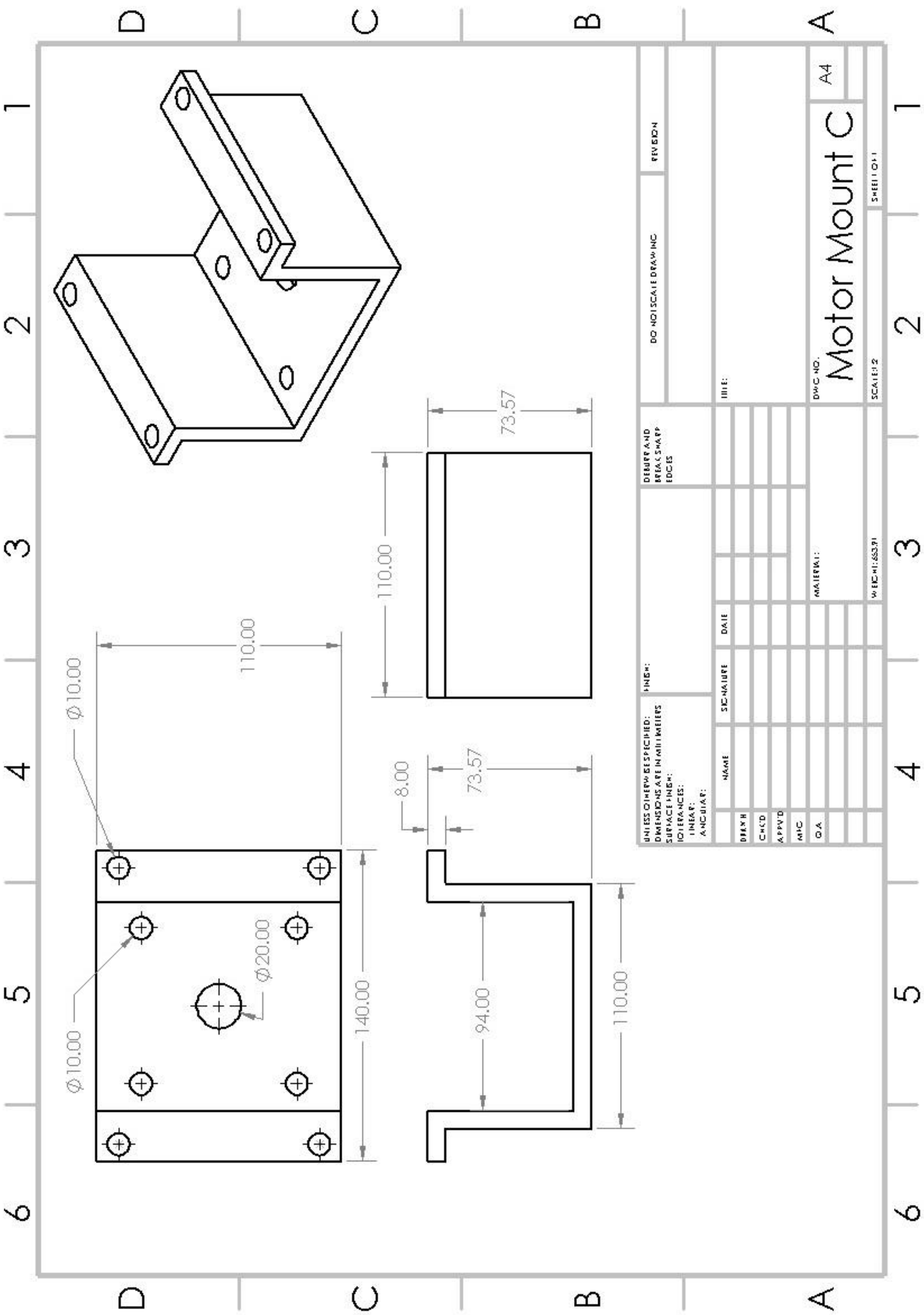

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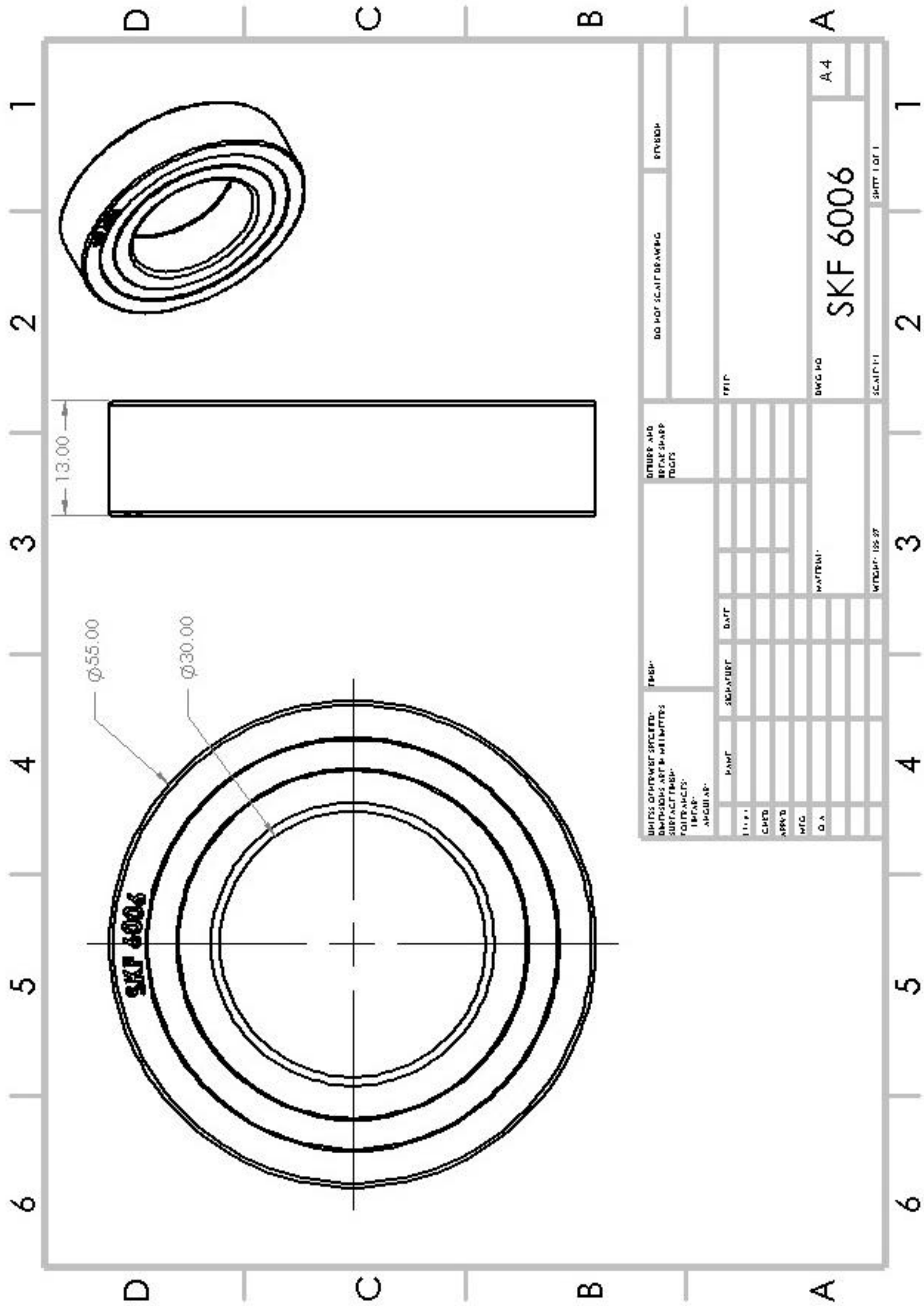

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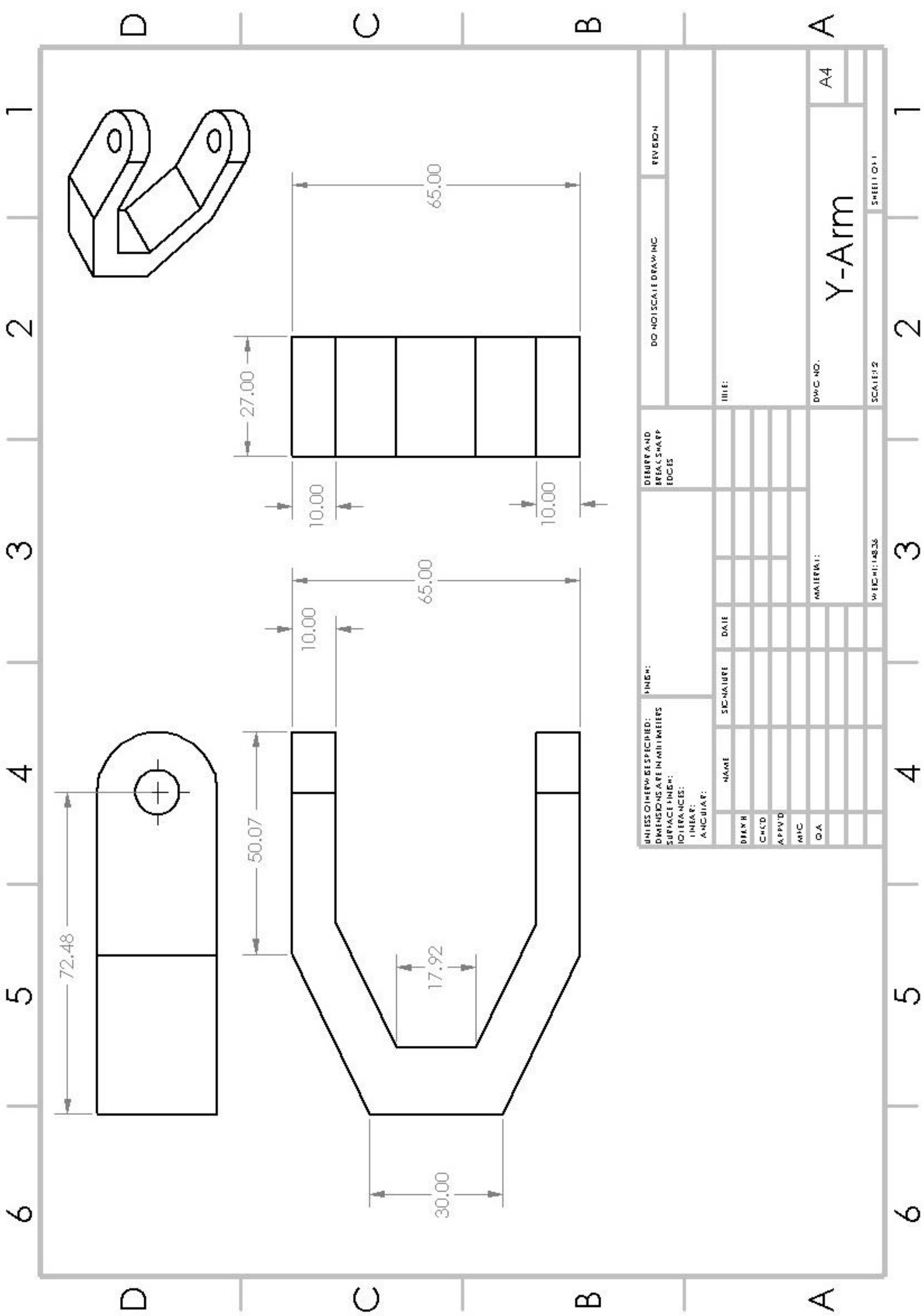
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APPENDIX II: G-CODES:

Front Plate

G21 ; Set units to millimeters
G17 ; Select XY plane
G90 ; Absolute positioning;
Begin milling operation
M6 T1 ; Select tool
M3 S2000 ; Start spindle at 2000 RPM;
Rapid move to initial position
G0 X0 Y0 Z5;

Loop for multiple passes
G10 P0 L0 Z0 ; Set initial Z position
G0 Z0 ; Rapid move to safety height
G21 L1 ; Set units to millimeters in subsequent blocks
M98 P1000 L9 ; Call the subprogram 9 times, passing a depth of 2mm each time; Return to home

G0 Z5 ; Raise above the workpiece
G0 X0 Y0 ; Rapid move to home position
M05 ; Stop spindle
M30 ; End of program;
Subprogram to perform a single pass
O1000
G91 ; Incremental mode
G1 Z-2 F200 ; Lower to cutting depth at a feed rate of 200 mm/min
G90 ; Absolute mode
G1 X0 Y0 F500 ; Move to starting point at a feed rate of 500 mm/min;
Follow profile
G1 X15.29517622 Y0
G1 X59.17438793 Y27.39941822
G1 X74.63090609 Y27.39941822
G1 X74.63090609 Y45.09941822
G1 X94.63090609 Y45.09941822
G1 X94.63090609 Y27.39941822
G1 X105.567789 Y27.39941822
G1 X109.5513299 Y8.558339901
G1 X121.4868635 Y8.558339901
G1 X121.4868635 Y23.49661806
G1 X139.6309061 Y27.46541241
G1 X139.6309061 Y45.16541241
G1 X159.6309061 Y45.16541241
G1 X159.6309061 Y27.46541241
G1 X183.6309061 Y27.46541241
G1 X183.6309061 Y43.04393815
G1 X200.2950048 Y43.04393815
G1 X200.2950048 Y66.86929886

G1 X219.490711 Y67.86929886
G1 X219.490711 Y83.16428287
G1 X204.2624213 Y83.16428287
G1 X199.2656626 Y216.0965899
G1 X205.2298296 Y220.9081676
G1 X205.2298296 Y251.2413798
G1 X219.6257362 Y255.9272297
G1 X219.6257362 Y279.4818327
G1 X202.3629279 Y279.4818327
G1 X197.9090673 Y283.9907697
G1 X197.9090673 Y306.217927
G1 X24.8982073 Y306.217927
G1 X24.8982073 Y295.2631897
G1 X4.563022838 Y291.2796488
G1 X4.563022838 Y225.3708171
G1 X-14.90780363 Y221.5677073
G1 X-14.90780363 Y202.9925255
G1 X35.07310465 Y202.9925255
G1 X38.69990328 Y50.92697318
G1 X16.64448055 Y35
G1 X0 Y35
G0 Z0 ; Rapid move to safety height
M99 ; Return from subprogram

Front Plate Holes
G21 ; Set units to millimeters
G17 ; Select XY plane
G90 ; Absolute positioning;

Begin drilling operation
M6 T2 ; Select drill tool
M3 S1500 ; Start spindle at 1500 RPM;

Drilling holes
G0 X50.2 Y35.25 ; Rapid move to first hole position
G1 Z-2 F200 ; Move to drilling depth
G81 R4 Z-18 F150 ; Begin drilling cycle at Z-18 with a retract plane of Z0 and feed rate of 150 mm/min
X104.49 Y35.63
X129.49 Y35.25
X172.4 Y35.87
X187.26 Y77.21
X187.26 Y127.21
X187.26 Y162.21
X150.93 Y173.24
X187.26 Y197.21
X187.26 Y232.21

X50.69 Y232.21
X50.69 Y197.21
X50.69 Y162.21
X50.69 Y127.21
X50.69 Y92.21
X50.69 Y57.21
G80 ; Cancel drilling cycle;
Drilling large hole
G0 X118.93 Y246.24 ; Rapid move to large hole position
G1 Z-2 F200 ; Move to drilling depth
G83 R26.75 Z-18 Q1 F150 ; Peck drilling with a retract plane of Z0, retract to 1mm above the last peck, and feed rate of 150 mm/min
G80 ; Cancel drilling cycle;
Drilling square shape
G0 X152.21 Y90.84 ; Rapid move to first corner of square
G1 Z-2 F200 ; Move to drilling depth
G1 X181.21 Y90.84 ; Move to next corner
G1 X181.21 Y119.84 ; Move to next corner
G1 X152.21 Y119.84 ; Move to last corner
G1 X152.21 Y90.84 ; Return to first corner to close the square
G0 Z5 ; Rapid retract
G0 X0 Y0 ; Rapid move to home position
M05 ; Stop spindle
M30 ; End of program

Base Plate with Holes
G21 ; Set units to millimeters
G17 ; Select XY plane
G90 ; Absolute positioning;

Begin milling operation
M6 T3 ; Select end mill tool
M3 S1500 ; Start spindle at 1500 RPM;

Rapid move to initial position
G0 X0 Y0 Z5;

Loop for multiple passes
G10 P0 L0 Z0 ; Set initial Z position
G0 Z0 ; Rapid move to safety height
G21 L1 ; Set units to millimeters in subsequent blocks
M98 P1000 L17 ; Call the subprogram 17 times, passing a depth increment of 1mm each time;
Return to home
G0 Z5 ; Raise above the workpiece
G0 X0 Y0 ; Rapid move to home position

M05 ; Stop spindle
M30 ; End of program;

Subprogram to perform a single pass
O1000
G91 ; Incremental mode
G1 Z-1 F200 ; Lower to cutting depth at a feed rate of 200 mm/min
G90 ; Absolute mode;

Inner slots - Slot 1
G0 X40 Y0 ; Rapid move to slot 1 start point
G1 X60 Y-20 ; Mill slot 1
G1 X142.52 Y30
G1 X60 Y0
G1 X157.52 Y30
G1 X104.9469 Y0
G1 X157.52 Y50
G1 X104.9469 Y-19.9316
G1 X142.52 Y50
G1 X124.9469 Y-19.9316
G1 X142.52 Y30
G1 X124.9469 Y0;
Slot 2
G0 X247.5 Y0 ; Rapid move to slot 2 start point
G1 X247.5 Y72.5 ; Mill slot 2
G2 X304.7461 Y116.9875 I95 J0
G2 X217.7984 Y228.8709 I0 J-95
G2 X97.997 Y236.4333 I-115 J0
G2 X0 Y138.4363 I-95 J0
G1 X0 Y0;
Circular profiles - Circle 3
G0 X20 Y95 ; Rapid move to circle 3 center
G1 Z-1 F200 ; Move to cutting depth
G2 X247.5 Y72.5 I0 J-95 ; Mill circle 3
G1 Z0 ; Rapid retract;
Circle 4
G0 X20 Y50 ; Rapid move to circle 4 center
G1 Z-1 F200 ; Move to cutting depth
G2 X154.57 Y159.86 I0 J-20 ; Mill circle 4
G1 Z0 ; Rapid retract
G0 Z0 ; Rapid move to safety height
M99 ; Return from subprogram

Mid Plate with holes and slots
G21 ; Set units to millimeters
G17 ; Select XY plane
G90 ; Absolute positioning;

Begin milling operation
M6 T4 ; Select end mill tool
M3 S1500 ; Start spindle at 1500 RPM;

Rapid move to initial position
G0 X0 Y0 Z5;

Loop for multiple passes
G10 P0 L0 Z0 ; Set initial Z position
G0 Z0 ; Rapid move to safety height
G21 L1 ; Set units to millimeters in subsequent blocks
M98 P1000 L17 ; Call the subprogram 17 times, passing a depth increment of 1mm each time;

Return to home
G0 Z5 ; Raise above the workpiece
G0 X0 Y0 ; Rapid move to home position

M05 ; Stop spindle
M30 ; End of program;
Subprogram to perform a single pass
O1000
G91 ; Incremental mode
G1 Z-1 F200 ; Lower to cutting depth at a feed rate of 200 mm/min
G90 ; Absolute mode;

Inner slots
G0 X0 Y0 ; Rapid move to start of inner slots
G1 X12.3884069 Y0 ; Mill slot 1
G1 X12.3884069 Y34.5647 ; Mill slot 2
G1 X16.6922553 Y39.516 ; Mill slot 3
G1 X28.1558507 Y41.1278 ; Mill slot 4
G1 X28.1558507 Y115.75 ; Mill slot 5 (Circular)
G3 X18.7 Y116.47 I24.88 J78.38 ; Mill circular slot 6
G1 X14.14 Y121.45 ; Mill slot 7
G1 X14.14 Y140.095 ; Mill slot 8
G1 X32 Y140.095 ; Mill slot 9
G3 X32 Y236.764 I24.88 J319.22 ; Mill circular slot 13
G1 X24.88 Y244.52 ; Mill slot 12
G3 X24.88 Y281.474 I24.88 J319.22 ; Mill circular slot 13
G1 X-9.8480519 Y356.96 ; Mill slot 14
G3 X-9.8480519 Y363.365 I24.88 J319.22 ; Mill circular slot 13
G1 X-24.606932 Y363.365 ; Mill slot 16
G1 X-24.606932 Y350.681 ; Mill slot 17
G3 X-45.229218 Y350.681 I-24.88 J319.22 ; Mill circular slot 18
G1 X-45.229218 Y332.362 ; Mill slot 19

G3 X-29.729218 Y332.362 I-24.88 J319.22 ; Mill circular slot 20
G1 X-29.729218 Y304.814 ; Mill slot 21
G1 X-64.58 Y304.814 ; Mill slot 22
G3 X-64.58 Y274.35 I-24.88 J319.22 ; Mill circular slot 23
G1 X-41.73 Y274.314 ; Mill slot 24
G3 X-41.73 Y219.18 I-24.88 J319.22 ; Mill circular slot 25
G1 X-46.23 Y214.68 ; Mill slot 26
G1 X-57.5 Y214.68 ; Mill slot 27
G1 X-57.5 Y198.595 ; Mill slot 28
G1 X-41.5 Y198.595 ; Mill slot 29;

Circular holes
G0 X0 Y0 ; Rapid move to start of circular holes
G3 X0 Y26.75 I0 J26.75 ; Mill circular hole 35
G3 X-41.5 Y26.75 I-41.5 J26.75 ; Mill circular hole 34
G3 X-41.5 Y69.3368 I-41.5 J69.3368 ; Mill circular hole 33
G3 X-64.348314 Y104.337 I-64.348314 J104.337 ; Mill circular hole 32
G3 X-45.229218 Y219.18 I-45.229218 J219.18 ; Mill circular hole 31
G3 X-45.229218 Y332.362 I-45.229218 J332.362 ; Mill circular hole 30

G0 Z0 ; Rapid move to safety height
M99 ; Return from subprogram