Palestine Polytechnic University

College of Engineering

Computer Numerical Control for Wood-working Router Machine

By

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Submitted to the College of Engineering

in partial fulfillment of the requirements for the

Bachelor degree in Mechatronics Engineering

Hebron, May 2017

Palestine Polytechnic University

Collage of Engineering

Mechanical Engineering Department

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Abstract

Since computer numerical control machines have become important tool in manufacturing process, this project aims to design a computer numerical control machine for wood-working that helps wood workers to have their products and to make wood-working easier. However, the target object within project must be treated in three dimensions. To make the design easier for assembly and maintenance a computer aided three-dimensional interactive application (CATIA) program is used. Here three independent stepper motors are used for these axes and the forth motor for drilling purposes. The spindle router is carried by depth-axis. Spindle router and depth-axis are carried on width-axis. Which is carried by length-axis. These axes move smoothly using sliding rods and slide bearing. A micro-controller is used to transfer the instructions from the computer to the motors drivers to control the direction as desired. These motors connected with screws which is used to drive these axes. The target designed using CATIA or ArtCam programs. These programs are used to design, draw or edit the desired work piece with the desired dimensions then get the sequential commands that describe axes movement to form the desired piece (G-Code) from these programs. Then transfer G-code to the microcontroller using Mach three which is connected to the computer and the motors drivers. Three dimensional products were produced using this machine with accuracy within 1 millimeter. Due to the machine size its can be used in the educational purposes to produce a simple three dimension products.

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Chapter 1

Introduction

1.1 Computer Numerical Control

Computer Numerical Control (CNC) is a famous term that involves different types of machines with different sizes, shapes, and functions [13]. CNC machine is a Numerical Control (NC) machine with an added feature of an onboard computer. The onboard computer is often referred as a machine control unit. The control unit is basically a hardware that delivers commands to control all machine parts [14]. In other words, it uses a computer to control a machine parts that carves out useful objects from solid blocks of material [13].

When a user has his own three-dimensional design using computer aided design (CAD), the computer converts the design into useful instruction. However with computer aided manufacturing (CAM), one can achieve more precision tolerance levels. CAM software uses different strategies and methods to generate CNC part programs [15].
CNC produces digitized data. These data control a set of motors and power electronics (drivers) to move the machine spindle router along machine axes.

1.2 Types of CNC Machine

There are several types of CNC machines such as:

1. Milling Machines:
   The milling machine use rotary cutters to cut variety of manufacturing materials. The cutters depend on CNC commands to dictate the depth, direction, and angle of the cut [16], an example of this type of machine can be shown in Figure 1.1.

2. Drilling Machine:
   Drilling machines are used for drilling of different-sized holes in a variety of materials at many different depths [17]. Drilling machine has one degree of freedom (i.e one-dimensional machine) where the tool moves in z-axis [18] as shown in Figure 1.2.

3. CNC Router:
   Routers can cut wood, plastic and sheet metal on three independent axes (X, Y and Z) and are primarily used for manufacturing large scale products [16], an example of CNC Router can be shown in Figure 1.3.

4. Lathes:
   Lathes machines rapidly rotate the workpiece material on a spindle. The material is then pressed against a carving or abrading tool while it spins to cut or shape it. Lathes are used basically for symmetrical objects such as cylinders [16].
   Lathe machines have often two degree of freedom (two dimensional machines; X and Z axes), an example of lathe is shown in Figure 1.4.

5. CNC Plasma Cutters:
   Plasma cutters are made for cutting a profile with two dimensions into sheet metal [19]. Plasma machines use Plasma to penetrate and heat the material enough to cut the material [20], an example of CNC Plasma cutter is shown in Figure 1.5.

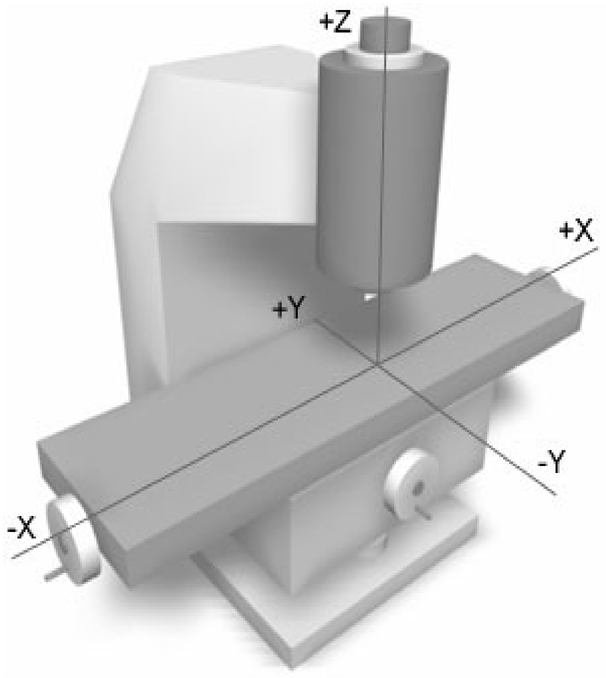


Figure 1.1 Milling Machine [1].

Figure 1.2 Drilling Machine [2].

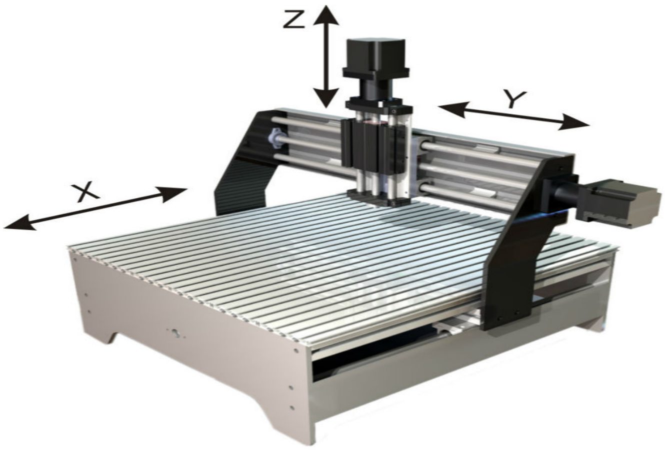


Figure 1.3 CNC Router [3].

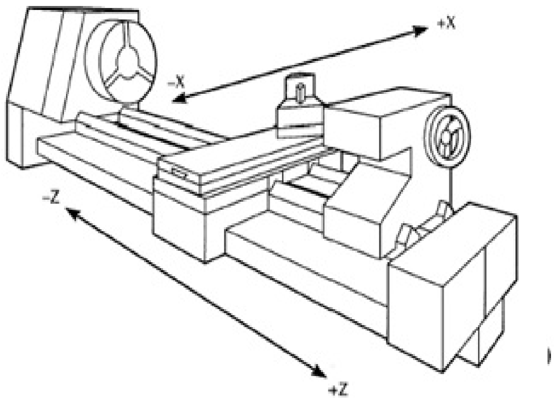


Figure 1.4 Lathes Machine [3].

Figure 1.5 CNC Plasma Cutters [4].

1.3 Requirements

CNC wood-working router machine is required to be done at the end of this project. Where the following requirements should be achieved.

1. The whole volume of the machine does not exceed $1\ m^3$.
2. Produce work piece with dimensions between $(50 \times 50 \times 5)\ mm$ and $(700 \times 400 \times 50)\ mm$.
3. Accuracy within $1\ mm$.
4. The axes of the machine move with speed between $1000\ to\ 4000\ mm/min$.
5. Single phase power source.
6. Using Arduino for controlling.
7. Easy to assemble and maintain.
8. Use End mill $2\ mm$ or $3\ mm$ for the operation (milling).
9. Machining wood piece without burns.

The project requirements have determined where the machine should be cheap as possible, useful in labs, do not occupy large space, and to produce a useful products with one fourth the dimensions in the wood market.

1.4 Goals of the Project

The project aims to design and build a CNC for wood-working machine, which helps wood workers to have their products and making wood-working easier. Therefore, the goal is to design and build CNC machine for wood-working by using mechatronics approach. By using CAD programmes wood workers will design their product. After that, by using CAM programmes they will be able to generate a code which so-called (G-code). This code describe the movement of the cutting tool. On the other hand, by using a microcontroller, it will be able to control the direction and speed of actuators to move the cutting tool.

In this machine a horse-like structure will be used. The target object should be treated in three dimensions (X, Y, and Z). Therefor, three independent actuators will be used; one for length-axis, one for width-axis, and one for depth-axis as described in the electrical design and other additional actuators for drilling purpose. The spindle router will be carried by depth-axis (Z-motor), spindle router and depth axis will be carried by width-axis (Y-motor). The components (spindle motor, depth- and width- axes) will be carried by length-axis (X-motors). Then a micro-controller such as Arduino will be used to transfer the instructions from the computer to the motors drivers to control the direction as desired.

1.5 History

The early history of CNC machining is "almost" as complex as a modern CNC machines. The earliest version of CNC technology was developed shortly after the second World War as a reliable, repeatable way to manufacture more accurate and complex parts for the aircraft industry [5]. In this machine version, numerical control was commissioned in 1947 by the US government. In the same period, Alfred Herbert Limited company [21] in the United Kingdom had their first NC machine tool operating, although Ferranti Limited company produced [22] a more reliable continuous path control system which became available in 1956 [13].

Nowadays, CNC machines becomes cheaper since the use of microprocessors. There is even markets for hoppy and personal CNC machine. CNC machining is still integral to manufacturing and will only continue as more refinements are made [5].

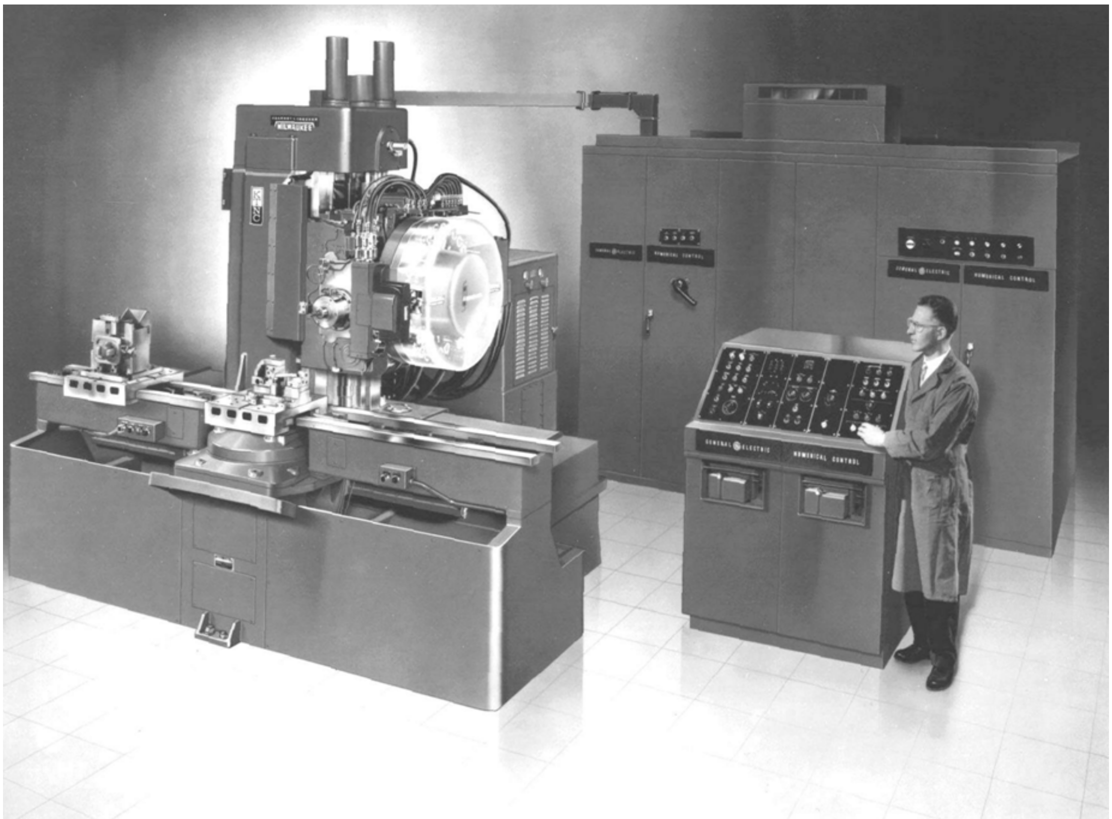


Figure 1.6 Old Computer Numerical Control Machine [5].

1.6 Project Schedule and Time plan

Table 1.1 First Semester Time Plan.

Tasks \ Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
T1	■	■	■	■	■											
T2				■	■	■	■									
T3					■	■			■		■			■		
T4						■	■	■		■			■	■		■
T5								■	■		■	■	■	■	■	■
T6											■			■	■	

where:

T1: Selection the idea of the project.

T2: Research about the idea of the project.

T3: Write the introduction of the project.

T4: Design the mechanical structure of the machine.

T5: Selection the electrical component.

T6: Selection the control software.

Table 1.2 Second Semester Time Plan.

Tasks \ Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
T7	■	■														
T8		■	■	■	■	■	■									
T9						■	■	■								
T10							■	■	■							
T11								■	■	■	■	■				
T12						■	■		■		■	■	■	■	■	■
T13																
T14																

where:

T7: Selection the motors .

T8: Order the components.

T9: Assemble the machine part.

T10: Testing and calibration.

T11: Implementation and validation.

T12: Write final report.

1.7 Cost

The cost of the project is explained in Table 1.3.

Table 1.3 Project Cost.

Elements	Cost (NIS)
Electrical components	1240
Frame	3500
Power screws and nuts	464
Rods and bearing	260+500
Connection components	280
Total cost	6240

Chapter 2

Mechanical Design

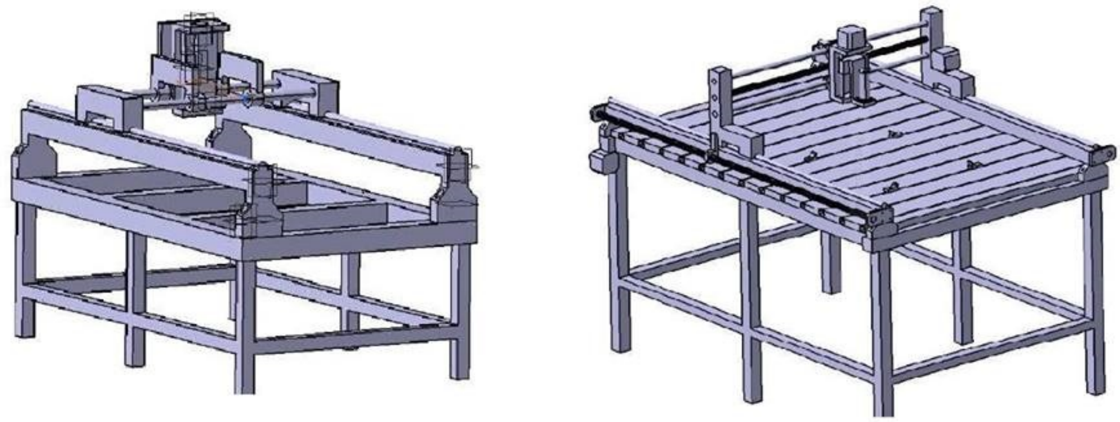
2.1 Introduction to Mechanical Design

This chapter presents the three dimensional drawings and designs of the CNC woodworking machine. The CNC machine supplied with fine product materials to exhibit the required need of the machine.

Ones the material and specification has been determined, the knowledge of mechanical parts as well as CAD software has been used to develop the plans and models to meet the project goals.

Through three designs as shown in Figure 2.1 and Figure 2.2. The first model Figure 2.1(a) is designed to achieve smooth movement. By using precision steel rod on length-, width-, and depth-axes with slide bearing, the axes move with negligible friction. Where the slide bearing of width-axis slides on the sliding rod of length-axis by rotating the screw that link width-axis and the actuator of length-axis. The slide bearing of depth-axis slides on the sliding rod of width-axis by rotating the screw that link depth-axis and the actuator of width-axis. The slide bearing of the spindle router slides on the sliding rod of depth-axis by rotating the screw that link spindle router and the actuator of depth-axis.

The first model can be improve into the second model of Figure 2.1(b) by change some of heavy parts to small parts, these small parts reduce the power that is needed to move the axes, after the model Figure 2.2 has been changed to improve the slight, maintenance, and assembly by using bolts, small parts and standard pieces that present in the market with standard dimensions.



(a) (b)

Figure 2.1 Mechanical Designs: a.First Model; b.Second Model.

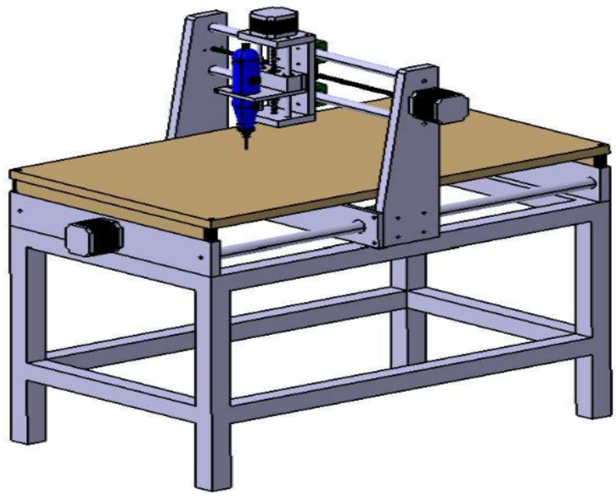


Figure 2.2 The Third Model.

The CNC wood-working machine consist of five main parts; main table, length-axis, width-axis, depth-axis and spindle router. The whole volume of the CNC wood-working machine is $(850 \times 630 \times 1080)\ mm$ since this machine is designed to be cheap as possible, useful in labs, do not occupy large space, and to produce a products with one third the dimensions in the wood market.

2.2 The Main Table

A main table is a table with four legs. These legs are connected together. The main table carries all parts of the machine; length-axis, width-axis, depth-axis,and spindle router as shown in Figure 2.2. The main table consist of one main parts; The main table.

- The main table:
  The main table has four legs of square steel tube with dimension of $40\ mm$ length, $40\ mm$ width, and $3\ mm$ thickness as standard for square steel tube and to carry the other parts without failure. These legs connected together to prevent failure and to be lightweight. The whole volume of the main table is $(850 \times 500 \times 600)\ mm$ to carry all other parts. These legs connected together as shown in Figure 2.3.

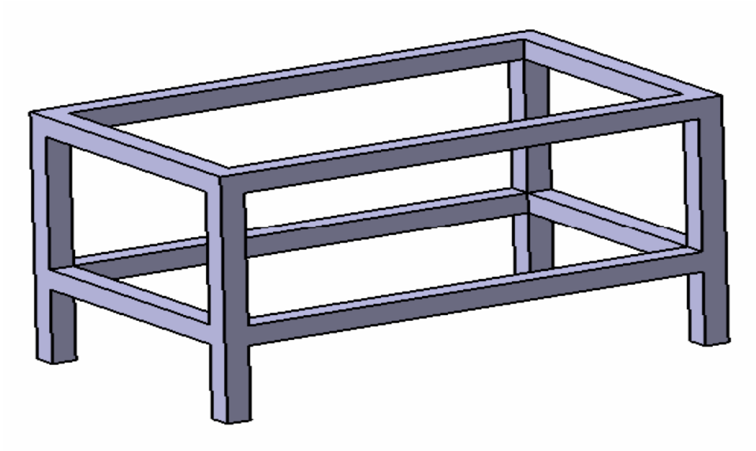


Figure 2.3 Main Table.

2.3 Length-Axis

In the length-axis, two parallel stands are located on the main table edge as shown in Figure 2.2 and Figure 2.4. These stands carry the sliding rod of length-axis, legs of width-axis, and mechanism of depth-axis as will as the spindle router of the machine.

Length-axis has two main part which is length-axis stands and work table. Length-axis allow width-axis to move in range varies from $(0\ to\ 700)\ mm$ to prevent shock between length-axis edge and width-axis.

- Length axis stands:

  Length-axis bar is aluminum stand with dimension of $(500 \times 80)\ mm$ and $20\ mm$ thickness since it will be located on the main table. Length-axis stands carry sliding rods which are carry all the other parts. Length-axis shown in Figure 2.4.

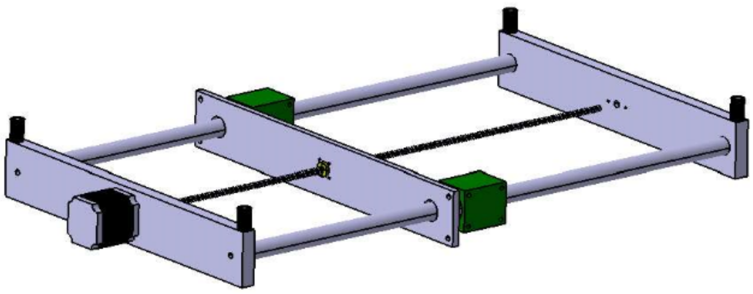


Figure 2.4 Length-axis.

- Work table:

  The work table is a plane shape of $(850 \times 490 \times 17)\ mm$ of wood to carry the wood piece and be consistent with length-axis stands. This work table prevents the failure of cutting tool if the tool exceeds the wood piece. It is fixed on the length-axis stand by four bolts. The work piece fixed on the work table by four wood screws. The work table is shown in Figure 2.5.

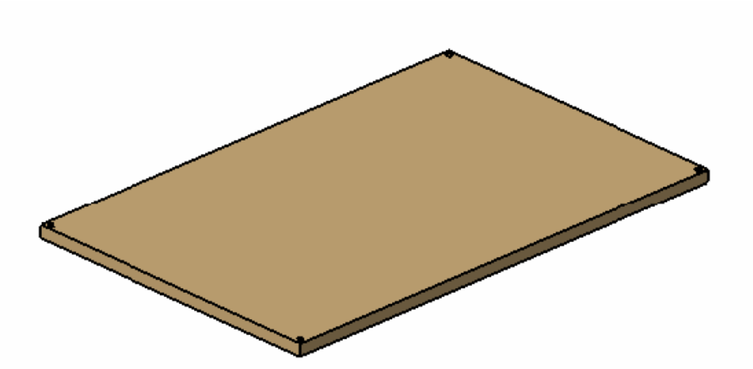


Figure 2.5 Work Table.

2.4 Width-Axis

The width-axis is built from two standing legs as shown in Figure 2.6 and carries depth-axis components and spindle router. Width-axis legs is carried by the length-axis sliding rods. Width-axis has two main part which is width-axis legs and length movement bar. Width-axis allow depth-axis to move in range varies from $(0\ to\ 400)\ mm$ since the dimension of the machine, safe distance to prevent shock between width-axis legs and depth-axis edge, and the center of the cutting tool is $50\ mm$ away from the depth-axis edge.

- Width-axis legs:
  The width-axis legs is aluminum with dimension of $(120 \times 400)\ mm$ and $20\ mm$ thickness to prevent failure the distance between the two legs is $510\ mm$ to allow depth-axis to move with right distance. Width-axis legs carry all other parts of width-axis. Width-axis shown in Figure 2.6.

- Length movement bar:

  Length movement bar is aluminum with dimension of $(550 \times 65)\ mm$ and $20\ mm$ thickness. Length movement bar used to connect width-axis legs with length-axis screw to move width-axis along length-axis. Length movement bar is shown in Figure 2.6.

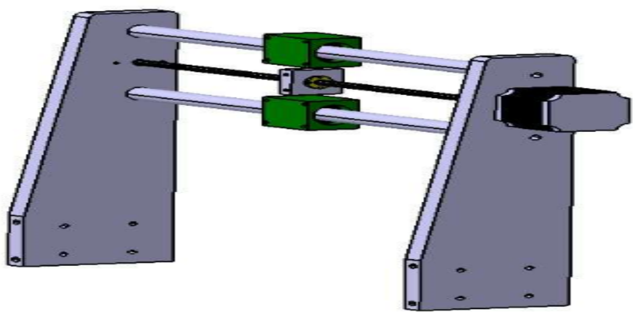


Figure 2.6 Width-axis.

2.5 Depth-Axis

The depth-axis carries spindle router. Depth-axis is carried by the width-axis legs. Depth-axis has two main parts; depth-axis carriage and motor clamp. As we design the depth-axis allow spindle router to move in range varies from $(0\ to\ 90)\ mm$ to make right distance to fix the wood piece and to drill varies depth of cut as we discussed in section 2.2. Depth-axis shown in Figure 2.7.

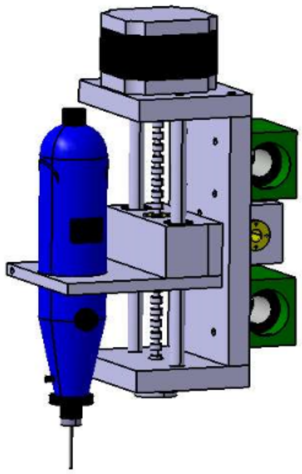


Figure 2.7 Depth-axis.

- Depth-axis carriage:
  The depth-axis carriage is aluminum since to be lightweight and it is strong enough. The carriage of depth-axis is designed with dimension of $(75 \times 100 \times 210)\ mm$ to fit with drill range. Depth-axis carriage carries all other parts of depth-axis.

- Motor Clamp:
  The motor clamp is made from aluminum since it must be lightweight. It is used to hold the spindle router to a piece by set of screws, which is connected to the sliding rods as shown in Figure 2.8.

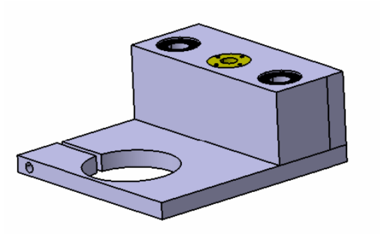


Figure 2.8 Motor Clamp.

2.6 Common Parts

1. Sliding rods:

   The machine has six sliding rods in length-, width-, and depth-axes with $25\ mm$ precision diameter for length-axis, $20\ mm$ precision diameter for width-axis, and $10\ mm$ precision diameter for depth-axis to prevent failure by using standard diameter and length of $810\ mm$ it the length-axis to be located on length-axis bars, $510\ mm$ in the width-axis to be located between width-axis legs, and $190\ mm$ in depth-axis to be located on depth-axis carriage. The sliding rods are made from carbon steel with smooth surface. So that we have minimum friction affects when the axes move. Sliding rod shown in Figure 2.9.

Figure 2.9 Sliding Rod [6].

2. Slide bearings and linear ball bearings:

   The machine has four slide bearings and two linear ball bearings. Two of slide bearings are used to make the width-axis slide on the length-axis sliding rods with negligible friction. The other slide bearings are used to make the depth-axis slides on the width-axis sliding rods with negligible friction. The linear ball bearing used to make the motor clamp carriage slides on the depth-axis sliding rods with negligible friction. Slide bearing shown in Figure 2.10 and the linear ball bearing shown in Figure 2.11.

Figure 2.10 Slide Bearing [6].

Figure 2.11 Linear Ball Bearing [6].

3. Anti-Backlash Nut:

   The backlash is a "measurable" space in the nut as it changes its position and move direction it affects the machine accuracy. The anti-backlash nuts are used to improve the accuracy of the machine where the anti-backlash nut prevent the backlash. In this machine there are three anti-backlash nuts; One for Length axis connect between the length-axis screws and the width-axis legs and one for width-axis connect between the width-axis screw and the depth-axis carriage. Anti-Backlash nut consist of two nuts connected together and spring make them far away from each other to prevent backlash as shown in Figure 2.12.

Figure 2.12 Anti-Backlash Nut [6].

4. Screws:

   The machine has four screws, two used for length-axis with length $850\ mm$ to be located on length-axis bars, one for width-axis with length $526\ mm$ to be located between width-axis legs, and one for depth-axis with length $200\ mm$ to be located on depth-axis carriage. The screws are connected with the motors to drive the axes each one is connected with one motor in one side and in the other side it connect with flanged bearing bore. Screw is shown in Figure 2.13.

Figure 2.13 Screw [6].

5. Motor Coupler:

   Motor coupler is used to make sure that the motors are connected with the screws.

The motor coupler connects the motor shaft with the screw, it is designed to meet the different diameters of motor shafts and screws. Motor Coupler is shown in Figure 2.14.

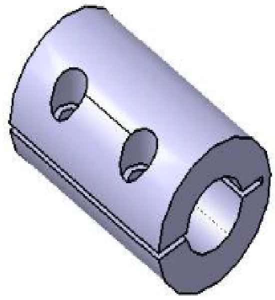


Figure 2.14 Motor Coupler.

6. Flanged Bearing:
   Flanged bearing bore used to hold the screw horizontally or vertically from the other last end of the screw. Flanged bearing bore is shown if Figure 2.15.

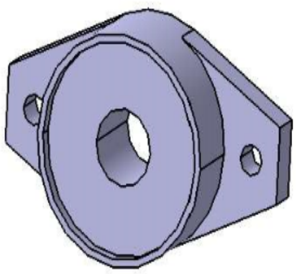


Figure 2.15 Flanged Bearing.

7. Bolts:
   Bolts Figure 2.16 are used for assembly of multiple parts in this machine.

Figure 2.16 Bolts [6].

2.7 Static Analysis

The main object of this section is to show how the machine system is safe without structure failure. The main particles that are in expected to fail or have deformation are the beams (The sliding rods) that carry the weight of the axes. We need to determine structural loads, geometry, support conditions, and materials properties.

2.7.1 Reaction

- Width-axis beam:

  First calculate the reactions exerted on the width-axis beams. Initially the free body diagram of the depth-axis carriage as shown in Figure 2.17. The carriage is supported at point A and B. The reaction in (Newton) are denoted by R_{Az}, R_{Ax}, R_{Bz}, and R_{Bx}. Using the principle of reaction the forces are the same for both beams but difference in direction for X-axis.

  Using CATIA software to get mass and center of mass for each part. CATIA is acronym of computer aided three-dimensional interactive application. CATIA enables the creation of three-dimensional parts, from three-dimensional sketches. CATIA enable user to model and simulate a wide range of complex systems. From CATIA software the mass of the whole depth-axis with spindle router is $4.7\ Kg$.

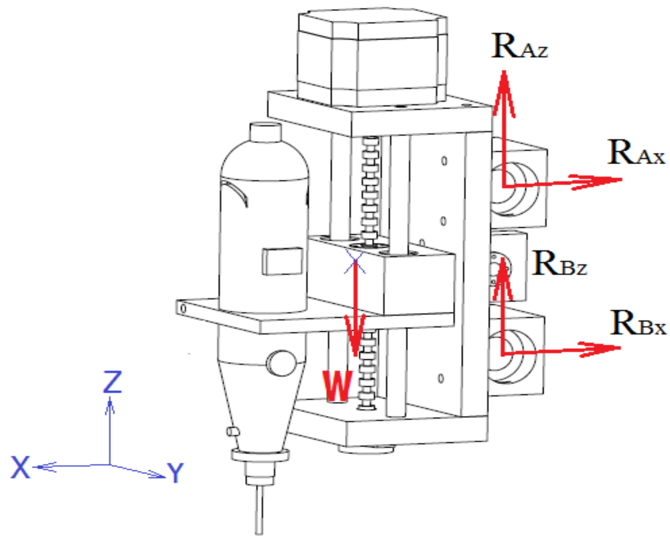


Figure 2.17 Depth-axis Free Body Diagram.

The weight $(W_{depth-axis})$ of it is.

$$W_{depth-axis} = mg = 4.7 \times 9.81 = 46.107N. \tag{2.1}$$

where:

m: mass in Kilogramme.

g: acceleration of gravity in $[meter/second^2]$.

The weight is assumed to be about $47\ N$. By using CATIA software to get the center of mass(CM) of the depth-axis is shown in Figure 2.18 in Y-Z plane and Figure 2.19 in X-Z plane.

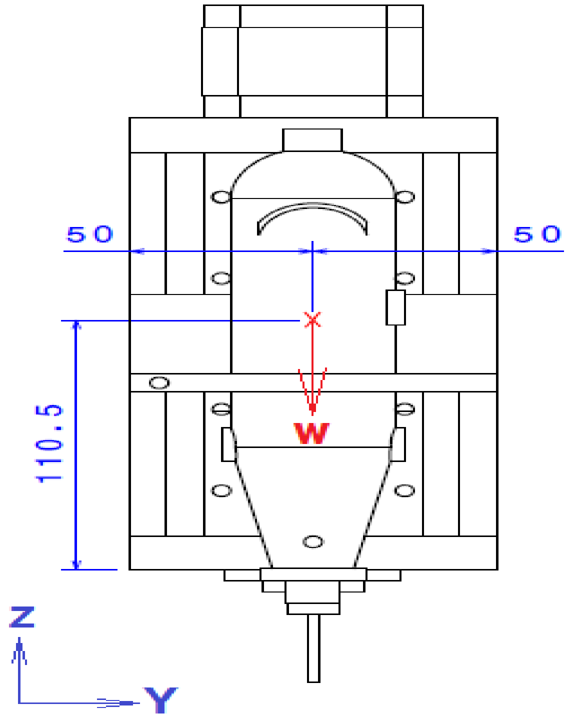


Figure 2.18 Center of Mass in Y-Z Plane.

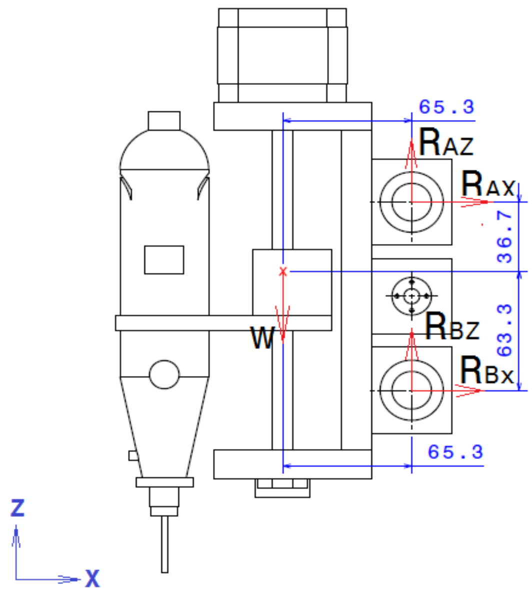


Figure 2.19 Center of Mass in X-Z Plane.

Summing the moment at point A or B

$$\sum M_{A,B} = 0 \tag{2.2}$$

$$W_{depth-axis} \times 0.0633 - R_{Bx} \times (0.0633 + 0.0367) = 0$$

$$R_{Ax} = 30.7\ N$$

$$R_{Bx} = 30.7\ N$$

where:

M: moment in $[Newton.meter^2]$.

W: weight in Newton.

R: reactions in Newton.

Summing the forces in Z-direction

$$\sum F_Z = 0 \tag{2.3}$$

$$R_{Az} + R_{Bz} = W_{depth-axis}$$

where:

F: force in Newton.

R: reaction in Newton.

From this equation the maximum force of R_{Az} and R_{Bz} in Z-direction is $22.5N$.

Since the location, magnitude, and the direction of the reaction forces in depth-axis beams have been determined. These reactions affect on width-axis beams as shown in Figure 2.20. The weight of the beams will be treated as distributed load. The distributed load means the load per length in (Newtons/meter). To find the effect of the beam load, we assumed that the mass is uniform across the beam. The weight of beam depends on various parameters such as a density, a diameter, and a length of a beam.

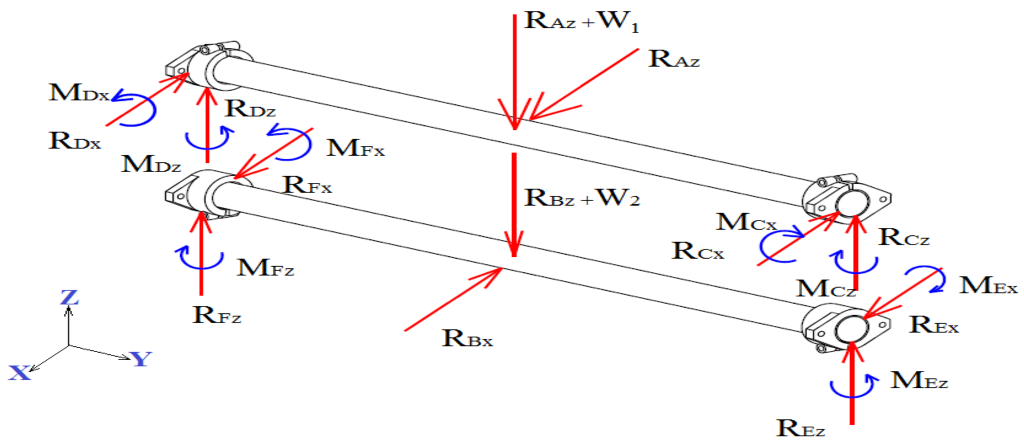


Figure 2.20 Width-axis Free Body Diagram.

The weight equals.

$$W = wl \tag{2.4}$$

where w is the distributed load and l is the length of the beam. The distributed load is found by.

$$wl = mg$$

$$wl = \rho g l \frac{\pi d^2}{4}$$

$$w = \frac{\rho g \pi d^2}{4} [N/m]$$

$$w = 24.2 \; [N/m]$$

where:

ρ: density of the carbon steel in $[kilogramme/meter^3]$.

g: acceleration of gravity in $[meter/second^2]$.

l: length of the rod in meter.

d: rod diameter in meter.

Using Appendix I the reaction forces (R_{Cx}, R_{Cz}, R_{Dx}, R_{Dz}, R_{Ex}, R_{Ez}, R_{Fx}, and R_{Fz}) and reaction moments (M_{Cx}, M_{Cz}, M_{Dx}, M_{Dz}, M_{Ex}, M_{Ez}, M_{Fx}, and M_{Fz}) for $beam_{C-D}$ and $beam_{E-F}$ have been obtained.

Since the forces on $beam_{C-D}$ are equal the forces on $beam_{E-F}$ the force reaction and the moment reaction for both are the same, but the direction of the force and moment are opposites in X-direction. Figure 2.21 shows the force and moment reactions in Y-Z plane and Figure 2.22 shows the force and moment reactions in X-Y plane.

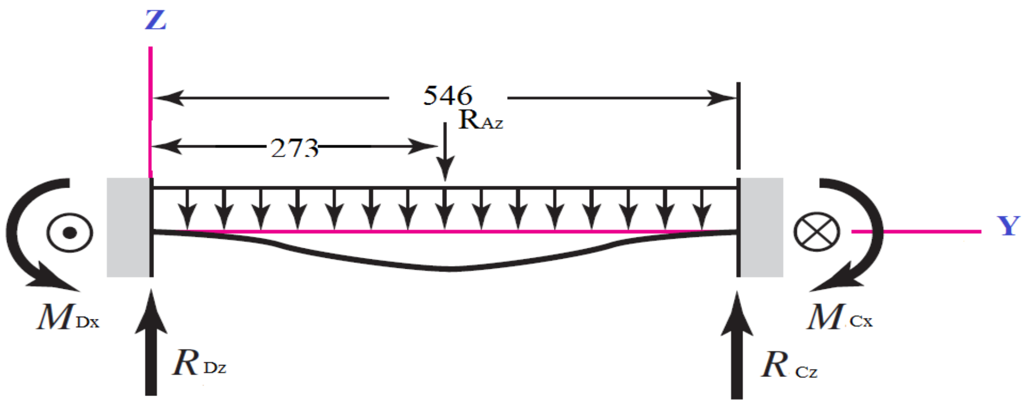


Figure 2.21 Reaction on $beam_{C-Dbeam}$ or $beam_{E-F}$ in Y-Z Plane.

$$R_{Cz} = R_{Dz} = 18.3614\ N$$

$$R_{Ez} = R_{Fz} = 18.3614\ N$$

$$M_{Cx} = M_{Dx} = 2.2055\ N.m$$

$$M_{Ex} = M_{Fx} = 2.2055\ N.m$$

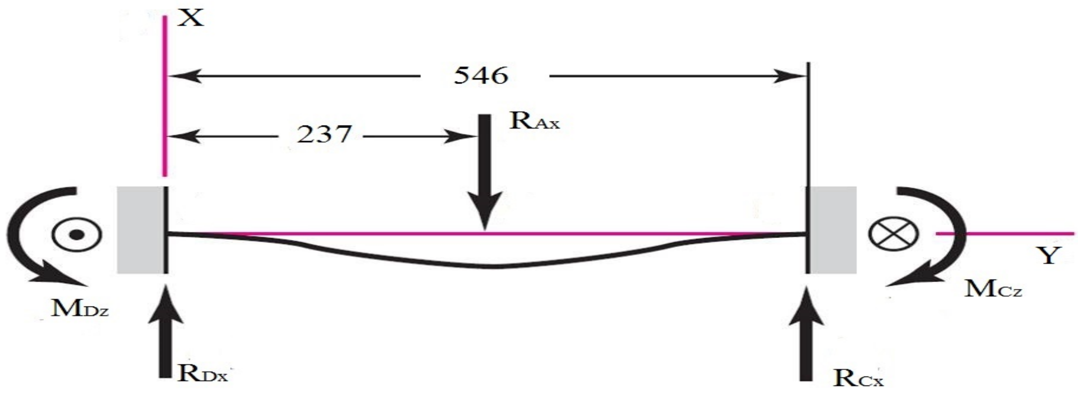


Figure 2.22 Reaction on $beam_{C-Dbeam}$ or $beam_{E-F}$ in X-Y Plane.

$$R_{Cx} = R_{Dx} = 15.35\ N$$

$$R_{Ex} = R_{Fx} = -15.35\ N$$

$$M_{Cz} = M_{Dz} = 2.1\ N.m$$

$$M_{Ez} = M_{Fz} = -2.1\ N.m$$

The maximum force reaction and moment reaction on point C or D and point E or F will be when the depth-axis is $110\ mm$ away from beam edge since the dimension of the machine, as shown in Figure 2.23 and Figure 2.24.

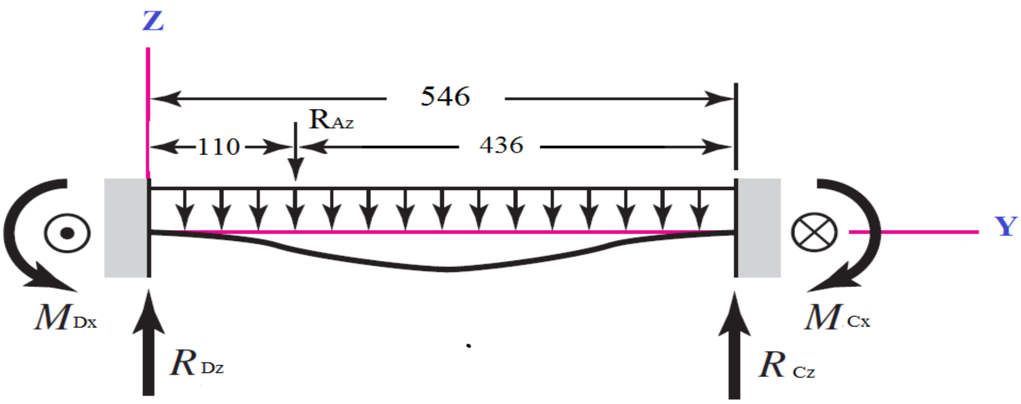


Figure 2.23 Maximum Reaction on $beam_{C-Dbeam}$ or $beam_{E-F}$ in Y-Z Plane.

$$R_{Cz} \text{ or } R_{Dz} = 27.6343\ N$$

$$R_{Ez} \text{ or } R_{Fz} = 27.6343\ N$$

$$M_{Cx} \text{ or } M_{Dx} = 2.25\ N.m$$

$$M_{Ex} \text{ or } M_{Fx} = 2.25\ N.m$$

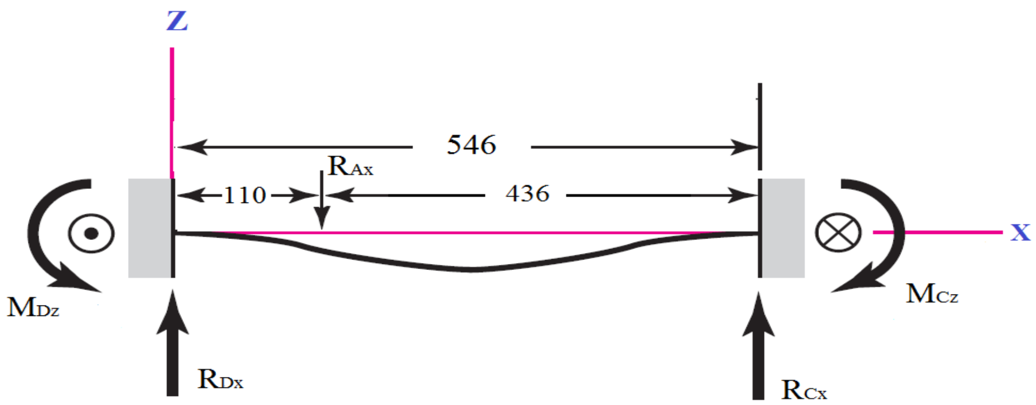


Figure 2.24 Maximum Reaction on $beam_{C-Dbeam}$ or $beam_{E-F}$ in X-Y Plane.

$$R_{Cx} \text{ or } R_{Dx} = 27.5\ N$$

$$R_{Ex} \text{ or } R_{Fx} = -27.5\ N$$

$$M_{Cz} \text{ or } M_{Dz} = 2.15\ N.m$$

$$M_{Ez} \text{ or } M_{Fz} = -2.15\ N.m$$

- Length-axis beam:

  After determine the force reactions and moment reactions on width-axis beam, the reaction exerted on the length-axis beams would be calculated. Initially the free body diagram of the width-axis legs Figure 2.25, the legs is supported on the slide bearing, the reactions are replaced in one reaction equal sum of all of them since it easier to determine and have the same result.

The reaction that will be used to determine the length-axis reaction will be the maximum reaction exerted on point C or D and point E or F.

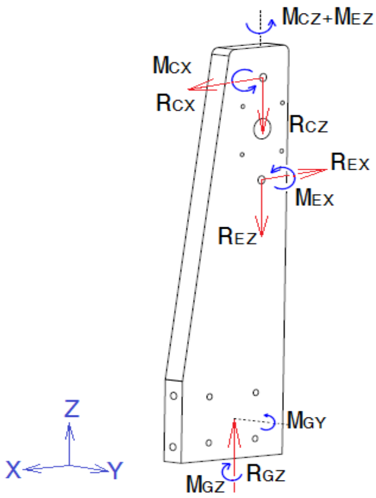


Figure 2.25 Width-axis Carriage Free Body Diagram.

From CATIA software the mass of the whole width-axis legs is $2.2Kg$. The weight of it is.

$$W_{width-axis-carriage} = mg = 2.2 \times 9.81 = 21.6\ N. \tag{2.5}$$

where:

W: weight in Newton.

m: mass in Kilogramme.

g: acceleration of gravity in $[meter/second^2]$.

The weight is assumed to be about $22\ N$. Using CATIA software to get the CM of the depth-axis is shown in Figure 2.26.

By summing the moment at point G

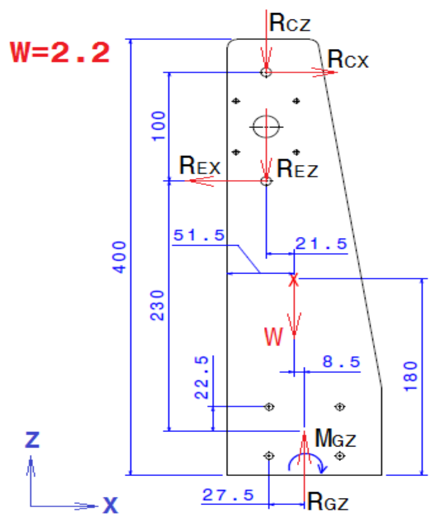


Figure 2.26 Center of Mass and Reactions for Width-axis Carriage

$$\sum M_G = 0 \tag{2.6}$$

$$-M_{Gy}+W_{width-axis-carriage}\times0.0085+R_{Cz}\times0.03+R_{Ez}\times0.03-R_{Cx}\times0.33+R_{Ex}\times0.23=0$$

$$M_{Gy} = -0.9\ N.m$$

where:

M: moment in $[Newton.meter^2]$.

W: weight in Newton.

R: reactions in Newton.

Summing the forces in Z-direction

$$\sum F_Z = 0 \tag{2.7}$$

$$R_{Gz} - R_{Cz} - R_{Ez} - W_{width-axis-carriage} = 0$$

$$R_{Gz} = 77.27\ N$$

where:

F: forces in Newton.

R: reactions in Newton.

Summing the force in X-direction

$$\sum F_X = 0 \tag{2.8}$$

$$R_{Cx} - R_{Ex} = 0$$

where:

F: forces in Newton.

R: reactions in Newton.

From Equation **??** there is no force at point G in X-direction, and the reaction moment about Z-axis (M_{GZ}) equal zero.

$$\sum M_z = -M_{Gz} + M_{Cz} - M_{Ez} \tag{2.9}$$

$$M_{Gz} = 0$$

Since the location, magnitude, and the direction of the reaction forces in width-axis legs have been determined. These reaction affected on length-axis beams as shown in Figure 2.27. The weight of the beams will be treated as distributed load due to their weights. From Equation 2.4 the weight equals.

$$w = 37.84\ [N/m]$$

where:

w: the distributed load in [Newton/meter].

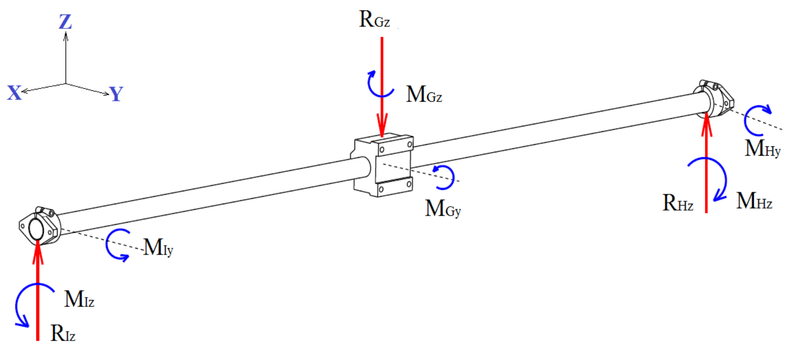


Figure 2.27 Length-axis Free Body Diagram.

Using Appendix I the force reactions (R_{Hy}, R_{Hz}, R_{Iy}, R_{Iz}, R_{Jy}, R_{HJz}, R_{Ky}, and R_{Kz}) and moment reactions (M_{Hz}, M_{Hy}, M_{Iz}, M_{Hy}, M_{Jz}, M_{Jy}, M_{Kz}, and M_{Ky}) for $beam_{H-I}$ and $beam_{J-K}$ have been obtained, as shown in Figure 2.28.

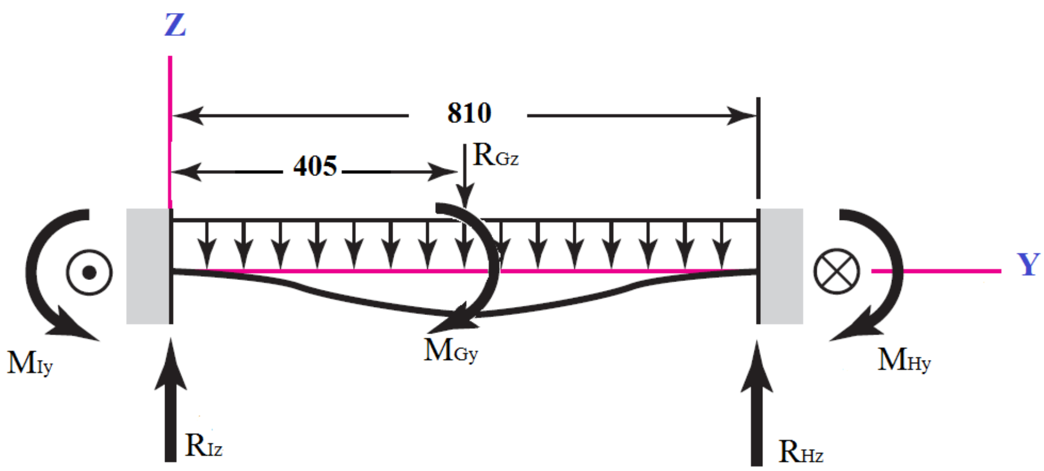


Figure 2.28 Reaction on $beam_{H-Ibeam}$ or $beam_{J-K}$ in X-Z Plane.

$$R_{Hz} = 53.66\ N$$

$$R_{Iz} = 55.77\ N$$

$$R_{Jz} = 53.66\ N$$

$$R_{Kz} = 55.77\ N$$

$$M_{Hy} = 9.6\ N.m$$

$$M_{Iy} = 11.4\ N.m$$

$$M_{Jy} = 9.6\ N.m$$

$$M_{Ky} = 11.4\ N.m$$

In X-Y plane there is no reaction since the moment cancelation.

2.7.2 Maximum Deflection

After determine the diameter size of the sliding rods, we determine the maximum deflection on each rods due to the forces uploaded to them. Applying the deflection equations in Appendix I at the middle of the rods since the maximum deflection is achieved when the forces in the middle. The maximum deflection of $beam_{C-D}$ and $beam_{E-F}$ is the same since it has the same forces. The maximum deflection of $beam_{H-I}$ and $beam_{J-K}$ is the same since it has the same forces.

The deflection of $beam_{C-D}$ and $beam_{E-F}$ in Z-direction is determined as follow.

$$y_{max} = -\frac{R_{Az} l^3}{192EI} - \frac{wl^4}{384EI} \tag{2.10}$$

where:

R_{Az}: the reaction force in Newton.

l: length of the rod in meters.

E: modulus of elasticity in Pascal of the rod and it is equal $205GPa$.

I: second moment of area in m^4.

w: continuous load of the rod weight in [N/m].

$$y_{max} = -1.5 \times 10^{-5}\ m$$

The deflection of $beam_{C-D}$ and $beam_{E-F}$ in X-direction is determined as follow.

$$y_{max} = -\frac{R_{Ax} l^3}{192EI} \tag{2.11}$$

where:

R_{Ax}: the reaction force in Newton.

l: length of the rod in meters.

E: modulus of elasticity in Pascal of the rod and it is equal $205GPa$.

I: second moment of area in m^4.

$$y_{max} = -1.6 \times 10^{-5}\, m$$

The deflection of $beam_{H-I}$ and $beam_{J-K}$ in Z-direction is determined as follow.

$$y_{max} = -\frac{R_{Gz} l^3}{192EI} - \frac{wl^4}{384EI} \tag{2.12}$$

where:

y: deflection in meter.

R_{Gz}: the reaction force in Newton.

l: length of the rod in meters.

E: modulus of elasticity in Pascal of the rod and it is equal $205GPa$.

I: second moment of area in m^4.

w: continuous load of the rod weight in Newtons per meter.

$$y_{max} = -7.5 \times 10^{-5}\, m$$

2.8 Dynamic Analysis

The main goal of this section is to determine the size of the actuators on each axis.

2.8.1 Power Screw

The power screw is a drive used in machinery to convert a rotary motion into a linear motion for power transmission. Since it produces uniform motion the nut moves axially along the screw in which the nut fixed with the axis carriages. The linear movement along each axis in the machine is being controlled using a power screw attached to a stepper motor by flexible coupling, Figure 2.29 shows power screw mechanism.

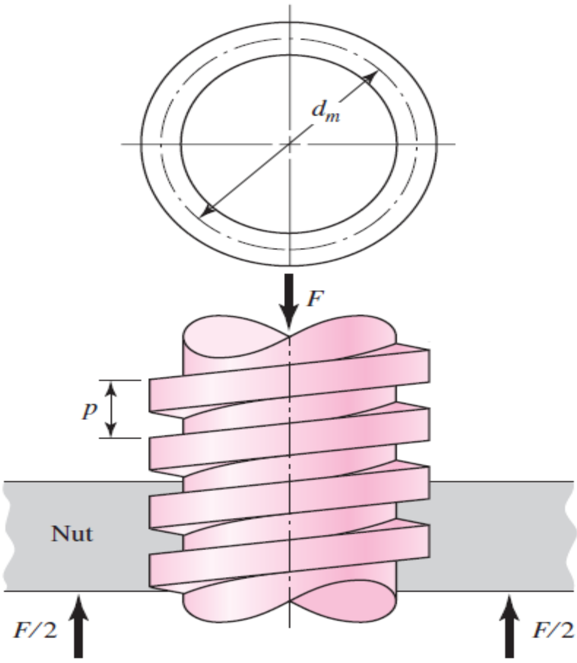


Figure 2.29 Lead Screw Mechanism [7].

2.8.2 Trapezoidal Screw

The form is that we will used is the trapezoidal threads. The trapezoidal screws are more popular in CNC machines. The shape of the trapezoidal with a wider base of the tooth gives it a better carrying of loads. The trapezoidal screws have high efficiency and low friction forces and low radial loads. Figure 2.30 shows the trapezoidal screw.

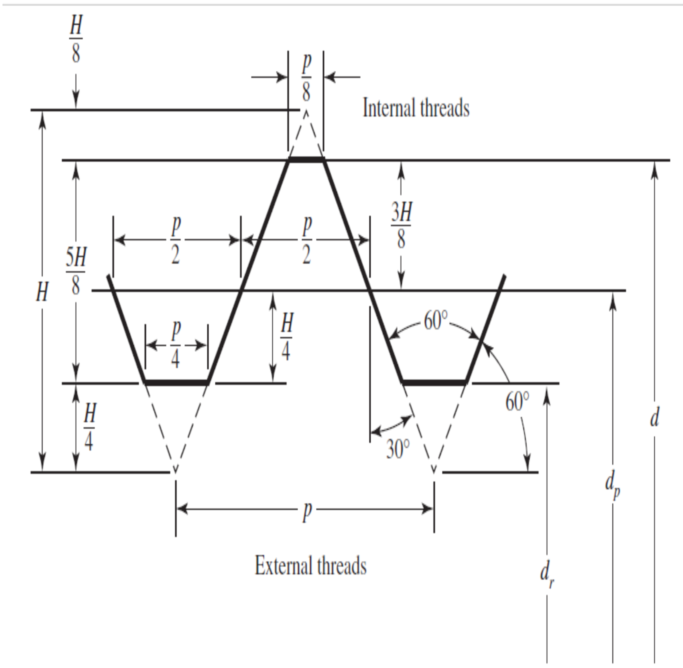


Figure 2.30 Trapezoidal Screw [7].

2.8.3 Power

For depth-axis the torque needed to move the spindle router in Z-direction should be found. The spindle router moves in Z-direction depends on the geometry of the screws, the nurture of the material, and the relatives friction between the nut and the power screw.

The torque required to rise and lower the spindle router is obtained by assuming the system equilibrium by taking the forces need to weight forces, rise or lower forces, and the friction forces. The raising torque is required to overcome the thread friction and to raise the load in Z-direction. The raising torque T_R is given by [7]

$$T_R = \frac{F d_m}{2} \frac{l + \pi f d_m \sec\theta}{\pi d_m - f l \sec\theta} \tag{2.13}$$

where:

F: force in Newton.

d_m: mean diameter in meter. l: the power screw lead that demonstrates the traveling distance of the nut when the screw shaft makes one rotation and it is equal $number - of -$

$threads(n) \times pitch$.

f: friction coefficient and it is equal 0.23.

The lowering torque required to lower the spindle router and overcome the spindle router of friction $T_L$is found by [7]

$$T_L = \frac{Fd_m}{2} \frac{\pi f d_m \sec\theta - l}{\pi d_m + f l \sec\theta} \tag{2.14}$$

where:

F: force in Newton.

d_m: mean diameter in meter.

l: the screw lead that demonstrates the traveling distance of the nut when the screw shaft makes one rotation and it is equal $number - of - threads(n) \times pitch$.

f: friction coefficient and it is equal 0.23.

The self-locking in depth-axis is the most thing must be achieve since if there is no self-locking the spindle router will be move in Z-direction due to its weight. The self-locking is achieved when the following equation is achieved.

$$\pi f d_m > l \tag{2.15}$$

where:

d_m: mean diameter in meter.

f: friction coefficient and it is equal 0.2.

By applying Equation 2.15 we chose a screw $T_r 8 \times 2$ for depth-axes and it has the following specification in Table 2.1.

Table 2.1 Screw Specification

Major Diameter (d)	**Minor Diameter** (d_r)	**Mean Diameter** (d_m)	**Pitch** (p)	**Lead** (l)	**Thread Angle** (2θ)
8	6	7	2	2	30

A typically router at around a $4000\ mm/min$ would need an acceleration on the order of $2300 rad/s^2$.

- The calculation of the depth-axis:

  Calculate the inertia (J).

  The mass of spindle router and the carriage equal $M = 1.7\ Kg$.

  The mass of the screw

$$m_{screw} = \frac{1}{2}\pi r^2 length \times density \tag{2.16}$$

$$m_{screw} = 0.04\ Kg$$

$$J_{load} = \frac{Mp^2}{4\pi^2} \tag{2.17}$$

$$J_{load} = 1.73 \times 10^{-7}\ Kg.m^2$$

$$J_{screw} = \frac{1}{2} m_{screw} r^2 \tag{2.18}$$

$$J_{screw} = 3.2 \times 10^{-7}\ Kg.m^2$$

$$J_{total} = J_{load} + J_{screw} \tag{2.19}$$

$$J_{total} = 4.93 \times 10^{-7}\ Kg.m^2$$

$$T_a = \alpha J_{total} \tag{2.20}$$

$$T_a = 1.134 \times 10^{-3}\ N.m$$

From Equation 2.13

$$F = mg \tag{2.21}$$

$$F = 16.68\ N$$

$$T_R = 0.021\ N.m$$

$$T_{total} = T_R + T_a \quad (2.22)$$

$$T_{total} = 0.022\ N.m$$

For Factor of safety K_s equal 2.

$$T_{motor} = K_s T_{total} \quad (2.23)$$

$$T_{motor} = 0.044\ N.m$$

The lowering torque T_L by using Equation 2.14

$$T_L = 9.95 \times 10^{-3}\ N.m$$

- The calculation of the width-axis:

  Screw specification for length- and width-axes is showin in Table 2.2.

Table 2.2 Screw Specification

Major Diameter (d)	**Minor Diameter** (d_r)	**Mean Diameter** (d_m)	**Pitch** (p)	**Lead** (l)	**Thread Angle** (2θ)
8	6	7	2	8	30

Calculate the inertia (J).

The mass of spindle router,depth-axis, and the carriage equal $M = 4.7Kg$.

The mass of the screw

$$m_{screw} = \frac{1}{2}\pi r^2 length \times density \quad (2.24)$$

$$m_{screw} = 0.11\ Kg$$

$$J_{load} = \frac{Mp^2}{4\pi^2} \quad (2.25)$$

$$J_{load} = 4.76 \times 10^{-7}\ Kg.m^2$$

$$J_{screw} = \frac{1}{2} m_{screw} r^2 \tag{2.26}$$

$$J_{screw} = 8.8 \times 10^{-7}\ Kg.m^2$$

$$J_{total} = J_{load} + J_{screw} \tag{2.27}$$

$$J_{total} = 13.56 \times 10^{-7}\ Kg.m^2$$

$$T_a = \alpha J_{total} \tag{2.28}$$

$$T_a = 3.12 \times 10^{-3}\ N.m$$

The frictional component of the torque, this is given by

$$T_f = \frac{F_{total} p}{2\pi e} \tag{2.29}$$

where:

T_f: frictional torque in Newton.meter.

F_f: frictional force in Newton.

p: pitch in meter.

e: efficiency and it is equal 30% for trapezoidal screws (bronze nut on steel) [23].

$$F_f = M g f_c \tag{2.30}$$

where:

M: depth-axis mass.

f_c: static friction coefficient and it is equal 0.23 [23].

From Equation 2.30

$$F_f = 10.6\ N$$

$$F_{total} = F_f + F_{cutting} \tag{2.31}$$

where:

$F_{cutting}$: cutting force and it is equal $2\ to\ 5\ N$ [23].

$$F_{total} = 15.6\ N$$

From Equation 2.29

$$T_f = 16.6 \times 10^{-3}\ N.m$$

$$T_{total} = T_f + T_a \tag{2.32}$$

$$T_{total} = 19.7 \times 10^{-3}\ N.m$$

For Factor of safety K_s equal 4.

$$T_{motor} = K_s T_{total} \tag{2.33}$$

$$T_{motor} = 0.08 N.m$$

- The calculation of the length-axis:

  Calculate the inertia (J).

  The mass of width-axis, spindle router,depth-axis, and the carriage equal $M = 13Kg$.

  The mass of the screw

$$m_{screw} = \frac{1}{2}\pi r^2 length \times density \tag{2.34}$$

$$m_{screw} = 0.16Kg$$

$$J_{load} = \frac{Mp^2}{4\pi^2} \tag{2.35}$$

$$J_{load} = 13.17 \times 10^{-7} Kg.m^2$$

$$J_{screw} = \frac{1}{2} m_{screw} r^2 \tag{2.36}$$

$$J_{screw} = 12.8 \times 10^{-7} Kg.m^2$$

$$J_{total} = J_{load} + J_{screw} \tag{2.37}$$

$$J_{total} = 25.97 \times 10^{-7} Kg.m^2$$

$$T_a = \alpha J_{total} \tag{2.38}$$

$$T_a = 59.73 \times 10^{-4} N.m$$

The frictional component of the torque, this is given by

$$T_f = \frac{F_{total} p}{2\pi e} \tag{2.39}$$

where:

T_f: frictional torque in Newton.meter.

F_f: frictional force in Newton.

p: pitch in meter.

e: efficiency and it is equal 30% for trapezoidal screws (bronze nut on steel) [23].

$$F_f = M g f_c \tag{2.40}$$

where:

M: depth-axis mass.

f_c: static friction coefficient and it is equal 0.23 [23].

From Equation 2.40

$$F_f = 29.33\ N$$

$$F_{total} = F_f + F_{cutting} \tag{2.41}$$

where:

$F_{cutting}$: cutting force and it is equal $5\ N$ [23].

$$F_{total} = 34.33\ N$$

From Equation 2.39.

$$T_f = 36.43 \times 10^{-3}\ N.m$$

$$T_{total} = T_f + T_a \tag{2.42}$$

$$T_{total} = 42.4 \times 10^{-3}\ N.m$$

For Factor of safety K_s equal 4.

$$T_{motor} = K_s T_{total} \tag{2.43}$$

$$T_{motor} = 0.1696\ N.m$$

The motor torque that needed to move each axis is shown in Table 2.3.

Table 2.3 Motor Torque.

Axis	**Motor Torque (N.m)**
Length-axis	0.1696
Width-axis	0.08
Depth-axis	0.044

Chapter 3

Electrical Design

This chapter discusses electrical components that will be used in the project. Electrical system consists of hardware and software components.
Figure 3.1 shows the hardware components that are used in the system and relations between them.

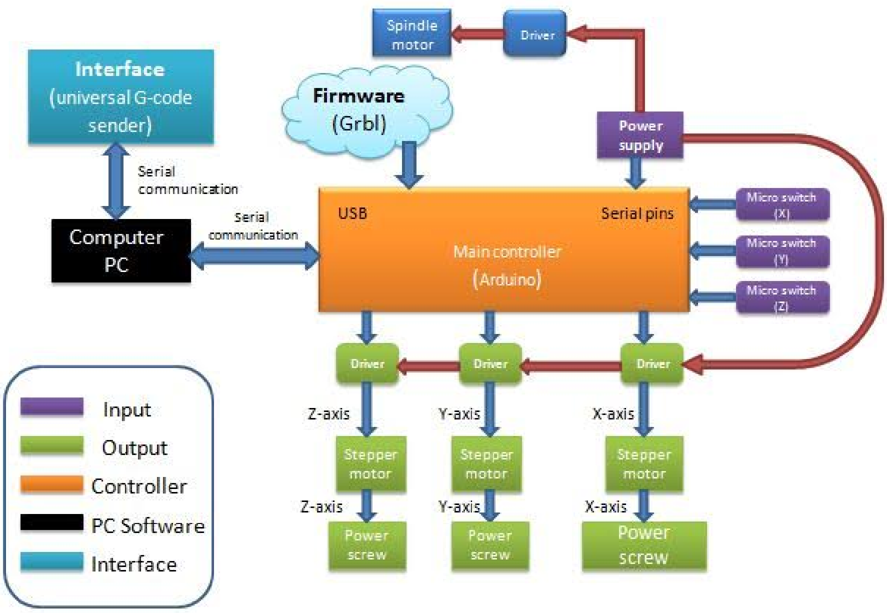


Figure 3.1 Block Diagram.

The following sections explain the functions of each part and what role it plays in the whole system

3.1 Motors

Motors are used in this machine to move the axes depend on the electrical signals from drivers which are connected to the controller. Two types of motors can be used in this machine, stepper motor and servo motor ,but before decide which one to use, we will define, explain, and compare the both types.

3.1.1 Stepper Motor

Stepper motors are direct current (DC) motors that move in discrete steps. It consists of a permanent magnetic rotating shaft, called the rotor, and electromagnets on the stationary portion that surrounds the motor, called the stator. It converts electrical pulses to rotational movements. The stepper motor depends on an open-loop electrical circuit (electrical circuit without feedback) provides the position at each coordinate given by the controller commands Figure 3.3. Its circuit provides "high" reliability, "good" low speed torque Figure 3.2, and "easy" to set-up. There are no errors since the stepper motor knows where the corresponding axis moves and when to stop by the controller commands [24] [25]. They have multiple coils that are organized in groups called phases. By energizing each phase in sequence Figure 3.4, the motor will rotate one step at a time. With a controlled stepping you can achieve very precise positioning and speed control [26].

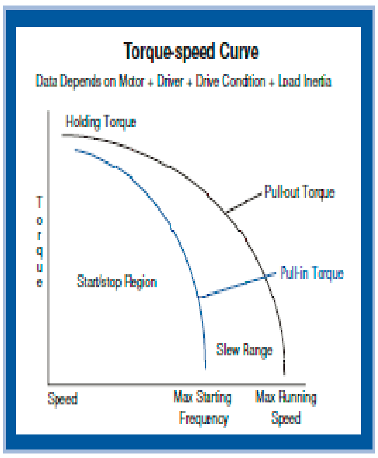


Figure 3.2 Torque Speed Curve [8].

Where:

1. Holding Torque:
   This is the torque that the motor will produce when the motor is at rest and rated current is applied to the windings.

2. Pull-out Torque:
   The maximum torque that the stepper motor can supply to a load at any given speed.

3. Pull-in Torque:
   The maximum torque and speed combination that an unloaded stepper motor can start or stop without any acceleration or deceleration.

4. Pull-in Torque:
   The torque and speed combination that a stepper motor with an inertial load can supply to a load and start or stop without any acceleration or deceleration.

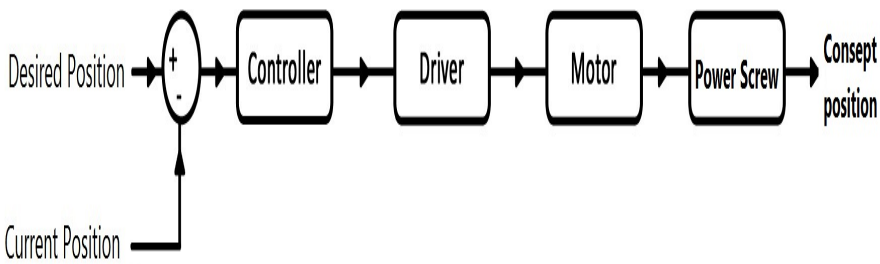


Figure 3.3 Open-loop Electrical Circuit [9].

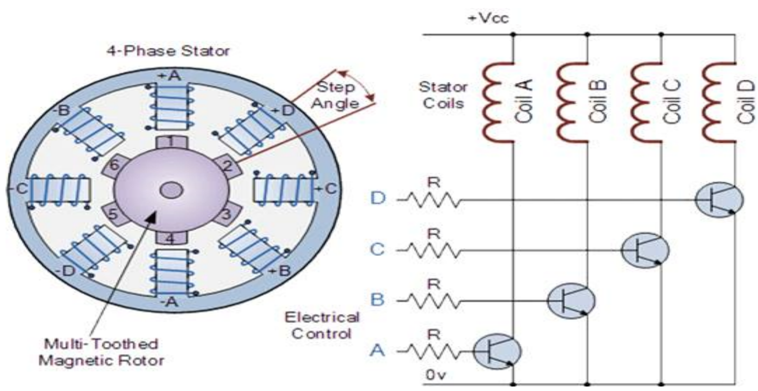


Figure 3.4 Internal Circuit of Stepper Motor [10].

3.1.1.1 Stepper Motor Working Principle

From Figure 3.4, if all coils are magnetized at a time, the rotor experiences forces of equal magnitude from all around it and so it does not move because all are of equal magnitude and are expressing opposite direction. Now if the coil D only magnetized, Teeth 1 on rotor experiences an attractive force towards point +D and Teeth 5 of rotor experiences a repulsive force opposing the point -D, theses two forces are represents an additive force clock wise. So the rotor moves to complete a step. After that it stops for the next coil to energize to complete next step. This goes on until the four steps are complete. For the rotor to rotate this cycle of pulsing must be going on [10].

3.1.2 Servo Motor

Servo motors and stepper motors can physically resemble each other when viewed from the outside. It is the configuration of the rotor and stator inside that makes the difference between the two types. A servomotor allows for precise control of angular or linear position, velocity and acceleration. It consists of a suitable motor coupled to a encoder (device, transducer, or software program that converts information from one format or code to another, for the purposes of standardization, speed or compressions) for position feedback. It also requires a relatively "complicated" controller, often a dedicated module designed specifically for use with servomotors [27]. Servomotors are not a specific class of motor although the term servomotor is often used to refer to a motor suitable for use in a closed-loop control system (system with feedback) [28] [26].

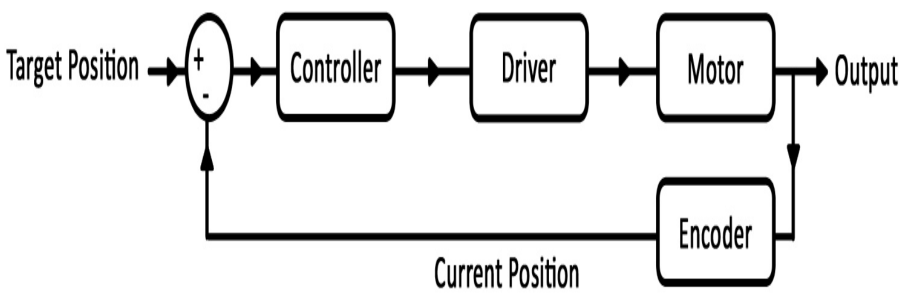


Figure 3.5 Closed-loop Electrical Circuit [9]

3.1.3 Comparison of Stepper Motor and Servo Motor

Table 3.1 summarize the differences between servo and stepper motors.

Table 3.1 Comparison Between Stepper Motor and Servo Motor [11] [12].

Comparison item	Servo Motor	Stepper Motor
Cost	The cost of servo motor is higher than stepper motor with equal power rating.	Steppers are generally cheaper than servo motors that have the same power rating.
Reliability	More reliable than stepper motor since it has encoder.	less reliable then servo motor since it dose not have an encoder.
Frame Sizes	Servo motors are available in a wide variety of frame sizes, from small to large motors capable of running huge machines. Many of the motors come in The National Electrical Manufacturers Association (NEMA)[1] standard sized.	Stepper motors do not have as many size selections as servo motors in the large sizes. However stepper motors may still be found in a variety of NEMA frame sizes.
Setup Complexity	Servo motors require tuning of the proportional integral derivative controller (PID)[2] closed- loop variable circuit to obtain correct motor function.	Stepper motors are almost plug-and-play. They require only the motor wires to be wired to the stepper motor driver.
Low Speed High Torque	Servo motors will do fine with low speed applications.	Stepper motors provide most torque at low speed Figure 3.2.
Availability	Servo motors are not as readily available to the masses as are stepper motors.	Stepper motors are far easier to find than quality servo motors.
Noise	Servo motors produce very little noise.	Stepper motors produce a slight hum due to the control process. However a high quality driver will decrease the noise level.

[1] A standard of the National Electrical Manufacturers Association defines a product, process, or procedure.

[2] Proportional Integral-Derivative control used to improve the behaviour of the system.

Overload Safety	Servo motors may malfunction if overload mechanically.	Stepper motors are unlikely to be damages by mechanical overload.
Motor Simplicity	Servo motors are more mechanically complex duo to their internal parts and the external encoders.	Stepper motors are very simple in design with no designed consumable parts.
Resonance and Vibration	Servo motors do not vibrate or have resonance issues.	Stepper motors vibrate slightly and have some resonance issues because of how the stepper motor operates.
Direct Drive Capability	Servo motors usually require more gearing ratios due to their high revolution per minute(RPM). It is very rare to see a direct drive servo motor setup.	Stepper motors will work fine in direct drive mode. Many people simple use a motor couple and attach the motor shaft directly to the leads crew or balls crew.
Power Range	Because servo motors are available in DC and AC servo motors have a very wide power availability range.	The power availability range for stepper motors is not that of servo motors.

The stepper motor is not much different from the servo. In this application either one could be used. Stepper motor will be used in our machine to move the axes, since it is cheaper than servo motor, also it is easier to build up its connection and programming as mentioned in the comparison table.

Based on motor torque calculations in Chapter 2, stepper motor NEMA 23 [29] is selected to drive the axes where NEMA is a type of stepper motors. Stepper motors NEMA have a good quality, cheap, and high torque. The data-sheet for the stepper motors are in Appendix IV.

A micro-stepping drivers are selected to drive the stepper motors that are used. The micro-stepping drivers link between the stepper motors and the micro-controller and they are used to drive the motor. Table 3.2 shows the connector pin configurations of the micro-stepping driver [30].

The Figure 3.6 show the typical connection of the micro-stepping driver.

Table 3.2 Pin Configurations of the Micro-stepping Driver.

Pin functions	Details
PUL+(+5V) PUL-(PUL)	Pulse signal: In single pulse mode, this input represents pulse signal, active at each rising or falling edge; 4-5V when PUL-HIGH, 0-0.5V when PUL-LOW. In double pulse mode, this input represents clockwise (CW) pulse, active at high level or low level. For reliable response, pulse width should be longer than 1.2 micro second. Series connect resistors for current-limiting when +12V or +24V used.
DIR+(+5V) DIR-(DIR)	Direction signal: In single pulse mode, this signal has low or high voltage levels, representing two directions of motor rotation; in double pulse mode, this signal is counter-clock (CCW) pulse, active for high level or low level. For reliable motion response, DIR signal should be ahead of PUL signal by 5 micro second at least. 4-5V when DIR HIGH, 0-0.5V when DIR LOW. Please note that motion direction is also related to motor-driver wiring match. Exchanging the connection of two wires for a coil to the driver will reverse motion direction.
ENA+(+5V) ENA-(ENA)	Enable signal: This signal is used for enabling or disabling the driver. High level for enabling the driver and low level for disabling the driver. Usually left (unconnected).

3.2 Spindle Router

spindle is a rotating axis of the machine, which often has a shaft . The shaft itself is called a spindle. A spindle router is a tool used to hollow out an area in the face of a relatively hard workpiece, typically of wood or plastic. The main application of routers is in woodworking, especially cabinetry. The spindle plays an important role in machining operations because it provides the cutting speed of the tool and is part of the force chain between the machine structure and the workpiece (wood) [27].

LX134MO Electronic Variable Speed Sander has been chosen to be the spindle router of our project, since it achieves the specific requirements.

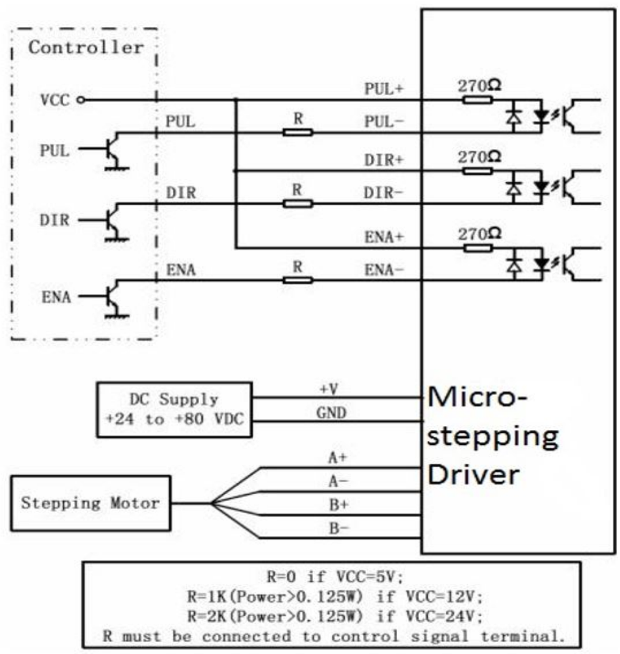


Figure 3.6 Micro-stepping Driver Connection.

3.3 Arduino

Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards are able to read inputs and turn it into outputs. You can tell the board what to do by sending a set of instructions to the micro-controller on the board. To do so you use the Arduino programming language. Arduino provides integrated development environment (IDE) software, based on the processing language project [31].

In this machine Arduino is the main controller which receives commands from the computer and send the desired signals to the motors drivers which move the motors. More details in chapter 4.
Because of its simple and accessible user experience, Arduino has been used in thousands of different projects and applications. The Arduino software is easy-to-use because it uses C programming language (High level language using for programming) which is easy to use since it uses English language for programming [31].

3.4 Power Supply

All controllers will have some form of incorporated power supply that provides the designed voltage and ampere necessary to drive the motors [28].

A power supply is an electronic device that supplies electric energy to an electrical load. The primary function of a power supply is to convert one form of electrical energy to another and as a result, power supplies are sometimes referred to as electric power converters. Some power supplies are discrete, stand-alone devices (any mechanism or system that can perform its function without the need of another device, computer, or connection) [32].

Every power supply must obtain the energy it supplies to its load, as well as any energy it consumes while performing that task from an energy source. Depending on its design, a power supply may obtain energy from various types of energy sources, including electrical energy transmission systems.

3.5 Limit Switch

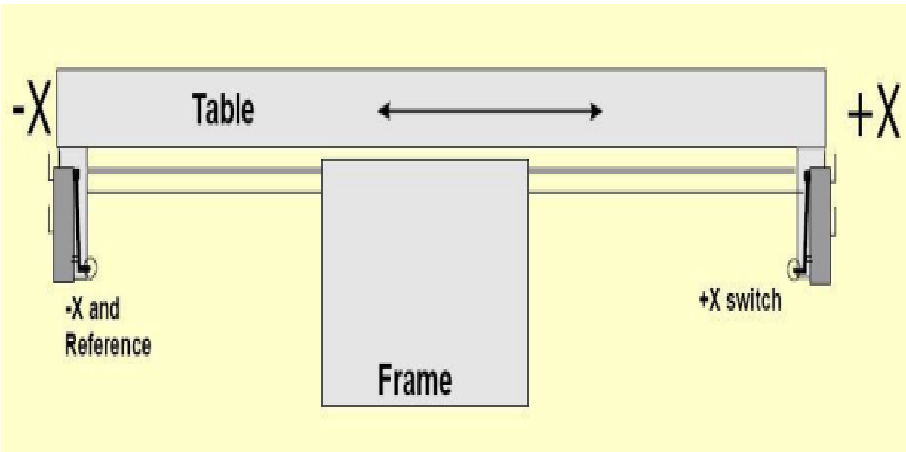


Figure 3.7 Two Limit Switches Operated by Frame.

limit switch is a switch operated by the motion of a machine part or presence of an object. Limit switches are used to prevent any linear axis from moving too far and causing damage to the structure of the machine. You can run a machine without them, but the slightest mistake in setting up or programming can cause a lot of expensive damage. Limit switches are used in a variety of applications and environments they can determine the presence or absence of an object [33].

3.6 Emergency Push Button

Is a safety mechanism used to shut off a device or machinery in an emergency situation in which it cannot be shut down in the usual manner. Unlike a normal shut-down switch, which shuts down all systems in an orderly manner and turns the machine off without damaging it, an emergency switch is designed and configured to completely and as quickly as possible end the operation (even if this damages equipment) and be operable in a manner that is quick and simple.

Chapter 4

Control Design

The CNC controller acts as the brain of the CNC system. All parts (electrical and mechanical) of the CNC controller are integrated together to serves the machine tasks. The primary task of the controller is to receive digital signals; a digital signal is a signal that represents a sequence of discrete values, from a computer and translate these signals into mechanical motion through motor drivers.

This chapter explains the controller design and the software program which will be used to control the movement of the axes.

Open-loop control system will be used to control the machine since we use stepper motor as mentioned in Chapter 3 as comes in Section 4.1.

4.1 Open-loop Control System

Open-loop system Figure 4.1 is a type of continuous control system in which the output has no influence or effect on the control action of the input signal. In other words, in an open-loop control system the output is neither measured nor fed-back for comparison with the input. Therefore, an open-loop system is expected to truly follow its input command or set points regardless of the final result [34].

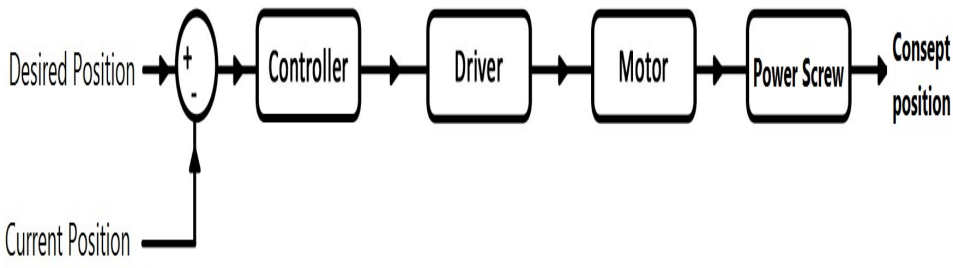


Figure 4.1 Open-loop Control System.

In open-loop control system the controller receive the desired and current position of the cutting tool from computer before the CNC controller create the necessary steps and direction signals to perform the desired task and send it to motor driver. The driver lead the stepper motor to rotate the power screw which convert the rotational movement to linear movement in millimeters.

Feed rate, depth of cut, and spindle speed must be known to produce products with "good" quality and surface finish. These concepts are discuss in the following sections.

4.2 Feed Rate

Feed rate is the rate at which the cutting tool crosses the work piece; The rate at which material is removed in the direction of the tool motion. Feed rate is defined by millimeters per minute (mm/min) or mm per revolution (mm/rev).
Feed rate value depends on the work piece material. For wood, the feed rate is between $1000\, to\, 2000\, mm/min$ due to wood worker experience, if feed rate exceed $2000\, mm/min$ the work piece will have bad surface finish and if the feed rate less than $1000\, mm/min$ the work piece will be burns.

4.3 Depth of Cut

Depth of cut is defined as how much the tool exceed in the work piece. Depth of cut is defined by millimeters (mm).

4.4 Spindle Router Speed

The rotational speed of the spindle measured in revolutions per minute (RPM). Spindle speed for wood should be between $15000\, to\, 32000\ RPM$ due to wood worker experience. Excessive Spindle speed cause premature tool wear, breakages, and tool cheep. Using the correct spindle speed will increase tool life and the quality of the surface finish.

4.5 G-Code

The G-code language is an alpha-numeric American Standard Code for Information Interchanged (ASCII) based machine-command language that can be understood by the controller into discrete movements and modes. However, this is not a type of programming language that requires to be compiled, but it does need to follow to a specific dialect that the controller can understand and make use of [32].

G-code can be considered an industry standard for machine tool-control language. There are a finite number of commands that construct the language and depend upon the supplier of the controller software. There may be additional codes or parameters supported by their implementation.

In the following, we show some G-code commands that can be used for milling industry, where there after Table 4.1 summaries that commands.

1. G00: this command is used for linear motion when the tool is far away from work

piece (no cutting process). For example, G00 X100.0 Y100.0 Z10.0, where X, Y, and Z are the tool position in mm.

2. G01: this command is used for linear motion when the tool is exceed the work piece (cutting process). For example, G01 X100.0 Y100.0 Z10.0 F2000, where X, Y, and Z are the tool position in mm and F is the feed rate in mm/min.

3. G02: this command is used for clockwise circular motion when the tool is exceed the work piece (cutting process). For example, G02 X10.0 Y10.0 R10.0 F2000, where X and Y are the tool position in mm, R is radius value in mm, and F is the feed rate in mm/min.

4. G03: this command is used for counterclockwise circular motion when the tool is exceed the work piece (cutting process). For example, G03 X10.0 Y10.0 R10.0 F2000. Where X and Y are the tool position in mm, R is radius value in mm, and F is the feed rate in mm/min.

5. G90: this command is used for absolute distance mode (distance from origin).

6. G91: this command is used for incremental distance mode (distance from tool position).

7. G20: this command is used for inch unit.

8. G21: this command is used for metric unit.

9. G41: this command is used to start tool radius compensation when the cutting is from the left side of the tool.

10. G42: this command is used to start tool radius compensation when the cutting is from the right side of the tool.

11. G40: this command is used to cancel tool radius compensation.

12. G81: this command is used for drilling operation. For example, G81 Z-5.0 R1.0 F1000, where Z is depth of drilling in mm, R safe distance in mm, and F is feed rate in mm/min.

13. G82: this command is used for drilling operation with dwell. For example, G81 Z-5.0 R1.0 P2 F1000, where Z is depth of drilling in mm, R safe distance in mm, P is dwell in seconds, and F is feed rate in mm/min.

14. G83: this command is used for drilling operation with peck. For example, G81 Z-5.0 R1.0 Q0.5 F1000, where Z is depth of drilling, R safe distance, Q is peck distance in mm, and F is feed rate.

Table 4.1 Some G-Code Commands.

G-code commands	**Command meaning**
G00	Rapid positioning
G01	Linear interpolation
G02	Clockwise circular
G03	Counterclockwise circular
G10	Coordinate system origin setting
G12	Clockwise circular pocket
G13	Counterclockwise circular pocket
G20	Inch unit
G21	millimeter unit
G41	Start cutter radius compensation left
G42	Start cutter radius compensation right
G81	drilling
G82	drilling with dwell
G83	peck drilling
G90	Absolute distance mode
G91	Incremental distance mode

4.6 Micro-controller

By connecting micro-controller with computer, it can receive the desired commands (G-code) from the computer, these commands indicate to the desired and current position of the cutting tool. The micro-controller converts these commands to electrical signals (steps and direction), these signals are sent by micro-controller to the motor drivers which move the motors. A "popular" library turns Arduino to very capable CNC machine is called grbl library, where grbl is a free source library for controlling the motion of the

CNC machines and it is compatible the Arduino.

After determine the desired and current position for cutting tool and send it to the Arduino, grbl library determine the number of steps, direction, and signal frequency depending on feed rate and displacement to perform the desired task and send it to motor driver.

4.6.1 Grbl Library

Grbl library is a free source library is written by C++ programming language and is designed for CNC machines. Uploading grbl on Arduino allows to communicate with software programs as comes in Section 4.6.2.

4.6.2 Setup Grbl on Arduino

Grbl library must be setup on Arduino to control the CNC machine. First grbl library must be extract to get the file (grbl-master)and copy the grbl file to the Arduino library and then upload this file to Arduino micro-controller using Arduino promote command.

Figure 4.2 shows the final view that enable us to program the CNC with G-code and grbl library.

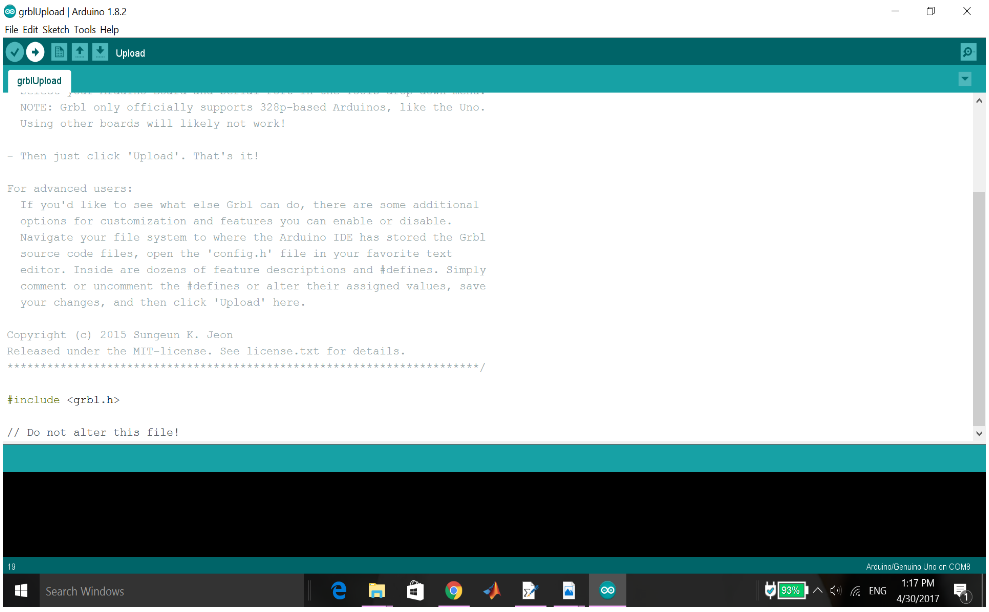


Figure 4.2 Uploading Grbl Library to Arduino.

4.7 Software Program

After upload the grbl library on Arduino, universal G-Code sender program will be used to run the grbl to control the machine. The universal G-code sender is a personal computer (PC) program used for interfacing with CNC controllers like grbl.

4.7.1 Setup Universal G-Code Sender

Universal G-Code sender should be setup to run and interface the grbl library to control the CNC machine. Universal G-Code sender is a free source program.

After opening universal G-code sender it must be connected with the Arduino using grbl library. To connect it with Arduino, it must be in the same port and firmware (grbl). The Arduino is connected with COM8 prot so the connection for universal G-code sender must be in COM8 and firmware grbl, as shown in Figure 4.3.

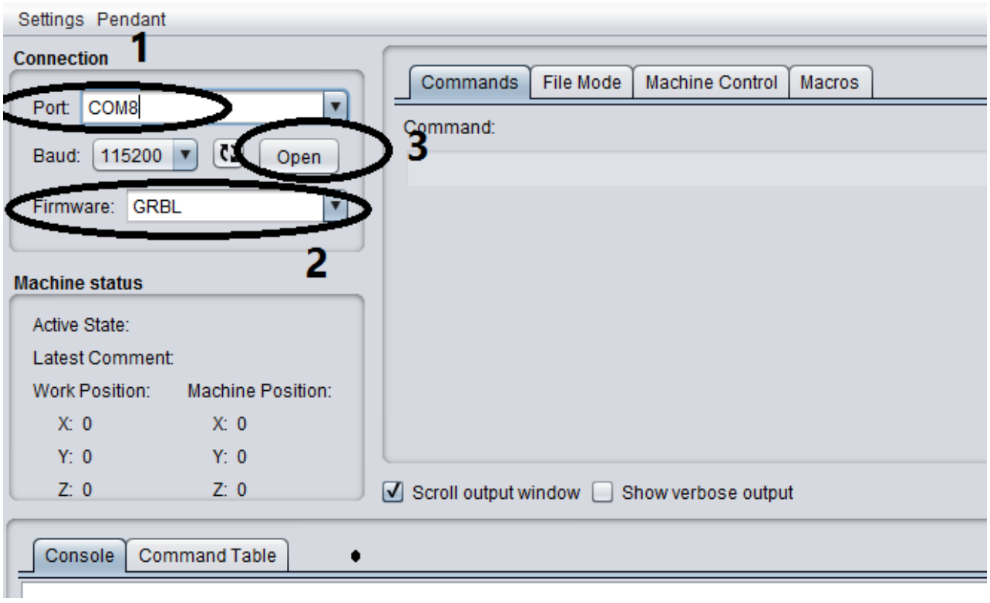


Figure 4.3 Universal G-Code Connection.

4.7.2 Motors Steps Per Millimeter

Number of steps of stepper motors per mm should be calculated for controlling the movement of stepper motors. Since a micro-stepping drivers have been used, there are many choices for number of steps per revolution. Therefor, a 1600 steps per revolution for depth-axis and 6400 steps per revolution for length- and width-axes have been chosen to achieve the desired accuracy.

To calculate the number of steps per mm the number of steps per revolution and the power screw lead must be known. Since a 1600 and 6400 steps per revolution and power screw with 2 and 8 mm lead have been chosen, the number of steps per mm are calculated as follow.

For length- and width-axes

$$Sm = \frac{Sr}{L} \tag{4.1}$$

$$Sm = \frac{6400}{8}$$

$$Sm = 800\ steps/mm$$

For depth-axis

$$Sm = \frac{1600}{2}$$

$$Sm = 800\ steps/mm$$

Where Sm is step per millimeters, Sr is step per revolution, and L is the screw lead value.

4.8 Grbl Settings

Adjustment the number of steps per mm, feed rate, and acceleration is needed for controlling the stepper motors using universal G-Code sender. The desired grbl settings is shown in Figure 4.4.

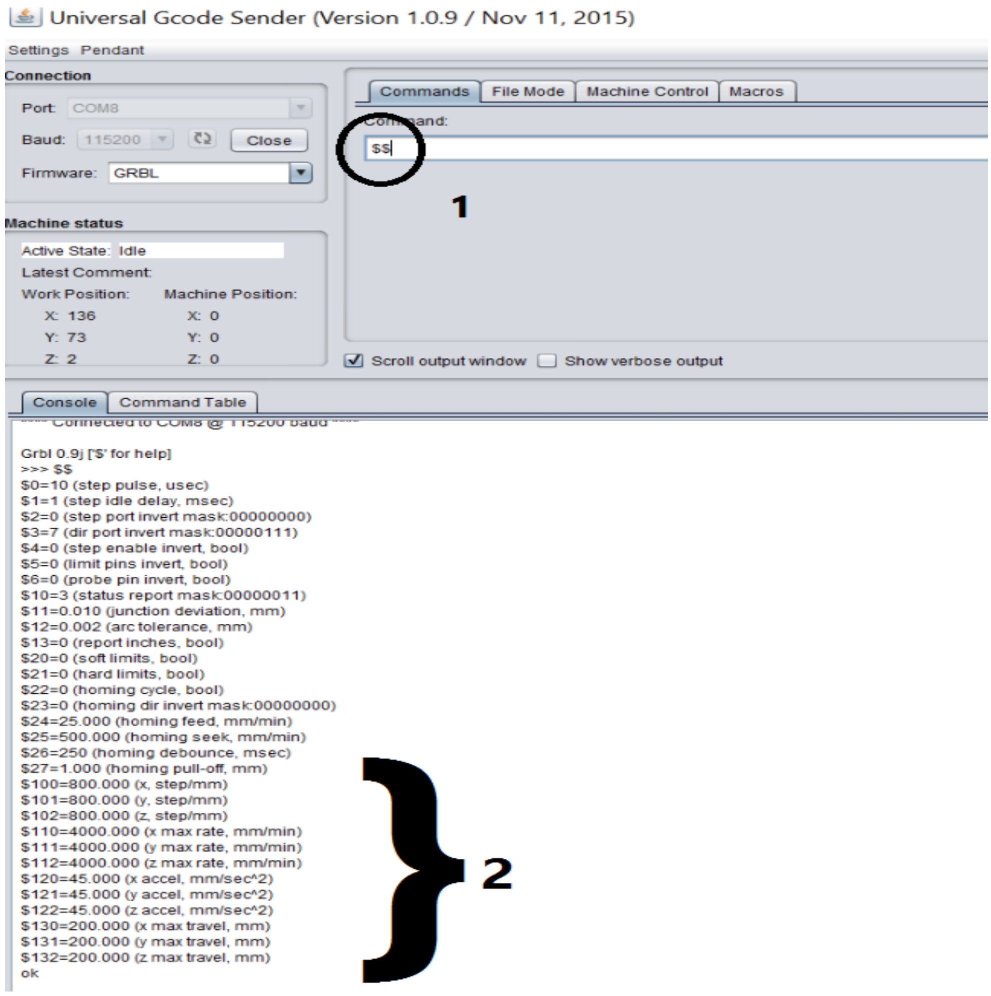


Figure 4.4 Grbl Settings.

Table 4.2 Setting Commands

Command	Value	Meaning
$100	800	Used for X-axis (length-axis) steps per mm.
$101	800	Used For Y-axis (width-axis) steps per mm.
$102	800	Used For Z-axis (depth-axis) steps per mm.
$110	4000	Used for X-axis (length-axis) feed rate in mm/min.
$111	4000	Used for Y-axis (width-axis) feed rate in mm/min.
$112	4000	Used for Z-axis (depth-axis) feed rate in mm/min.
$120	45	Used for X-axis (length-axis) acceleration in mm/s^2.
$121	45	Used for Y-axis (width-axis) acceleration in mm/s^2.
$122	45	Used for Z-axis (depth-axis) acceleration in mm/s^2.

Table 4.2 shows the commands that are used for grbl setting.

4.9 Executing G-Code

After generate G-code for the work piece (design) it must be executed using universal G-code sender. To execute the G-code, there are many steps. First, locating the origin of the work piece. To determine the origin of the work piece move and reset the axes as shown in Figure 4.5.

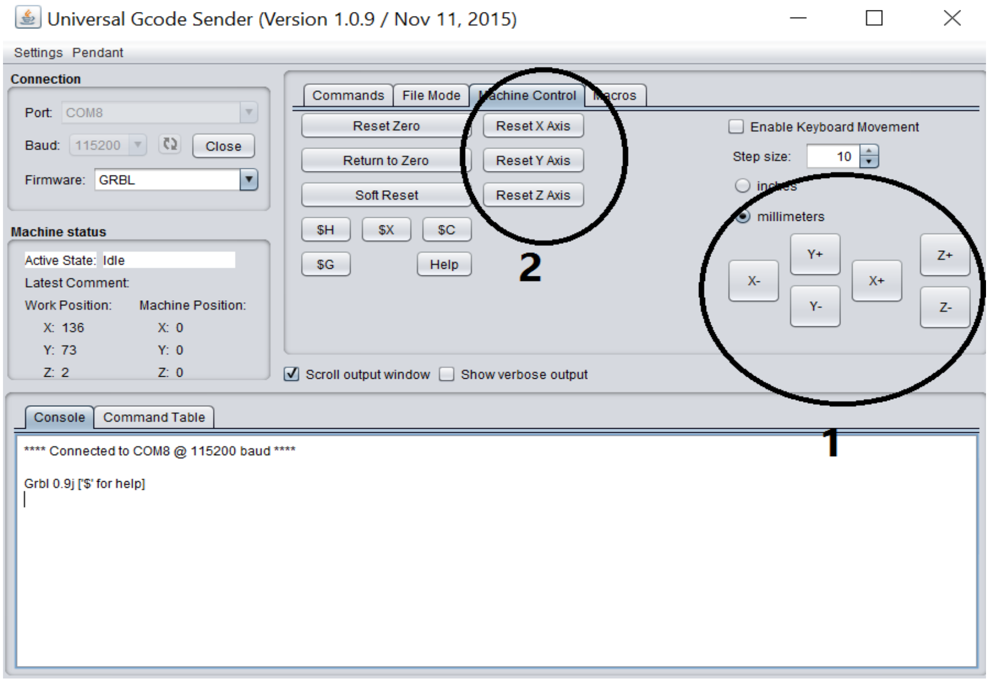


Figure 4.5 Determine Work Piece Origin.

After determine the origin of the work piece select work piece G-code and run it as shown in Figure 4.6.

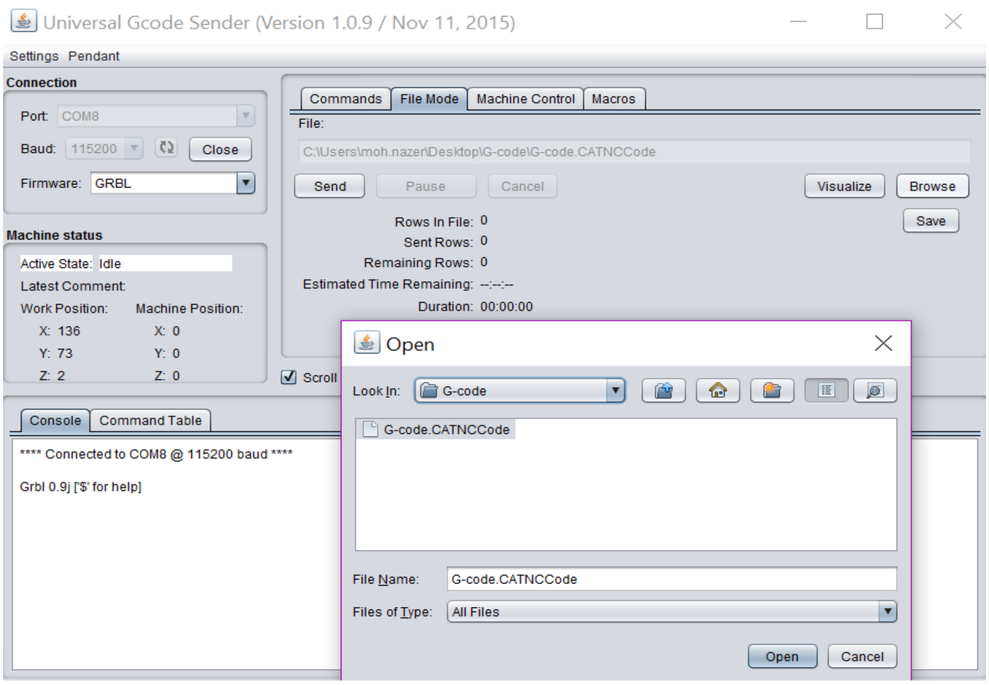


Figure 4.6 Executing Work Piece G-code.

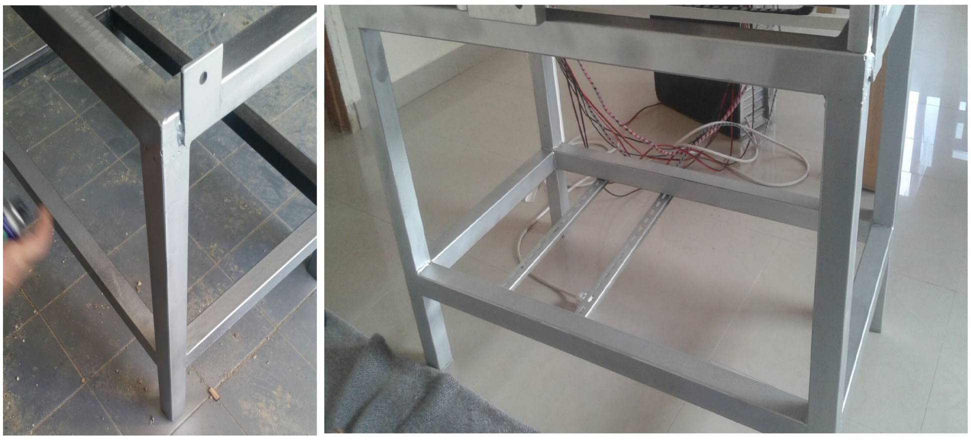
Chapter 5

CNC Machine Setup

This chapter explains the setup steps that are used in this project. Seven steps are used to build this machine; cutting, welding, drilling, turning, finishing, threading, and coating. In the following, the setup steps are explained for each part of the machine.

5.1 Main Table

Three steps are used to build the table. First, cutting the square steel tubes with the desired dimension. Then weld the cutting pieces as the desired shape. Finally clean and coat it. Figure 5.1(a) shows the main table while coating process and Figure 5.1(b) show the main table after all manufacturing processes.



a b

Figure 5.1 Main Table: a.Coating Main Table; b.Main Table After all steps.

5.2 Length-axis

Four steps are used to build length-axis. These steps are cutting two aluminum plates with the desired dimension using Plasma CNC machine, finishing, drilling, and threading them to fix them with the main table and to fix the sliding rods and the stepper motor on them, as shown in Figure 5.2.

a

b

Figure 5.2 Length-axis: a.Sliding Rod Assemble With Length-axis stands; b.Motor and Main Table Assembly With Length-axis stands.

5.3 Width axis

Four steps are used to build width-axis. These steps are cutting two aluminum plates with the desired dimension using Plasma CNC machine, finishing, drilling, and threading them to fix them with the slide bearing, the sliding rods, and the stepper motor, as shown in Figure 5.3.

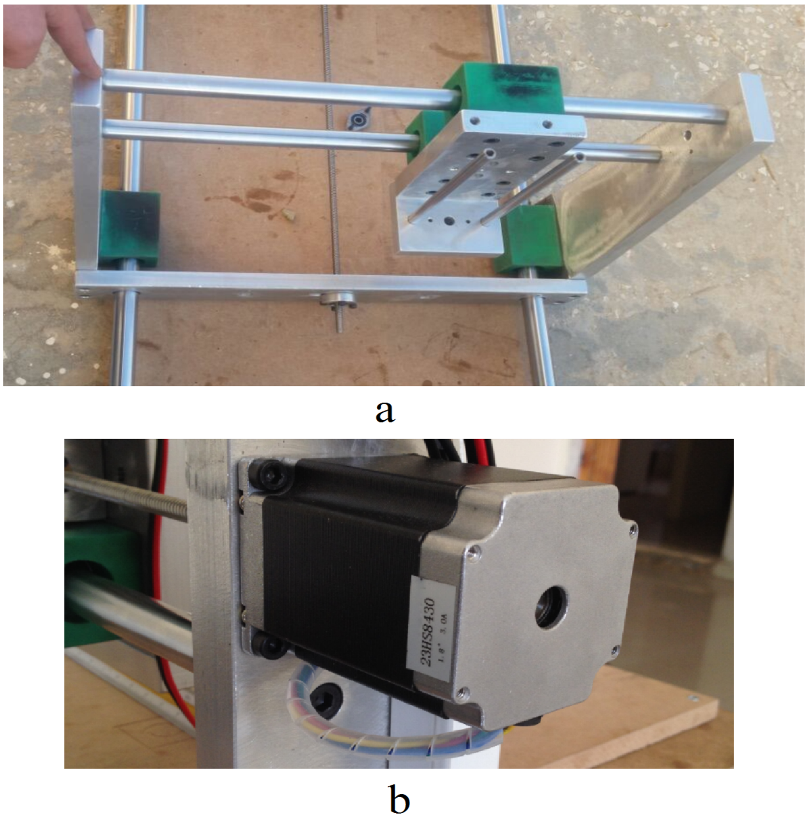


Figure 5.3 Width-axis: a.Sliding Rod, Slide Bearing, and Anti-backlash Nut Carriage Assemble With Width-axis Legs; b.Motor Assemble With Width-axis Legs.

5.4 Depth-axis

Four steps are used to build depth-axis. These steps are cutting three aluminum plates as the desired dimension using Plasma CNC machine, finishing, drilling, and threading them to fix them with the slide bearing, the sliding rods, and the stepper motor, as shown in Figure 5.4.

a b

Figure 5.4 Depth-axis: a.Slide Bearing Assembly With Depth-axis Carriage; b.Depth-axis Assemble With All Other Parts.

5.5 Slide bearings

The selected slide bearing mentioned in Chapter 2 does not found in the local market, so linear bearing is bought and combine it with a mold that suitable to fix it with the linear bearing. The linear bearing and its mold are fixed with depth-axis carriage and width-axis legs as shown in Figure 5.5.

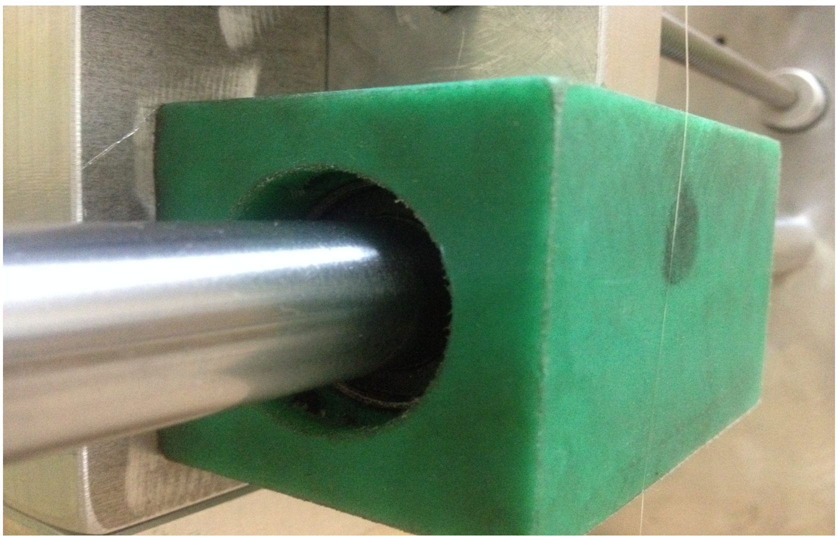


Figure 5.5 Slide Bearing.

5.6 Sliding Rods

Cutting and finishing are used to get the desired sliding rods. Where finishing is used to get the desired precision. The sliding rods are shown in Figure 5.6.

Figure 5.6 Sliding Rod.

5.7 Motor Clamp

Four steps are used to build motor clamps. These steps are cutting two aluminum plates as the desired dimension using Plasma CNC machine, finishing, drilling, and threading them to fix the spindle router as shown in Figure 5.7.

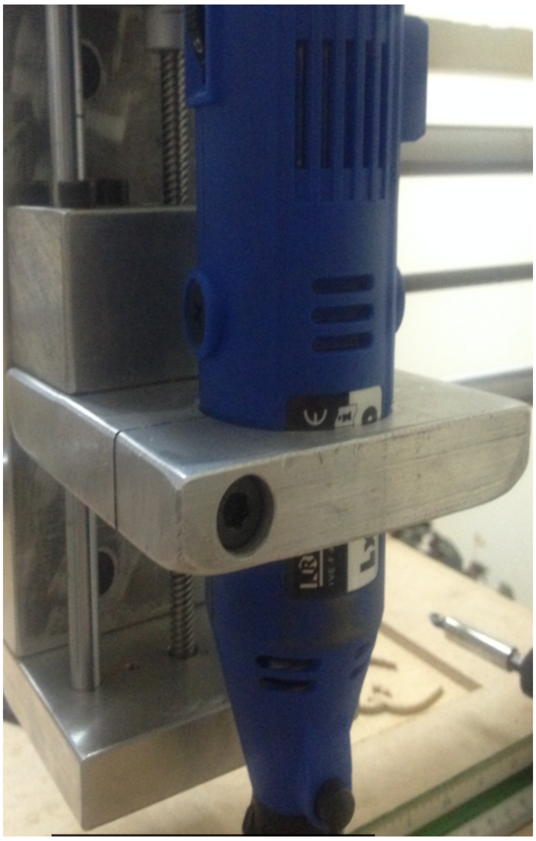


Figure 5.7 Motor Clamp.

Chapter 6

Testing

This chapter gives some examples of products that can be produced using this machine, also it explains the procedure to produce one of these products.

6.1 Simple Test

First simple test has been draw for testing such as simple square with dimension $(100 \times 100)\ mm$. This simple testing is made to check that the desired requirements have been met, such as quality. The G-code for this testing has been written on text file as Shown in Figure 6.1.

test square - Notepad

File Edit Format View Help

```
G90 G00 X0.0 Y0.0 Z5.0;
G90 G01 Z-2.0 F1500;
G90 G01 X100.0 Y0.0 F1500;
G90 G01 X100.0 Y100.0 F1500;
G90 G01 X0.0 Y100.0 F1500;
G90 G01 X0.0 Y0.0 F1500;
```

Figure 6.1 G-Code for Square.

Using the executing procedure that explained in Chapter 4 the square has been draw as shown in Figure 6.2. The square has been draw on the paper to test the machine feed rate, axes movement, and to avoid any dangerous situation such as cutting tool fracture or axes movement fault.

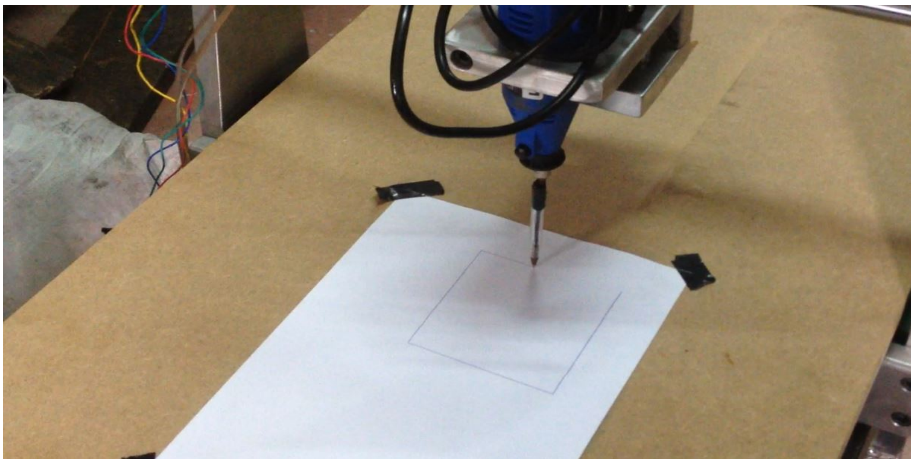


Figure 6.2 Drawing Square.

After testing the machine and draw the square on the paper, milling operation has been tested. This test provide that the milling operation is work as shown in Figure 6.3.

Figure 6.3 Mill Square on Wood.

After testing the machine (feed rate, axes movement, and milling operation), accuracy test has been done as comes in Section 6.2.

6.2 Accuracy Testing

This section shows the accuracy testing for the project by producing a simple design using CATIA program with $40\ mm$ radius, $60\ mm$ inner width, and $100\ mm$ inner length. The design is shown in Figure 6.4.

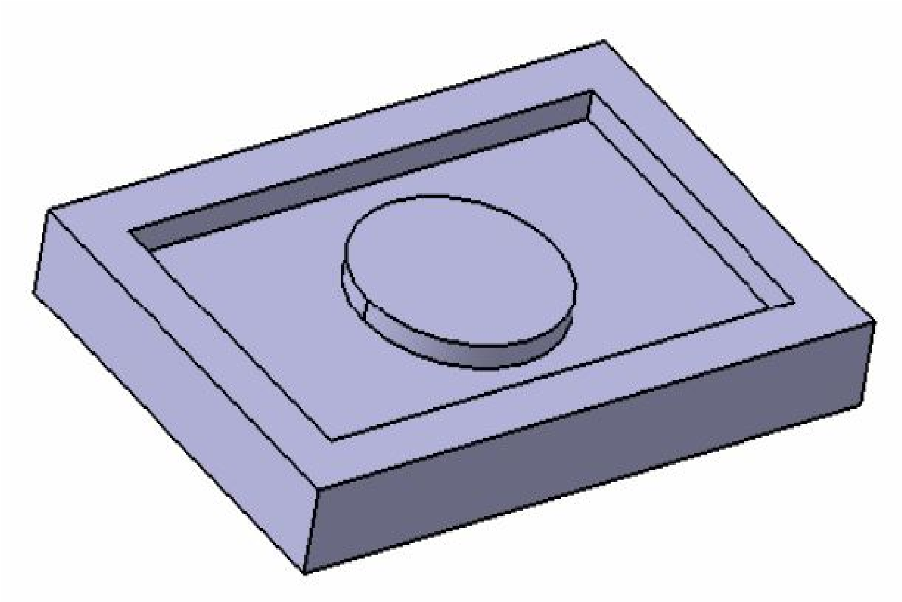


Figure 6.4 Accuracy Test Design.

After draw the sample using CATIA, the machining processes must be applied to get the G-code that contains the desired commands used to produce the sample. Open the machining processes as shown in Figure 6.5 and apply the shown processes as shown in Figure 6.6.

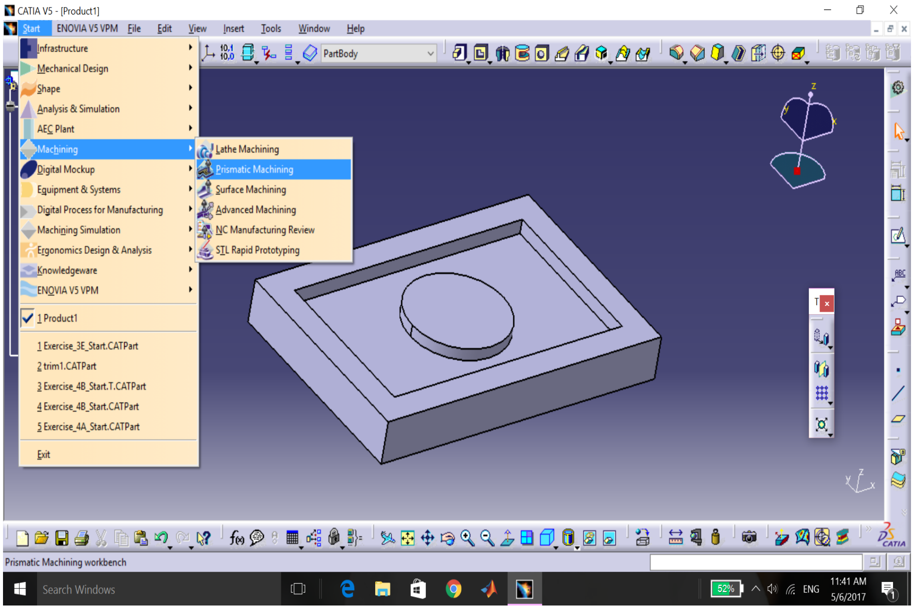


Figure 6.5 Machine Processes Icon.

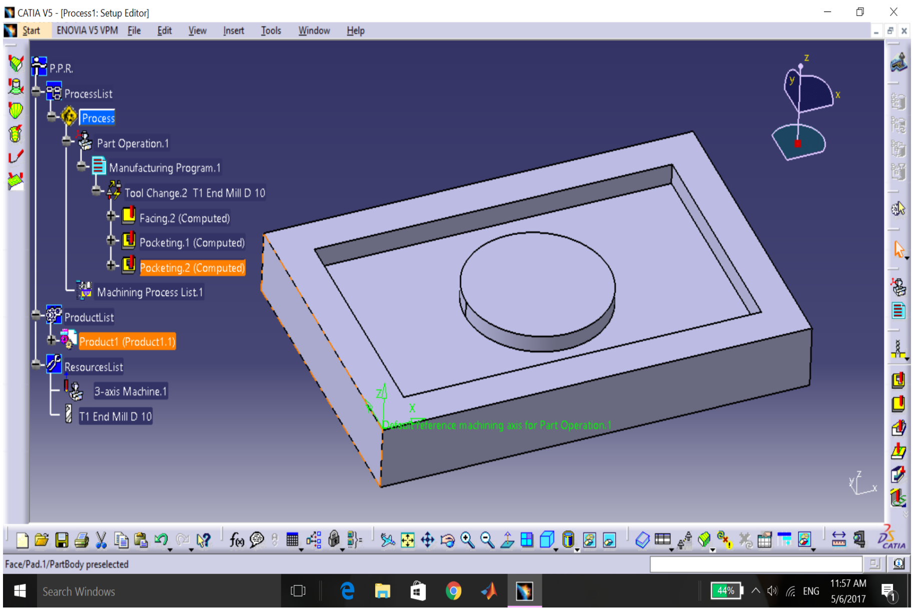


Figure 6.6 Machining Processes Instructions.

Then simulate these processes as shown in Figure 6.7.

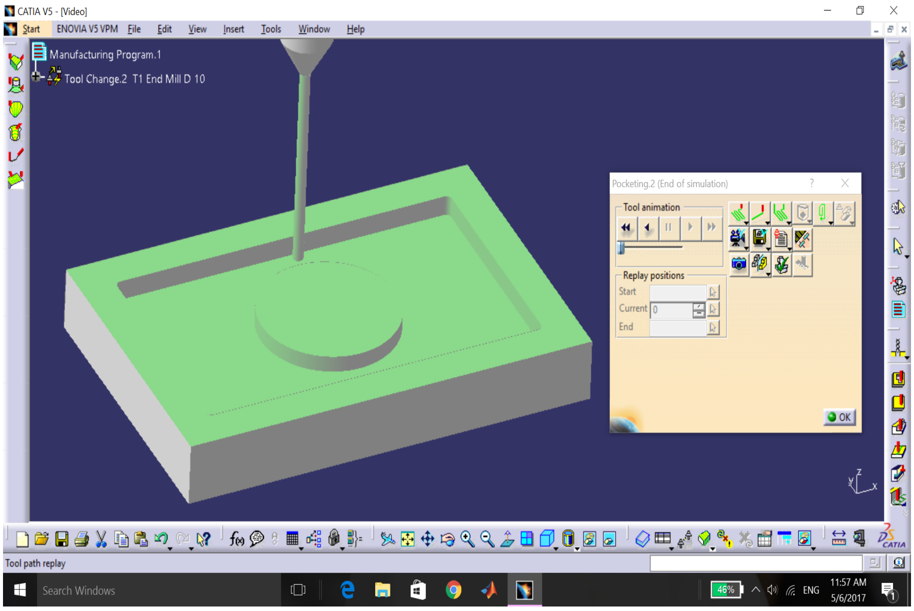


Figure 6.7 Machining Processes Simulation.

Then execute the G-code for the sample as shown in Figure 6.8.

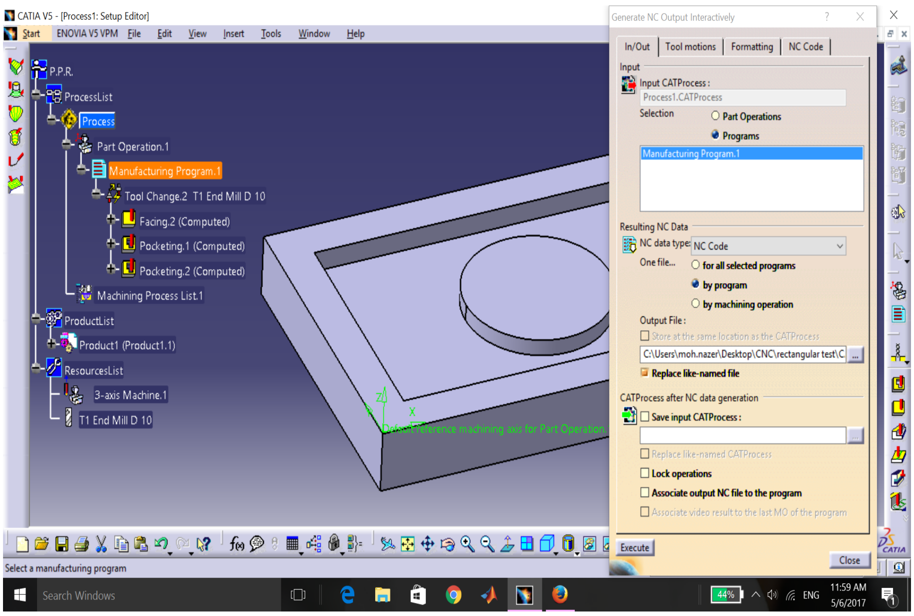


Figure 6.8 Machining Processes Simulation.

Then apply the G-code to produce the sample. The product is shown in Figure 6.9.

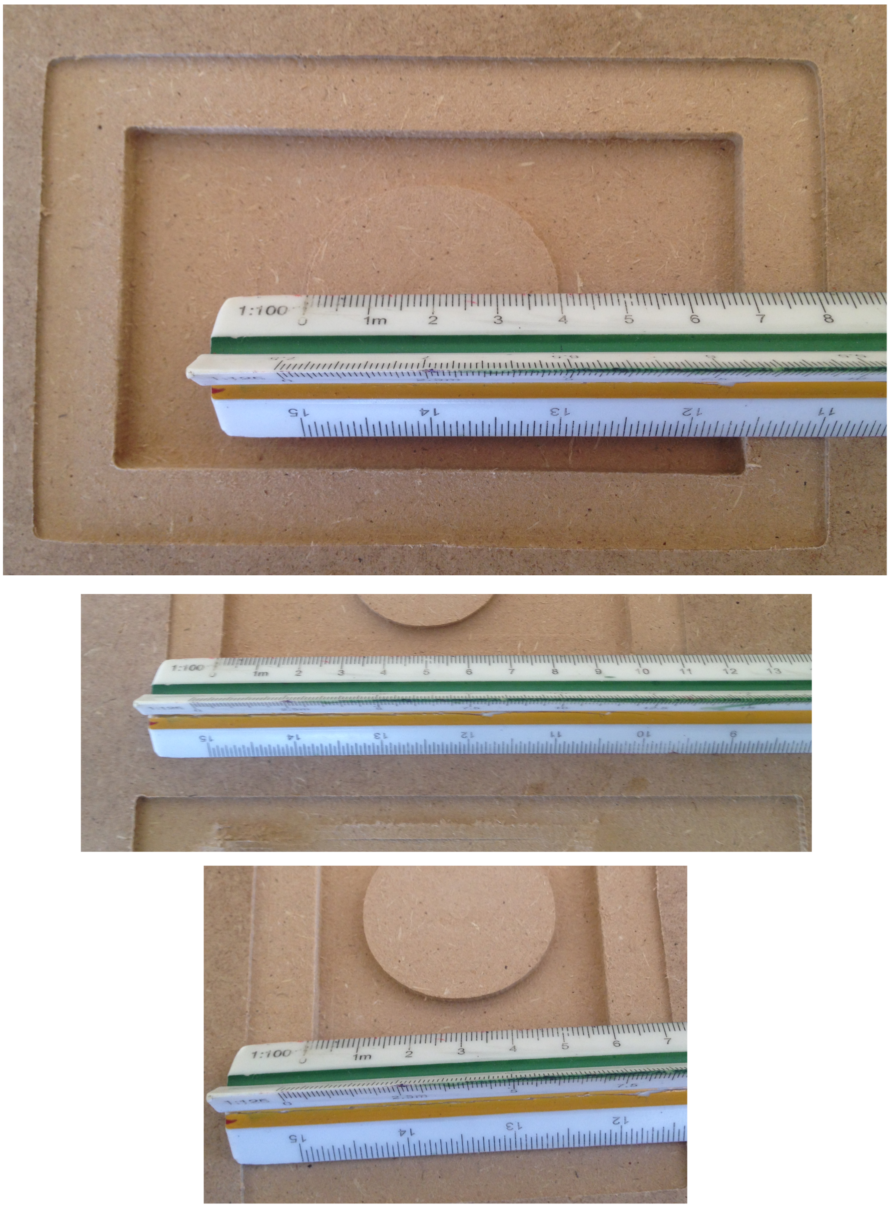


Figure 6.9 Final Product for Accuracy Test

6.3 Samples

This section shows the procedure to produce the drawing shown in Figure 6.10 using CAD and CAM programs and gives some other examples.

Figure 6.10 The Desired Picture.

1. Open ArtCAM pro, creat new model, and set the desired dimension as shown in Figure 6.11. Where ArtCAM program is used for CAD and CAM processes.

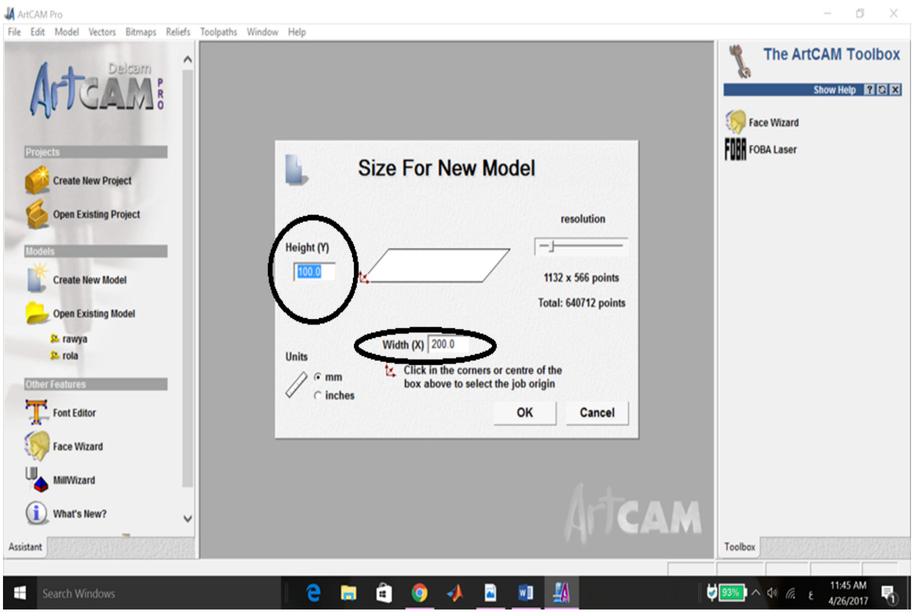


Figure 6.11 Dimension Set.

2. Pull the picture to the programs icon in the toolbar as shown Figure 6.12.

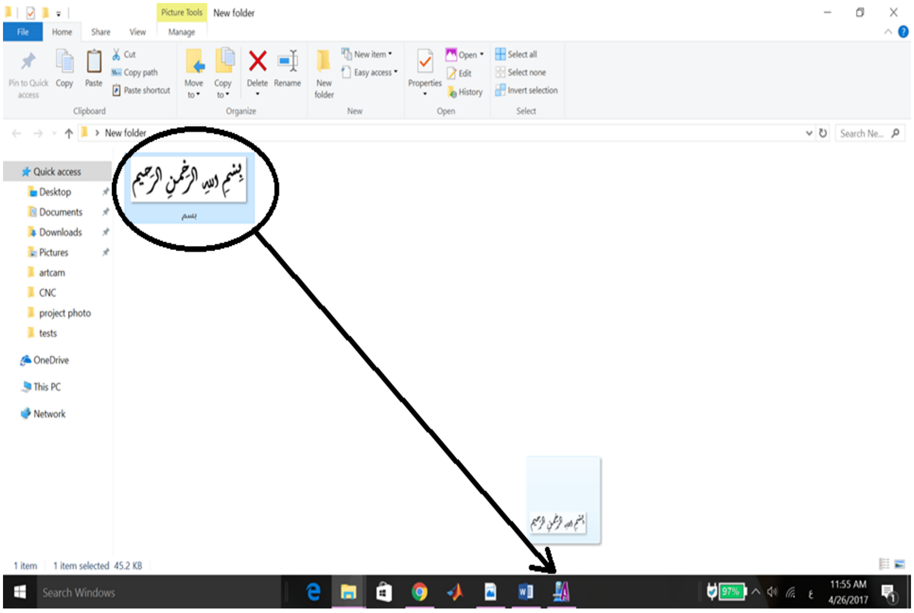


Figure 6.12 Pull The Picture.

3. Select image size and set the height or width of the picture then click ok as shown in Figure 6.13.

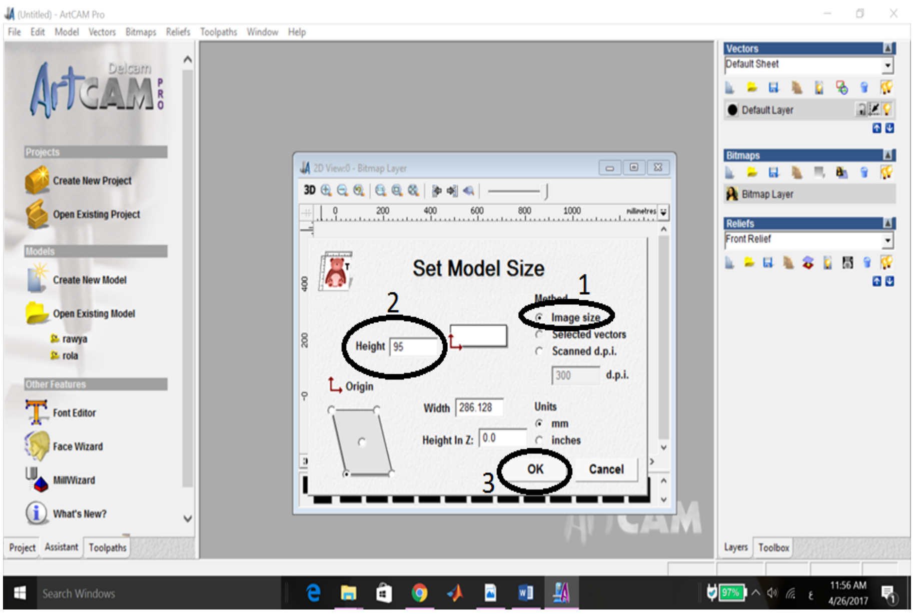


Figure 6.13 Image Size.

4. Click on reduce colour to make the design consist of two colours to creating the design vector without error as shown in Figure 6.14.

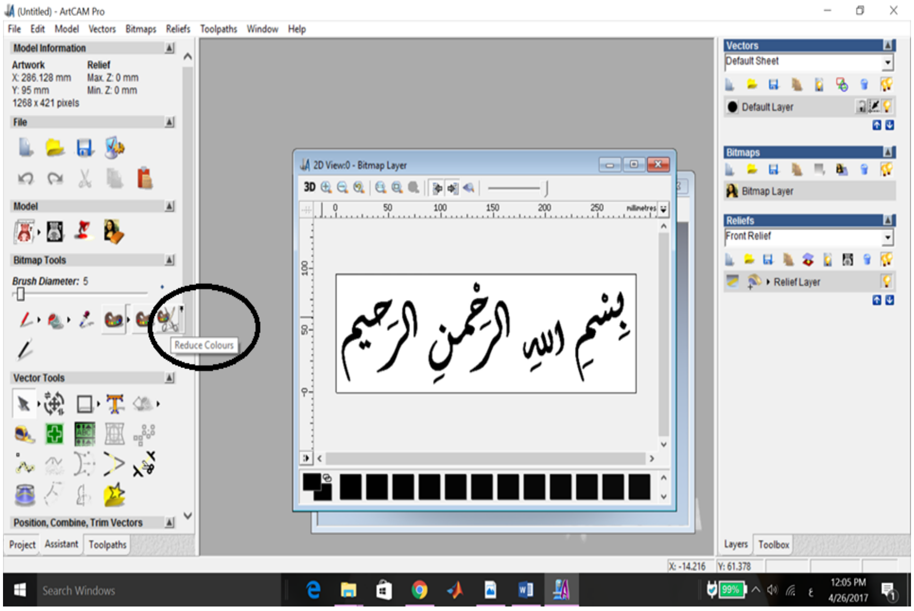


Figure 6.14 Reduce Colour Icon.

5. Click on Bitmap to vector to create design vector as shown in Figure 6.15.

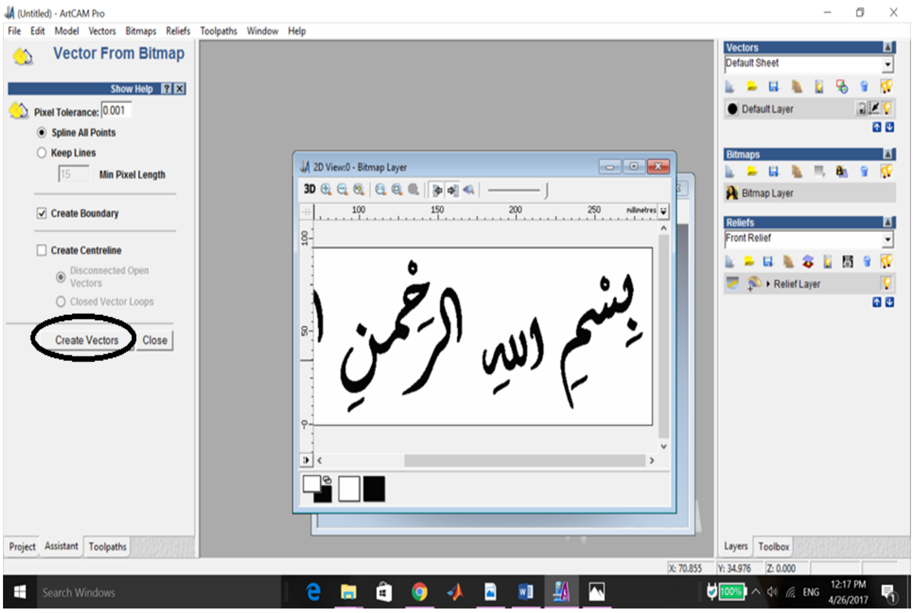


Figure 6.15 Create Vector for The Design.

6. Select the whole picture, copy, and paste it in new model as shown in Figure 6.16.

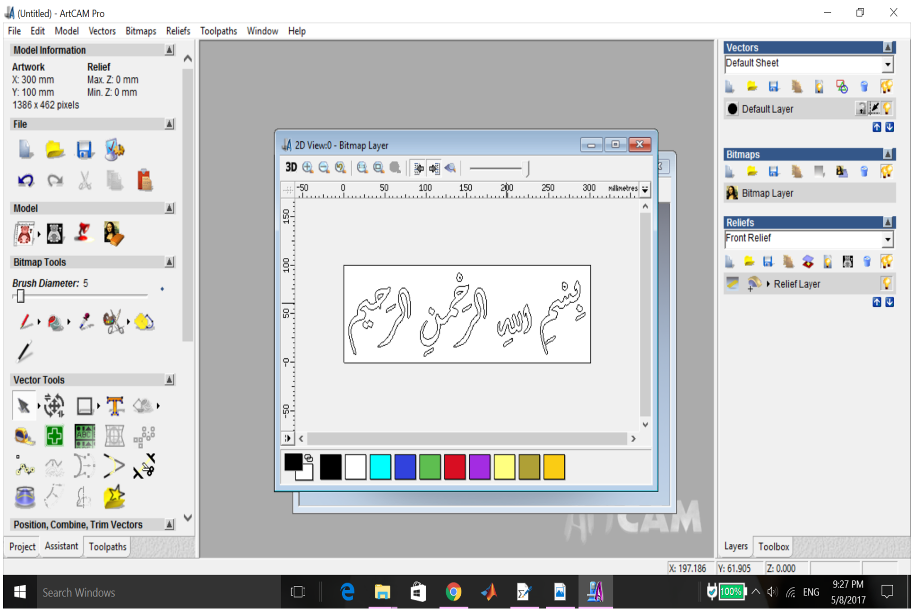


Figure 6.16 Design Vector.

7. Right click and select shape editor to create a three dimensional design as shown in Figure 6.17.

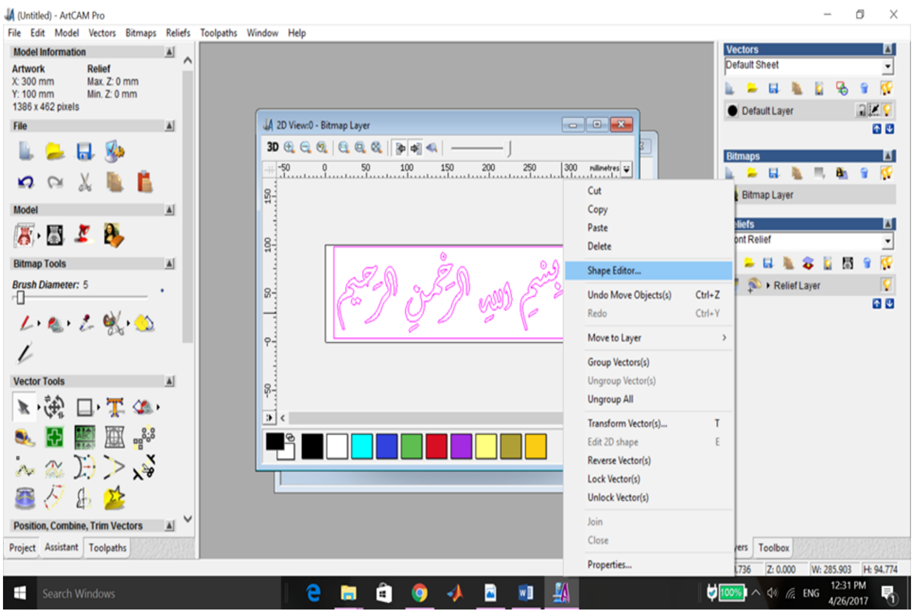


Figure 6.17 Shape Editor.

8. Use the shape you want and set the desired angle and height and then click apply as shown in Figure 6.18.

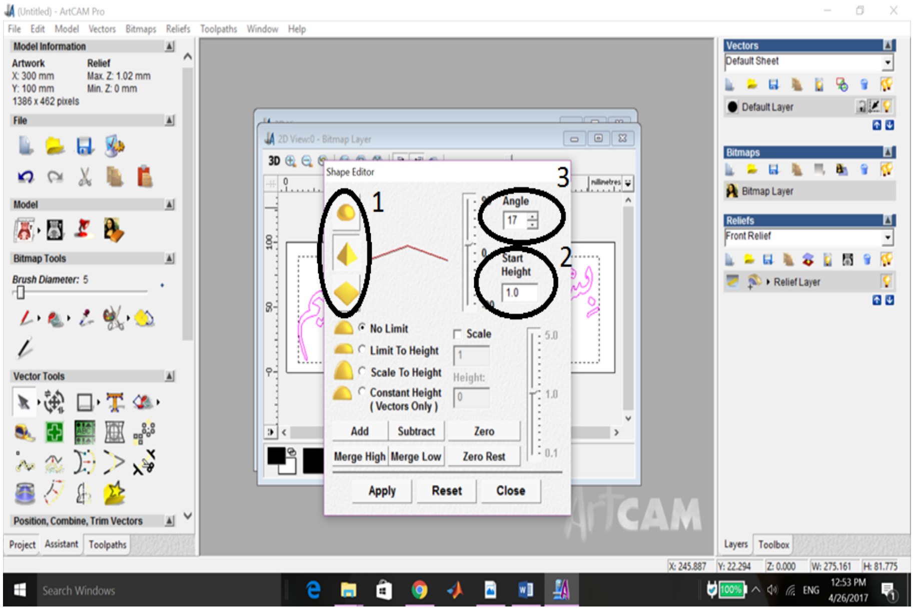


Figure 6.18 Shape Commands.

9. The final design is shown in Figure 6.19.

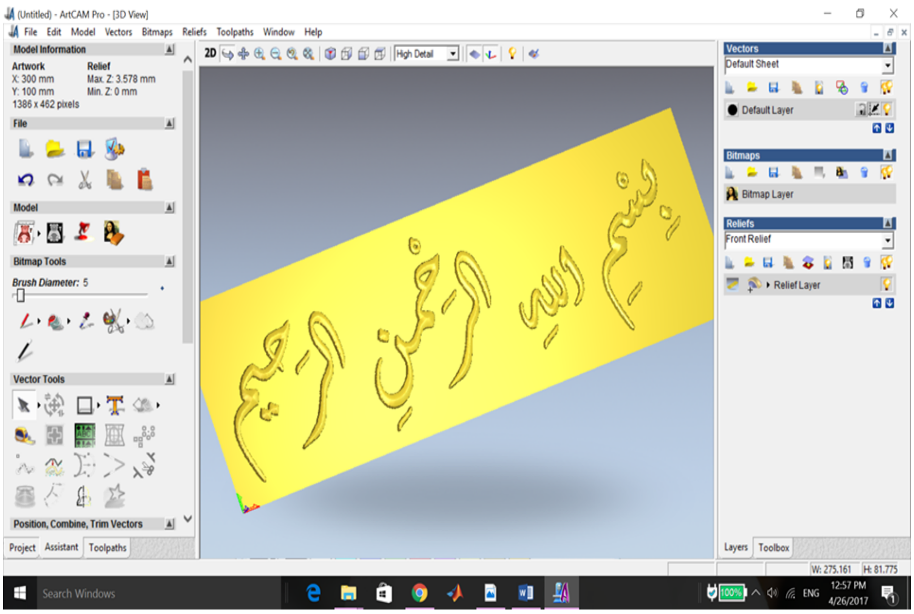


Figure 6.19 Final Design.

These steps show the CAD procedure that are used to design the product. After that CAM procedure should be apply to generate the desired G-code.

10. Click on the toolpath to apply the desired manufacturing commands to generate the desired G-Code as shown in Figure 6.20.

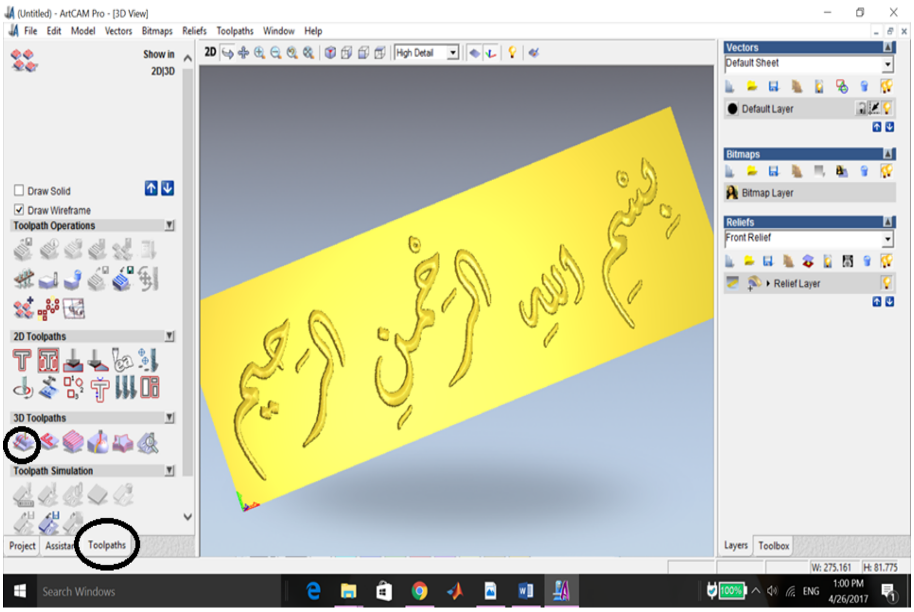


Figure 6.20 ToolPath.

11. Click on machine relief to create the three dimensional design as shown in Figure 6.20. This command is used to machine the design in three dimension.

12. Set the allowance and Tolerance as desired, then select the tool as shown in Figure 6.21.

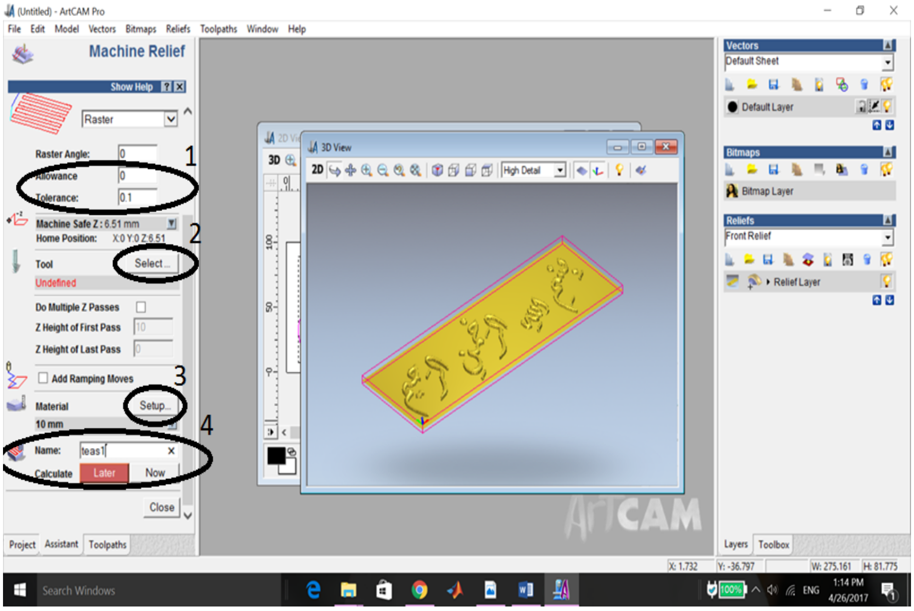


Figure 6.21 Manufacturing Processes.

13. Select the dimensions of the material of the product and name your operation, then click on now as shown in Figure 6.21.

14. Save the tool path as shown in Figure 6.22 and Figure 6.23 to generate the desired G-code.

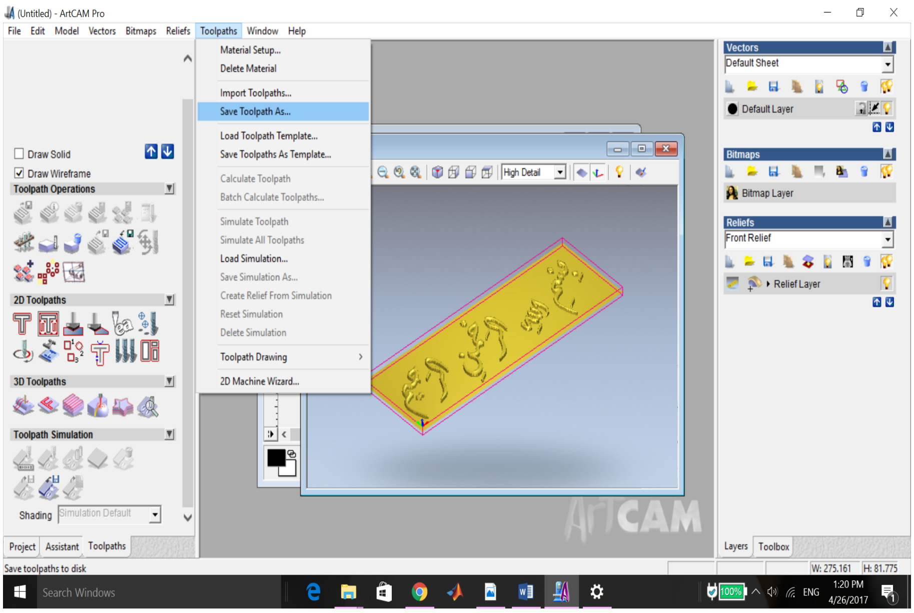


Figure 6.22 Save Tool Path.

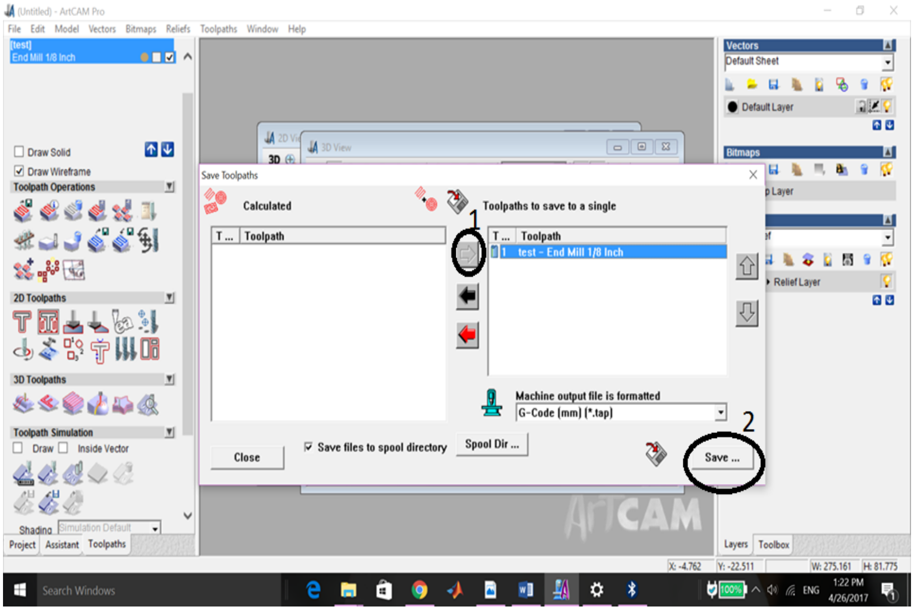


Figure 6.23 Save Tool Path as Text File.

The final product that produce from these procedure is shown in Figure 6.24 and Figure 6.25.

Figure 6.24 Product During Mill Process.

Figure 6.25 The Final Product.

6.4 Problems

During testing some of problems has been detect as follow.

- Problem 1

  The motor of depth-axis blocked during the movement. The motor of depth-axis rotates when the distance is small, but when the distance becomes high the motor rotates then get blocked. First, depth-axis motor has been disassembly from the machine to test it alone to know the reason of the problem. After testing the motor the same problem appears. There is no problem with small distance because the motor does not reach the maximum speed. The speed of the motor has been reduced to solve the long distance problem. To achieve the required speed, number of step per revolution is reduced. Then, the motor is tested with the required speed and it works without any problem, so 1600 steps per revolution is selected for depth-axis.

- Problem 2

  Length-axis vibration. During test operation length-axis shows some vibration due to bending in the lead screw. This problem was solved by reducing the speed of length-axis.

- Problem 3

  Wood dust. High amount of wood dust produces during carve out the wood. This problem is solved by adding Vacuum cleaner.

Chapter 7

Conclusions

7.1 Conclusion

We built a single-phase power source CNC for wood-working machine that helps the wood workers to have their own three dimensional products. This machine is controlled by an Arduino which receives signals from the computer and send it to the motor drivers to move the axes as desired. The desired structure has been achieved with dimensions of $(850 \times 630 \times 1080)\ mm$. Our machine produces a workpiece with a maximum dimensions $(700 \times 400 \times 50)\ mm$. After make some samples using our machine and measure the accuracy of these samples, this accuracy is within $0.05\ mm$. Our machine is easy to maintenance and assembly since we did not use welding to assemble the machine parts. Several types of bits could be used on spindle route to carved out different types of wood by this machine. The cutting ability depends on the type of bits that used.

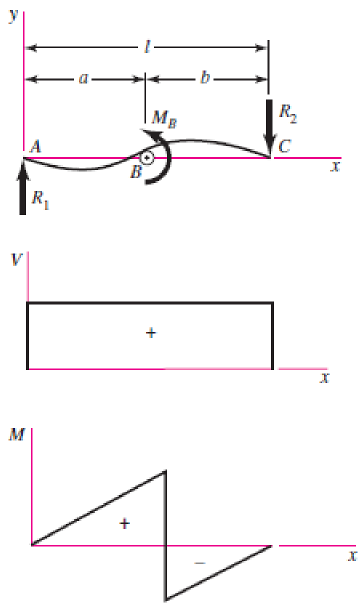
7.2 Outlook

Many things could be done to improve this machine. First, grid door could be added to improve safety. Second, improve the type of bearing and screw that are used in this machine to reduce the accuracy. Third, Human machine interface can be used instead of using computer. Fourth, this machine could be improved to be a four degree of freedom(4-DOF) machine. Fifth, the way to fix the workpiece could be improved.

Appendix I

Moment Shear and Deflection Diagrams

Simple supports—moment load



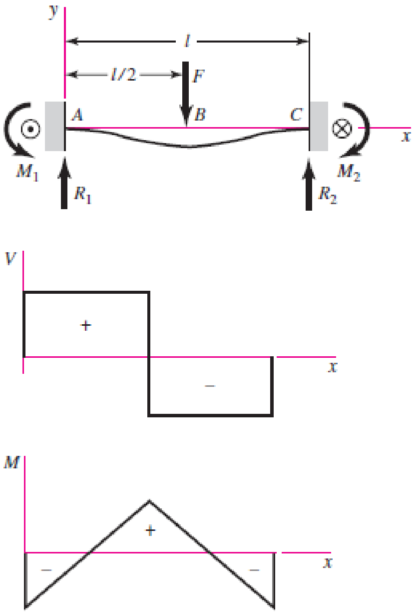
$$R_1 = R_2 = \frac{M_B}{l} \qquad V = \frac{M_B}{l}$$

$$M_{AB} = \frac{M_B x}{l} \qquad M_{BC} = \frac{M_B}{l}(x - l)$$

$$y_{AB} = \frac{M_B x}{6EIl}(x^2 + 3a^2 - 6al + 2l^2)$$

$$y_{BC} = \frac{M_B}{6EIl}[x^3 - 3lx^2 + x(2l^2 + 3a^2) - 3a^2 l]$$

Fixed supports—center load



$$R_1 = R_2 = \frac{F}{2} \qquad M_1 = M_2 = \frac{Fl}{8}$$

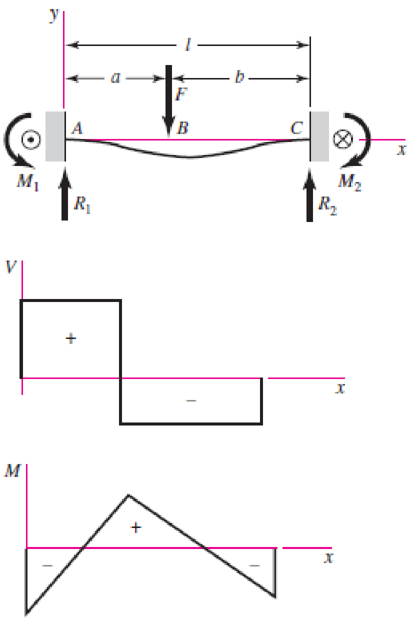
$$V_{AB} = -V_{BC} = \frac{F}{2}$$

$$M_{AB} = \frac{F}{8}(4x - l) \qquad M_{BC} = \frac{F}{8}(3l - 4x)$$

$$y_{AB} = \frac{Fx^2}{48EI}(4x - 3l)$$

$$y_{\max} = -\frac{Fl^3}{192EI}$$

Fixed supports—intermediate load



$$R_1 = \frac{Fb^2}{l^3}(3a + b) \qquad R_2 = \frac{Fa^2}{l^3}(3b + a)$$

$$M_1 = \frac{Fab^2}{l^2} \qquad M_2 = \frac{Fa^2b}{l^2}$$

$$V_{AB} = R_1 \qquad V_{BC} = -R_2$$

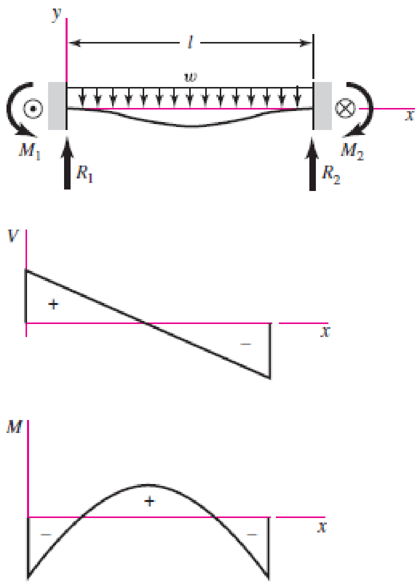
$$M_{AB} = \frac{Fb^2}{l^3}[x(3a + b) - al]$$

$$M_{BC} = M_{AB} - F(x - a)$$

$$y_{AB} = \frac{Fb^2x^2}{6EIl^3}[x(3a + b) - 3al]$$

$$y_{BC} = \frac{Fa^2(l - x)^2}{6EIl^3}[(l - x)(3b + a) - 3bl]$$

Fixed supports—uniform load



$$R_1 = R_2 = \frac{wl}{2} \qquad M_1 = M_2 = \frac{wl^2}{12}$$

$$V = \frac{w}{2}(l - 2x)$$

$$M = \frac{w}{12}(6lx - 6x^2 - l^2)$$

$$y = -\frac{wx^2}{24EI}(l - x)^2$$

$$y_{max} = -\frac{wl^4}{384EI}$$

Appendix II

MATLAB®Code

$\%modulus\ of\ elasticity$

$Dy = 0.02;$

$E = 205000000000;$

$Iy = pi * Dy^4/64;$

$Dx = 0.025;$

$Ix = pi * Dx^4/64;$

$\%Depth - axis\ reaction$

$\%Depth - axis\ weight$

$Wdz = 47;$

$\%length\ between\ A\ and\ B$

$LAB = 0.1;$

$\%length\ between\ W\ and\ A, B\ in\ X - direction$

$LWBinY = 0.0653;$

$LWAinY = 0.0653;$

$\%length\ between\ W\ and\ A, B\ in\ Z - directin$

$LWAinZ = 0.0367;$

$LWBinZ = 0.0633;$

$\%reactin\ (RAz,\ RAx,\ RBz,\ and\ RBx)$

$RAz = Wdz;$

$RAx = Wdz * LWAinY/LAB;$

$RBz = Wdz;$

$RBx = Wdz * LWBinY/LAB;$

$\%Widt - axisreaction$

$\%length\ beam\ distributed\ load$

$wy = 7858 * 9.81 * pi * (Dy^2)/4;$

$\%length\ between\ C\ and\ D\ and\ between\ E\ and\ F$

$LCD = 0.546;$

$LEF = 0.546;$

$\%Reactin\ for\ C - D\ beam\ and\ E - F\ beam\ in\ Z\ direction$

$RCz = (RAz/2) + (wy * LCD/2);$

$RDz = RCz;$

$REz = RCz;$

$RFz = RCz;$

$\%Moment\ For\ C - D\ beam\ and\ E - F\ beam\ in\ Z\ direction$

$MCx = (RAz * LCD/8) + (wy * (LCD^2)/12);$

$MDx = MCx;$

$MEx = MCx;$

$MFx = MCx;$

$\%Reactin\ for\ C - D\ beam\ and\ E - F\ beam\ in\ X\ direction$

$RCx = (RAx/2);$

$RDx = RCx;$

$REx = -RCx;$

$RFx = -RCx;$

$\%Moment\ For\ C - D\ beam\ and\ E - F\ beam\ in\ X\ direction$

$MCz = (RAx * LCD/8);$

$MDz = MCz;$

$MEz = -MCz;$

$MFz = -MCz;$

$\%maximum\ reactin\ for\ C - D\ beam\ and\ E - F\ beam\ in\ Z\ direction$

$RCzmax = RAz * (0.436^2) * (3 * 0.11 + 0.436)/(LCD^3) + wy * LCD/2;$

$RDzmax = RCzmax;$

$REzmax = RCzmax;$

$RFzmax = RCzmax;$

$\%Maximum\ moment\ For\ C - D\ beam\ and\ E - F\ beam\ in\ Z\ direction$

$MCxmax = RAz * (0.11 * 0.436^2/0.546^2) + wy * LCD^2/12;$

$MDxmax = MCxmax;$

$MExmax = MCxmax;$

$MFxmax = MCxmax;$

$\%maximum\ reactin\ for\ C - D\ beam\ and\ E - F\ beam\ in\ X\ direction$

$RCxmax = RAx * (0.436^2) * (3 * 0.11 + 0.436)/(LCD^3);$

$RDxmax = RCxmax;$

$RExmax = -RCxmax;$

$RFxmax = -RCxmax;$

$\%Maximum\ moment\ For\ C - D\ beam\ and\ E - F\ beam\ in\ Z\ direction$

$MCzmax = RAx * (0.11 * 0.436^2/0.546^2);$

$MDzmax = MCzmax;$

$MEzmax = -MCzmax;$

$MFzmax = -MCzmax;$

$\%Maximum\ deflection\ in\ Z\ direction\ for\ C - D\ and\ E - F\ beams$

$YCDz = -(RAz * LCD^3)/(192 * E * Iy) - (wy * LCD^4/(384 * E * Iy));$

$\%maximum\ defliction\ in\ X\ direction\ for\ C - D\ and\ E - F\ beams$

$YCDx = -(RAx * LCD^3)/(192 * E * Iy);$

$\%Width - axis\ reaction$

$\%Depth - axis\ weight$

$Ww = 22;$

$\%length\ between\ G\ and\ Ww\ in\ X - direction$

$LGWwinX = 0.0085;$

$\%length\ between\ G\ and\ E, C\ inX - direction$

$LGCinX = 0.03;$

$LGEinX = 0.03;$

$\%length\ between\ G\ and\ E, C\ in\ Z-direction$

$LGCinZ = 0.33;$

$LGEinZ = 0.23;$

$\%moment\ about\ G\ around\ Y-direction$

$MGy = (-RExmax*LGEinZ)+(RCzmax*LGCinX)+(REzmax*LGEinX)+$

$(Ww*LGWwinX)-(RCxmax*LGCinZ);$

$\%reaction\ force\ in\ G\ in\ Z-direction$

$RGz = RCzmax+REzmax+Ww;$

$\%moment\ about\ G\ around\ Z-direction$

$MGz = MCzmax+MEzmax;$

$\%reaction\ force\ in\ G\ in\ X-direction$

$RGx = RCxmax+RExmax;$

$\%Length-axis\ reaction$

$\%length\ beam\ distributed\ load$

$wx = 7858*9.81*pi*(Dx^2)/4;$

$\%length\ between\ H\ and\ I\ and\ between\ J\ and\ K$

$LHI = 0.850;$

$LJK = 0.850;$

$\%Reaction\ for\ H-I\ beam\ and\ J-K\ beam\ in\ Z\ direction$

$RHz = (RGz/2)+(wx*LHI/2)+MGy/LHI;$

$RIz = (RGz/2)+(wx*LHI/2)-MGy/LHI;$

$RJz = (RGz/2)+(wx*LJK/2)+MGy/LJK;$

$RKz = (RGz/2)+(wx*LJK/2)-MGy/LJK;$

$\%Moment\ For\ C-D\ beam\ and\ E-F\ beam\ in\ Z\ direction$

$MHy = (RGz*LHI/8)+(wx*(LHI^2)/12)+MGy;$

$MIy = (RGz*LHI/8)+(wx*(LHI^2)/12)-MGy;$

$MJy = (RGz*LJK/8)+(wx*(LJK^2)/12)+MGy;$

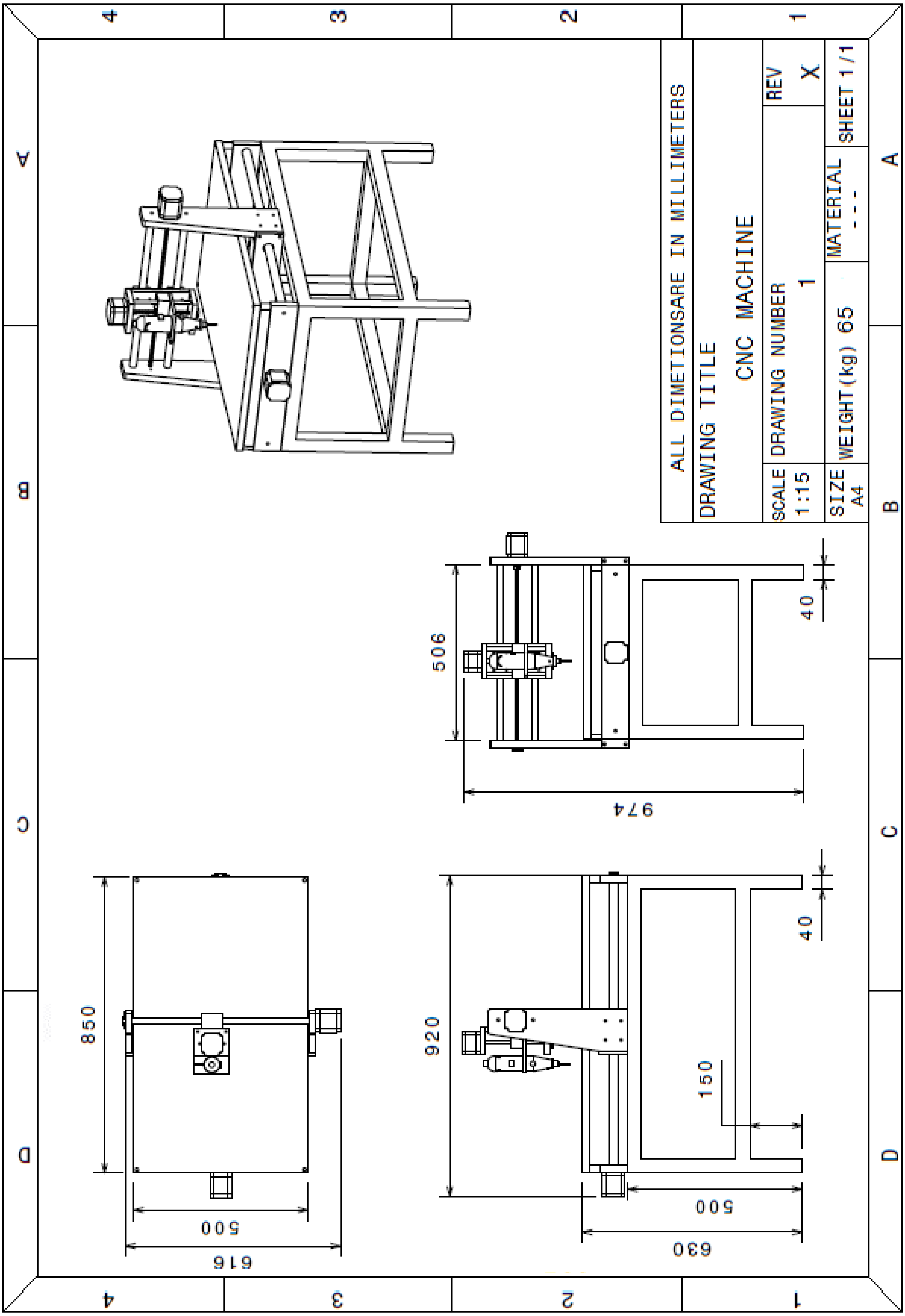
$MKy = (RGz*LJK/8)+(wx*(LJK^2)/12)-MGy;$

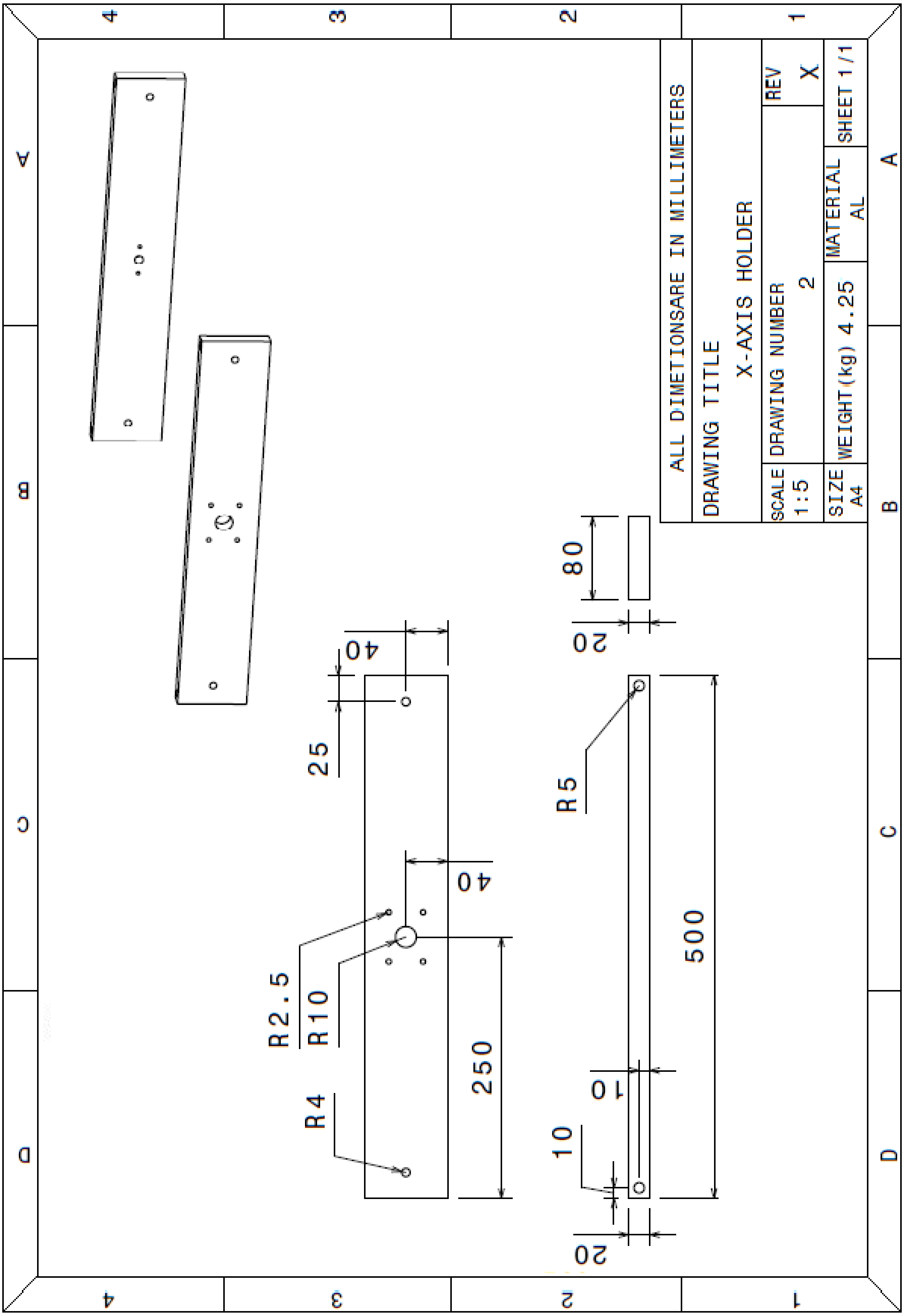
$\%Maximum\ deflection\ in\ Z\ direction\ for\ H-I\ and\ J-K\ beams$

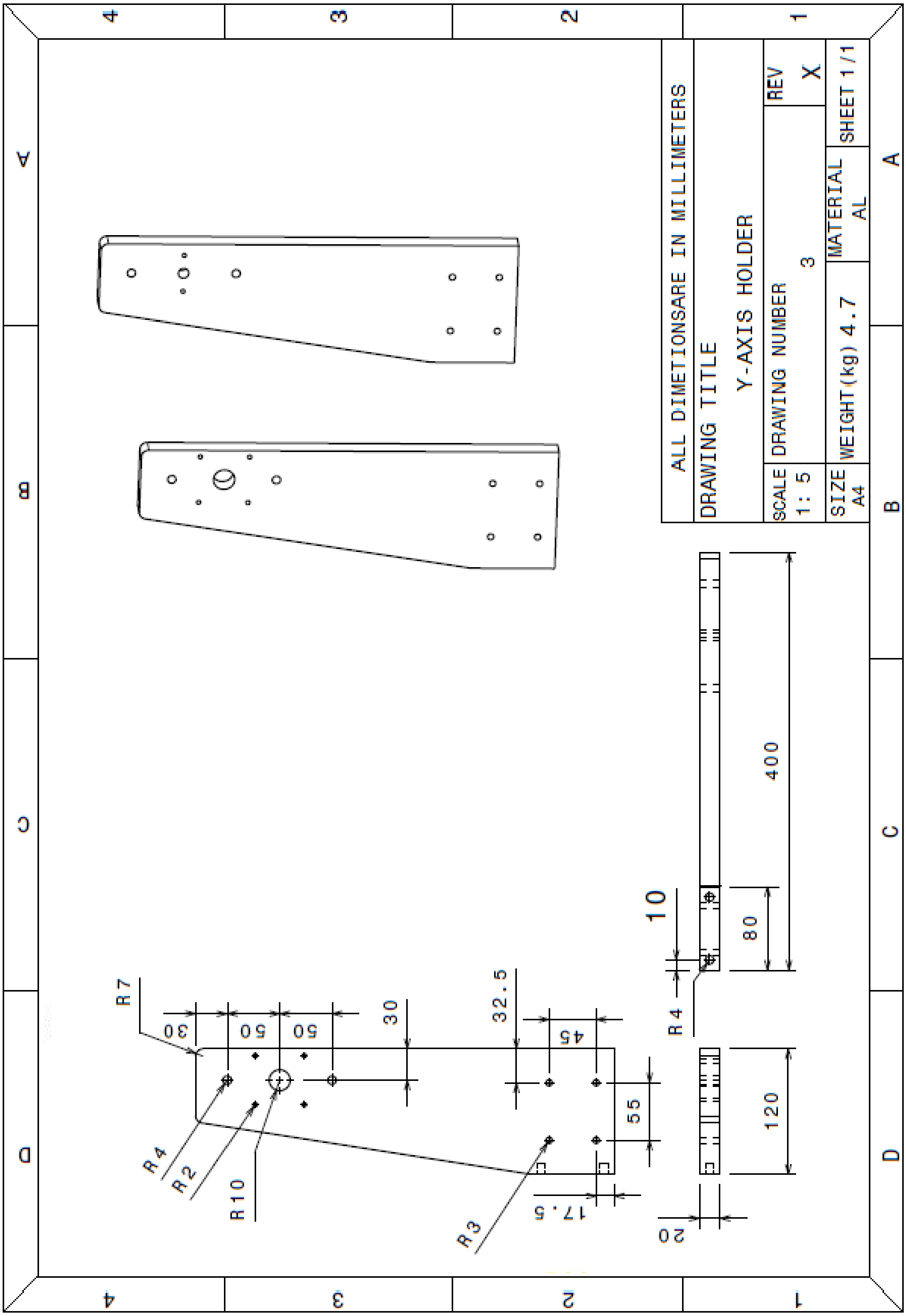
$$YHIz = -(RGz * LHI^3)/(192 * E * Ix) - (wx * LHI^4)/(384 * E * Ix);$$

Appendix III

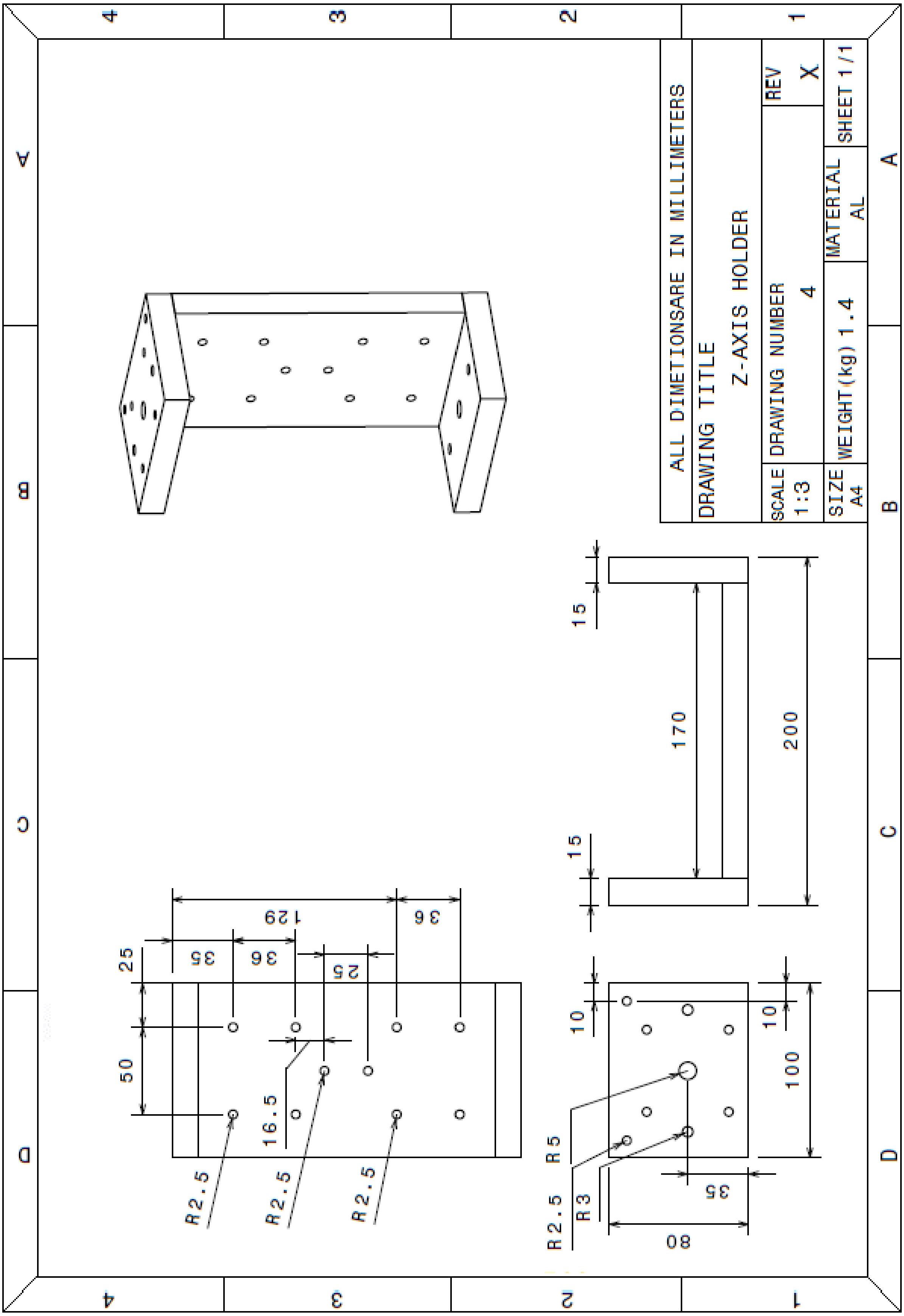
Fram Design Sheet

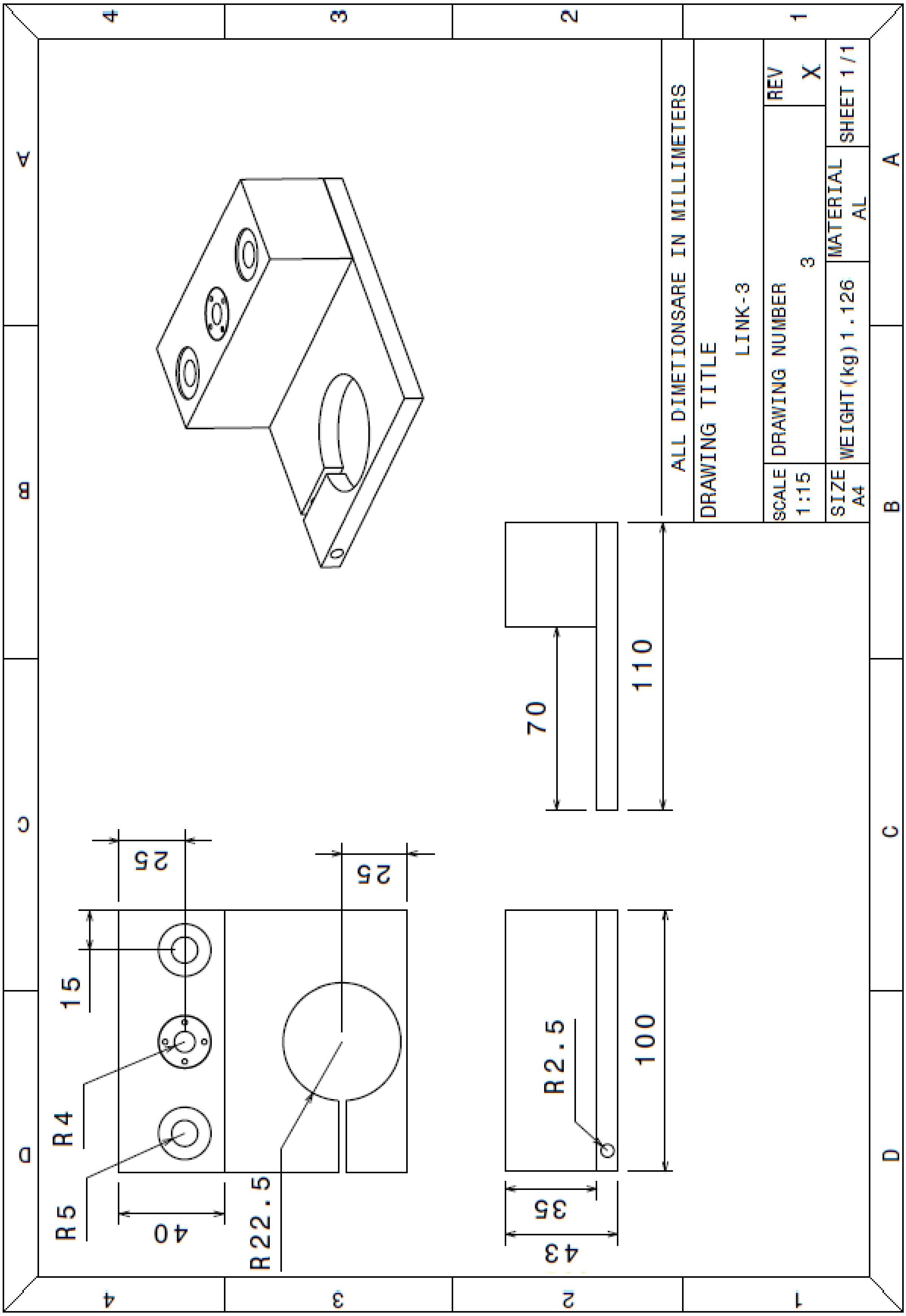

ALL DIMETIONSARE IN MILLIMETERS
DRAWING TITLE
CNC MACHINE
DRAWING NUMBER
1
REV
X
SCALE
1:15
SIZE
A4
WEIGHT(kg) 65
MATERIAL
- - -
SHEET 1/1
506
40
974
920
150
500
630
850
616


ALL DIMETIONSARE IN MILLIMETERS
DRAWING TITLE
X-AXIS HOLDER
REV
X
DRAWING NUMBER
2
SHEET 1/1
MATERIAL
AL
WEIGHT(kg) 4.25
SCALE
1:5
SIZE
A4
80
20
40
25
R5
40
500
R2.5
R10
250
R4
10
10
20
A
B
C
D
1
2
3
4



ALL DIMETIONSARE IN MILLIMETERS
DRAWING TITLE
Y-AXIS HOLDER
DRAWING NUMBER
3
REV
X
SCALE
1: 5
SIZE
A4
WEIGHT(kg) 4.7
MATERIAL
AL
SHEET 1/1
400
80
120
10
20
R 4
R 7
30
50
50
30
32.5
45
55
17.5
R 4
R 2
R 10
R 3


ALL DIMETIONSARE IN MILLIMETERS
DRAWING TITLE
Z-AXIS HOLDER
SCALE 1:3
DRAWING NUMBER 4
REV X
SIZE A4
WEIGHT(kg) 1.4
MATERIAL AL
SHEET 1/1


ALL DIMETIONSARE IN MILLIMETERS
DRAWING TITLE
LINK-3
DRAWING NUMBER
3
REV
X
SCALE
1:15
SIZE
A4
WEIGHT(kg)1.126
MATERIAL
AL
SHEET 1/1
70
110
100
R2.5
35
43
25
25
15
R4
R5
40
R22.5

Appendix IV

Stepper Motor Data-sheet

Two stepper motors NEMA 23 model number of 23HS8430 is selected to move length-axis and width-axis. The stepper motor NEMA 23 model number of 23HS8430 have the following specifications:

- Step angle: 1.8 degree.
- Holding torque: 1.9 (N.m).
- Number of phase: 2
- Rated Current: 3 A.
- Rated Voltage: 3.2 V.
- Wight: 1050 g.

Stepper motor NEMA 23 model number of 23HS5628 is selected to move depth-axis. The stepper motor NEMA 23 model number of 23HS5628 have the following specifications:

- Step angle: 1.8 degree.
- Holding torque: 1.8 (N.m).
- Number of phase: 2

- Rated Current: 2.8 A.
- Rated Voltage: 2.5 V.
- Wight: 700 g.

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