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THE IMPACT OF A THREE AXIS COMPUTER NUMERICAL CONTROL (CNC) SHAPING MACHINE ON DESIGNING

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ABSTRACT

Wood carving from the ancient time is an attractive work for the decorative purposes and basic pattern demand. Earlier it was done by few skilled labors but from past decade due to increase in demand of items for decoration because of high life style is been done with the help of machine tools. The scenario is totally changed with the invention of CNC machines. As the close tolerance is needed for this purpose, CNC machines are best suited for this work because with the CNC machine this is achieved which add towards the beauty of the carving. This study explores the design of the wood carving CNC router 3- axis machine and analysis of its performance. Computer numerical control (CNC) machining is a subtractive manufacturing process which typically employs computerized controls and machine tools to remove layers of material from a stock piece- known as the blank or work piece- and produces a custom-designed part (Newman, 2007). This process is suitable for a wide range of materials including metals, plastics, wood, glass, foam, and composites, and finds application in a variety of industries, such as large CNC machining and CNC machining aerospace parts (Rogers, 2019). Rapid prototyping is widely used to reduce time to market in product design and development (Frank, 2004). Today systems are used by engineers to communicate their product designs as well as make rapid tooling to manufacture the products. Computer numerically controlled (CNC) milling machines are part of this technology. This project will present the design of the MINI CNC router 3-axis machine and analysis of its performance. This machine has a characteristic demand by the industry and academic designers (Xu, 2006). Studying of the existing machines aids in setting the specification for the new design. Comparing the performance of the new machine with the existing machines will improve future designs. The Analysis of the machine tool components are done in solid works to check the deflection which add towards the tool deflection and main cause for the tool path deviation. So, optimization is done to minimize the deflection of machine tool components against its own self weight, cutting forces, long lengths of drives etc. In the present work, knowledge of machine design, solid mechanics and strength of materials is used to do the whole work. Due to the higher costs attached to the purchasing of the CNC machines, the locally acquired materials which are cheaper and affordable have been used in this design. Precision and accuracy of the machine is very cardinal, despite being made simple the products obtained using it have very close tolerances compared to the standard CNC machines made by well-established manufacturing companies. This machine is used in the manufacturing sector for drilling, milling, and reaming, boring and counter boring. The focus of this study is to ensure that small scale designers within our country should not lag behind in terms of improvements being devised in the design and technology industry on the global scale.

Keywords

CNC	Computer Numerical Control
FoS	Factor of Safety
MCU	Machine Control Unit
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
G-code	Geometrical code
USB	Universal Serial Bus
LAN	Local Area Network
WAN	Wide Area Network
PCB	Printed Circuit Board
IDE	Integrated Development Environment

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I. CHAPTER ONE

INTRODUCTION AND BACKGROUND TO THE STUDY

1.0 INTRODUCTION

This chapter elaborates the general introduction and background to the research topic- design of the CNC 3-axis router and analysis of its performance. It states the background of the study, research objectives, statement of the problem, purpose of the study, the scope and significance of the research and it outlines the general research work.

Wood working is one of the historic arts known to man that is being practiced from many centuries. In ancient era this was performed by hands using chisels and hammers which needed a tremendous amount of skill, labor and time. The birth of machine tools sparked the idea of automating this hard to master art so that wooden designs can be accurately created with less effort and in short span of time. Nowadays it is fashion to have sculptured design in the doors of the big hotels and homes of rich peoples. Not only the doors but demand of all other decorative objects made of wood carving is increasing. Many small-scale companies are there which offer various designs at very attractive costs. This is a result of revolutionized improvement and innovation in wood carving methods using computer-controlled machines known as CNC routers. One such 3-axis router is designed using today's available modeling software and then this design is optimized for best performance and building cost. The outlined procedure for this is discussed in forthcoming chapters of this thesis report.

1.0.1 Evaluation of wood carving

It is the propensity of human nature to embellish every possible article. Carving in wood is done with the help of tools, which results in a wooden sculpture, or in the beautification of a wooden object like wooden vases, doors etc. primitive wood carving was performed by hands with the help of chisels or some pointed objects. The finished artifact's quality was totally contingent on the labor skills which was very hard to master and consumed a good amount of time. Wooden patterns are preferred over other materials as it is cheap and available in abundance, it can be easily shaped into different forms and intricate designs, its manipulation is easy because of lightness in weight, good surface finish can be easily obtained by only planning and sanding and it can be preserved for a fairly long time by applying proper preservatives like shellac varnish. Though wood cannot endure for a long time due to its tendency to absorb moisture and being eaten by insects still in some places all over the world sculptured objects are found believed to be shaped thousands of years ago. There are reports of the North American Indian of carving their wooden fish-hook just as the Polynesian works patterns on his blade. The native of Guyana decorates with a well-conceived scheme of incised scrolls, while the inhabitant of Loango Bay carve their spoon with a design of perhaps figures standing up in full relief carrying a Hammock (Anon., 2019). In ancient effort to preserve the wooden figures for a long time, they were painted using colors. Work were made to perform the wood carving work mechanically using machines, but not until the eighteenth century. It was then that any positive and practical ideas were described. Sir Samuel Bentham, an Englishman, patented in 1791 and 1793 principles of wood working which are in use even today. His inventions included "Planning machines with rotary cutters to cut on several sides of the wood at once and veneer cutting machines, moulding and recessing machines, bevel sawing machines, saw sharpening machine, tenon cutting machine by means of circular saws, boring tools" (Anon., 2019). Though there are numerous tools available for wood working, either manually driven or electrically driven, but still there is need for skillful hands to wield them. Development in field of computers made it possible for the invention of computer-controlled wood carving machines also known as routers which made wood carving process fast, more precise and crafting skills independent. Though these machines are capable of taking wood carving to sky high level, still they need human to guide them and command them to let miracles happen.

The more one recognizes the individualities of wood, the better one can appreciate the degree of warmth and beauty that it brings to our lifestyle. As each grain pattern in all type of woods is a unique chef-d'oeuvre of design, texture and majesty, people all over the world that owns goods made of wood can be assured that they are the only one in the world who owns that specific grain pattern and its natural beauty. Even flaws like knots or other natural blemishes can add more beauty and character to any given piece of wooden artifact. The density of a wood represents its mechanical properties. With change in source of species, density of wood also changes. The taxonomy of wood has factually always been in terms of hard wood and soft wood. The hardwood for example wood from oak, maple, walnut is classified under dicotyledons and softwood for example pine and balsam are classified under Conifers.

1.0.2 CNC Router

A CNC router abbreviated as computer numeric control does carving with the help of machine tools. CNC router is the improved form of hand held routers. CNC routers are mounted on a device which guides the router through specified tool path. The tool travels on the confined path and used to cut a variety of materials varying from hardest to softest. A CNC router works similar to a CNC milling machine yet it differs from it in application of working material and so require tools that are significantly different in detail. The chip formation for both tools are different in terms of their mechanism, and according to the materials. Routing is applied to wood, plastics and Aluminum, as these materials are weak in small sections, routers may be run at extremely high speeds and so even a small router may cut rapidly. The wood router typically spins faster with a range of 13,000 to 24,000 RPM (Anon., 2019). A wood router is controlled with software specifically designed for use of wood routers. Computer numerical control is a very broad term that encompasses a variety of types of machines- all with different sizes, shapes, and functions. But the easiest way to think about CNC is simply to understand that it's all about using computers as a means to control a machine that carves useful objects from solid blocks of material. For example, a CNC machine might begin with a solid block of aluminum, and then carve away just the right material to leave you with a bicycle brake handle.

CNC machines can be divided into two groups: turning machines and milling machines. A turning machine is generally made up of a device that spins a work piece at high speed and a tool (sharp edge) that shaves off the undesired material from the work piece (where the tool is moved back and forth and in and out until the desired form is achieved)(SUZUKI, 2000). A milling machine is a machine that has a spindle (a device similar to a router) with a special tool that spins and cuts in various directions and moves in three different directions along the x, y, and z axes (Shneor, 2014). Historically, you wouldn't actually need a computer to create forms with a turning machine or a milling machine. Adding a computer to the mix allows you to design a product on a computer first and then specify how the machine should cut this product. To design the product is to produce a computer aided design (CAD) file (Zaborski, 2018). Then you specify how the machine should cut the product, and the result of that step is a computer-aided manufacturing (CAM) file (or G-code file, or NC file- there are many names for this type of file).

The CAM file remembers all of the operations that the milling machine must follow to cut out the parts for the product (Zaborski, 2018). The computer tells the CNC machine how to build the part by interpreting the CAM file into signals that the CNC machine can understand.

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1.1 Background to the Study

The main focus of this study is to assess the design of CNC router 3-axis machine and analysis of its performance a case study on the growing industry in Chimwemwe, Nakadoli area, Kitwe.

Metalworking and fabrication were performed by numerical controlled or NC machines before the invention of CNC machining. These NC machines were created in the late 1940s by John T. parsons, who worked closely with the Massachusetts Institute of Technology. The product being developed by them was commissioned by the United States Air Force. The goal of this work was to find a more cost-effective way to manufacture aircraft parts that had intricate geometries. During this time period NC became the industry standard. It was not till 1967 that the idea of computer-controlled machining started to circulate. The implementation of Computer Aided Design and Computer Aided Machining started developing in 1972 which lead to prominent developments in CNC machining. 1976 marked the first year 3D computer Aided Design/Computer Aided Machining systems were available. By 1989, these CNC machines had become the industry standard.

1.1.1 History of CNC machines

CNC is the combination of Numerical Control (NC, the controlling of machinery using numbers either to manipulate discrete controls, or more directly via punch cards or tapes or other electrical signals) and computers. The history starts with early efforts to automate industrial machinery such as looms.

1.2 Statement of the Problem

Most Zambian industries, to be more specific design and technology industries do not have effective machines to mitigate challenges faced by small scale designers. This does not only compromise the standard of the quality of the work produced but also individuals who operate in these industries are subjected to numerous accidents and the duration to complete the job is prolonged.

1.3 Justification

This project of the CNC 3-axis machine was produced locally with the view to empower local manufacturers to produce parts that could be of relevance to the consumer and to cut on time taken by the designer to finish the product for it to be on the market. This machine also produces components which are accurate as compared to other machines (Yemelyanov, 2018). Component of this machine such as the frame and others were locally made and some electronic components were imported making the machine cheaper compared to the imported and assembled ones.

1.4 Research Objectives

The main objective of the research is to assess the design of the CNC 3-axis and analyzing of its performance for the design and technology industry.

The specific objectives being;

1. Design of the CNC router 3-axis machine
2. Performance analysis of the CNC router 3-axis machine
3. Fabrication of the low-cost CNC router 3-axis machine using locally obtained materials

1.5 Purpose of the Study

The research will reveal vital benefits attached to the use of the CNC 3-axis machines, recommendations that will not favor individual designers but the country as a whole.

1.6 Significance of the study

The research will have a practical significance. Once the government and private sectors invest in this new technology, our products will not only be marketable locally but will also be competing on the world market. Further findings will also add on the skills required by the designers and also understanding the effective measures to take in order to curb against unnecessary accidents. For academics, the findings of this research will be of so much help in the sense that the knowledge acquired in courses like computer science will be put to good use.

1.7 Scope

The research focus was based on the growing industries that deal with the design and technology within Zambia. Since the model produced in this project is a MINI CNC machine which is a prototype, the size of the blank or work piece to be accommodated on this machine is small. This implies that only smaller pieces of work can be produced.

II. CHAPTER TWO:

LITERATURE REVIEW

2.0 Introduction

The previous chapter elaborates the general introduction and background to the research topic- design of the CNC router 3-axis machine and analysis of its performance for the modern design and technology industry in Zambia, stating the objectives and significance of the research and outlines the overall research work. This chapter reviews the relevant literature relating to the research study. In addition, it has discussed older versions and up-to-date machines and methods that have been put in place to mitigate, reduce or completely eradicate challenges faced by the operators of these machines.

From the literature it confirms that there are a number of machines which were invented before the new versions of the machines we have today. A number of them started as manual machines which depended entirely on the man power to perform its intended work effectively (Barlow, 2008). The first machines which were made required more power but as the improvements/upgrades were incorporated to these machines less power was consumed during its operation.

Worldwide, millions of people living in the rural and urban areas of third world countries depend on woodcarving industry as their source of livelihood (Mutinda, 2014). Economic benefits of woodcarving industry are now widely recognized in many parts of the world due to its commercialization, traditionally it started as a way of expressing people's culture through symbols sculptured to represent specific messages, people's beliefs and thoughts (Brusatte, 2012). In South Africa, Oaxaca and Mexico, the industry contributes around USD500, USD2000 and USD2500 respectively annually. Commercialization of the wood carving industry in Ghana had made its earnings from the industry rise up to more than USD 3000000 in 1996 as compared to USD 60000 in 1989(Laurent, 2009). In Zimbabwe the woodcarving industry has been an important rural livelihood method since the carvers are able to meet their primary needs and have been able to acquire property through it (Fadiman, 2008).

2.0.1 Machining Properties of Wood

Like other cellular solids wood is a highly anisotropic material exhibiting a nonlinear stress-strain Behavior (Stefan Holmberga, 1999). The material property data depends upon the species and growth condition. They suggest the micro-macro modeling approach to find out the realistic material description. In this method FEM modeling of the wood structure is done on different layers of the wood.

Increase in moisture content in wood structure enhances its machining property by decrease in cutting resistance but too much moisture content causes the tearing out of the fiber (S.Sali, 2003). The growth ring is composed of different layer of tissue density, the tool with circular motion when passes through these two alternative regions increases amplitude of vibration resulting in poor surface finish.

Tests were carried out to study machining properties and surface roughness of various wood species grown in different conditions (lu, 2007). Effects of the rake angle and the feed speed were observed. The relationship between rake angle and surface roughness were less smooth with increase in rake angle.

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Machining work on coconut wood was carried out; from the results they found out that the surface roughness changes with the feed rate (S. Rawangwong, 2011). The results also showed that keeping the feed rate low and with higher cutting speed surface, surface roughness reduces.

Behavior of cutting force on different wood-based material using the cutting tool helical in shape has been documented. Tooth is discretized further in order to form three orthogonal infinitesimal cutting forces from cutting constants. The methodology presented in this study can be improved in order to predict cutting forces for several materials and wood machining.

Wood cutting machine process is characterized by multi axes high acceleration and deceleration phases and requires relevant electric energy amount to operate (J'er'emie Boucher, 2007). This can cause electrical rack failure due to over-temperature operations, which decreases the efficiency of all the wood cutting process. Therefore, it is very important to install an energy recovery system into our machine which allows to store the amount of energy produced during deceleration phases and to use this energy during the acceleration phases of the machine axis.

2.1 Global Scale Woodcarving

2.1.1 Types of commercial CNC routers

The CNC routers are generally classified under a number of axes. The axis of CNC router increases following the complexity of the work to be performed.

2.1.1.1 2-axis CNC router

These are low-end routers that are used mostly by hobbyists for basic domestic items. These types of CNC routers do not have a true Z-axis implying that they are not prominent for industrial applications. These routers can produce figures on flat plate of constant depth. An example of such work is shown in the figure below.

Figure 2-1: Example of wood carving by 2-axis CNC router.

Author: (Barlow, 2008)

2.1.1.2 3-Axis CNC Router

The 3-axis CNC router is the most commonly used CNC router as it can move tools in 3 directions i.e. X, Y and Z direction. Z direction is always along the length of the tool. Using this router, carving perpendicular to the surface of a flat wooden plank can be done. An example of what these machines are capable of performing is shown below.

Figure 2-2: wood router.

Source:(Anon., 2000)

Figure 2-3: Example of wood carving by 3-axis CNC router.

Source:(Anon., 2017)

2.1.1.3 Turn Mill CNC Router

Turn mills are the machine tools having both the capability of rotating the tool as well as rotating the work piece. The figure below depicts a mill turn CNC router performing the turning as well as milling operation.

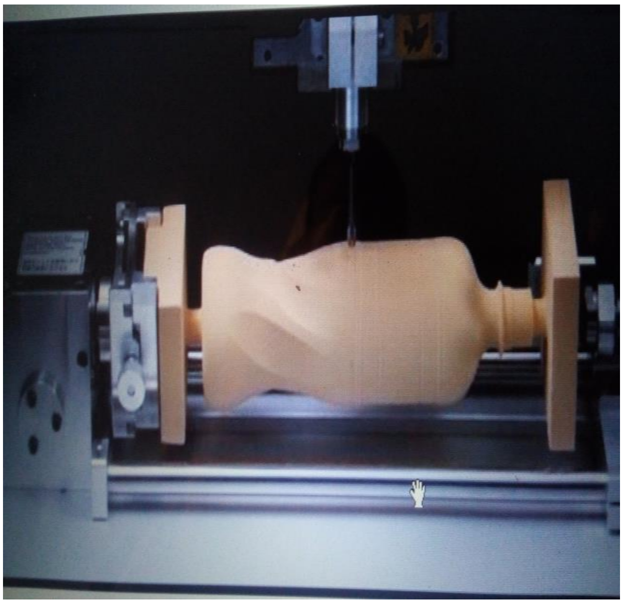

Figure 2-4: Turn mill configuration.

Author: (HM, 2017)

2.1.1.4 5-Axis CNC Router

To cut the three-dimensional object without moving the work pieces mainly used in Automobile, boat and aerospace industries 5-axis CNC routers are used which has additional 2-axes apart from the basic three axis of the machine.

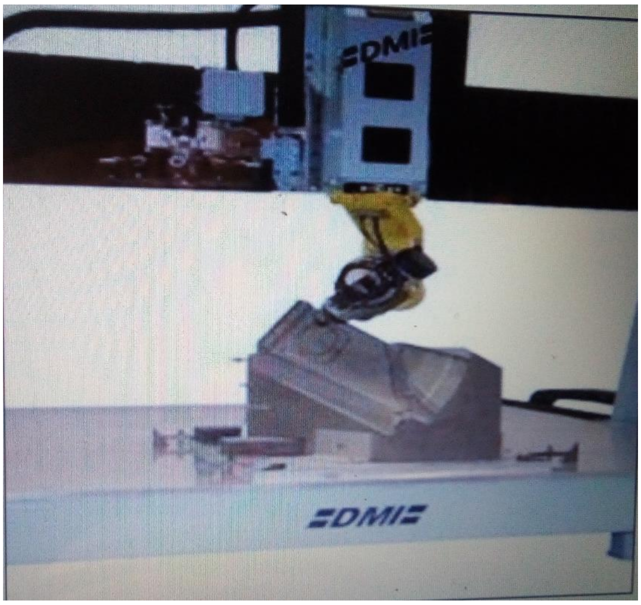

Figure 2-5: 5-axis CNC routers.

Source:(Lv, 2011)

2.2 African woodcarving

Woodcarving is considered as one of the best uses of wood in Kenya both in terms of its income returns and creation of employment opportunities to the woodcarvers. It is estimated to earn the country an annual income of more than USD 20 million through exports and supports over 80000 woodcarvers who are breadwinners for over 400000(T. Sunderland, 2004).

2.2.1 Wood carving Practices

Traditional and modern woodcarving practices are the two carving practices used by carvers in most parts of the world (J. Melorose, 2015). The two practices are discussed below;

2.2.1.1Traditional woodcarving practices

Traditional woodcarving is one of the oldest technologies which started during the stone and iron ages (Pandey, 2007). Traditionally woodcarving was carried out with the primary purpose being; preservation of culture and tradition of people, expression of the immediate way of life of people and it was also done for religious and sociocultural values (Shokorova, 2013). It was used to produce wood carved products which were used for aesthetics of most places and its artistic value (Koenig, 2016). Traditionally woodcarving was considered to be a male occupation because it was hardy, tiresome and indecent activity to be executed by women but as years passed by women started woodcarving but on their own peril (Amoh, 2009).

Traditional woodcarving was best demonstrated through decorating homes of most people but as time went by this tradition changed and wood carved products were used almost everywhere including hotels and other big institutions (Azeez, 2011). The type of wood used for carving was selected depending on the purpose of the sculpture and the beauty needed on the carving by the consumer. For example, pine tree was used to make carvings surface shinny and clean, Cedar was used to make big dishes while light wood was used to make large masks because it was not so heavy on the head (Azeez, 2011). Impervious wood is not easily damaged by termites and hard wood were the two characteristics considered by ancient woodcarver before felling any tree for carving functions (Utaberta, 2014).

Traditional woodcarving method was preferred but it changed as time went by depending on the purpose of the wood carved products (Dokter, 2010). Using green wood as the main raw material the traditional woodcarver carved simple products such as handles for spears, hoes, ploughs, arrow shafts and axes (Melorose, 2015). Over time, the skills were inherited from the outgoing and older wood carvers to their family members through inheritance and apprenticeship (Tobergte, 2013). Traditional woodcarvers used simple tools which were made by local blacksmith to carve their objects (Weikop, 2008). Some of the local tools used by ancient woodcarvers included; knives used to trim, cut and smoothen wood; gouges which are of different shapes and sizes and had a curved cutting edge for sweeping curves, carving hollows and rounds (pye, 2006). The chisels are of small and large sizes and have straight cutting edge which does the work of cleaning up flat wood surfaces; adze is another important tool used for blocking (Amoh, 2009). Other tools found in the carver's kit includes, spoke shave, machete, files, mallets and scrapper (George, 2007).

2.2.1.2 Modern woodcarving practices

Modern woodcarving technology came into its own as a specific method of woodcarving in the last few decades (pye, 2006). This was as a result of traditional woodcarving being a tiresome, time consuming and labor-intensive activity. Adoption of modern woodcarving technologies was expected to produce any kind of wood carved sculptures faster and without spending a lot of energy (Shokorova, 2013). Use of modern machines produces complex wood carved sculptures which have been difficult to produce using traditional methods which is dominated by use of simple tools made by local blacksmiths (Utaberta, 2014).

In most cases it becomes very difficult to purely use modern machines to carve sculptures (peters, 2007). As a result, woodcarvers combine both the traditional and modern woodcarving methods to make their sculptures (Weikop, 2008). The combination of these two methods produces impressive sculptures which are highly attractive to the eyes (Utaberta, 2014). The main advantage of using machines is that, speed of producing wood sculptures is increased and this makes cost of the sculptures to go down (Koenig, 2016). Consequently, families with low income levels can afford to buy wood carved products without much strain (peters, 2007). Another advantage of using machines in woodcarving process is that, tiny wood carved sculptures are quickly produced with high accuracy levels (peters, 2007).

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Modern woodcarving practices are characterized by use of modern carving machines such as the chain saw machines, Electric sanders, jig saws, planers, drilling machines and bench grinder (Tobergte, 2013). These tools depend on electricity for their operation (Weikop, 2008). Species of the wood and its hardness should be the key factors a woodcarver puts into consideration before selecting the machine to use in his/her work (Shokorova, 2013). Any person intending to adopt modern woodcarving technologies must possess carving skills, have skills on how to operate modern carving machines and be able to use computer software such as the adobe illustrator (Shokorova, 2013). This helps in designing their sculptures and drawing the sketches the carver intends to produce (Weikop, 2008). These skills can be learned from schools, woodcarver workshops and from other experienced woodcarvers who have the skills (Tobergte, 2013).

2.3 Local woodcarving practices

From the literature obtained from our case study area-Nakadoli industrial site, all the woodcarving processes carried out around this area are achieved either by the use of the router machine or the jig saw. A router is a hand tool or power tool that a worker uses to rout (hollow out) an area in relatively hard material like wood or plastic (Said, 2001). Routers are mainly used in woodworking, especially cabinetry. Routers are typically handheld or fastened cutting end-up in a router table. A jigsaw power tool is a jigsaw made up of an electric motor and a reciprocating saw blade. It is an engineering tool with the blade at the bottom used for cutting materials like wood, metal, laminate and PVC. It is used for making curved designs inside these material (Anon., 2019). The figures below show the two machines with the sample of the work obtained from their use.

Figure 2-6: woodcarving router.

Source: Author 2019

2.4 Summary

In this chapter, some generalities on CNC machines have been presented. Several axes of the CNC machines have been discussed which are differentiating features determining the types of work which can be obtained when they are used. Comparisons have been made starting from CNC machines used on the global scale to regional up to local which is within our country's design and technology industrial sector.

III. <u>CHAPTER THREE: METHODOLOGY</u>

3.0 Introduction

A survey was conducted within the industrial area of Chimwemwe, township and it was discovered that no one has a modern machine which can be programmed to produce objects with very complicated geometry in a single process. To come up with the design of the project some procedures were carried out in three steps; the first step was to elaborate the gathering of obtainable CNC 3-axis machines which was done purely through internet. The second step was to design an appropriate device from locally obtained materials that was going to produce 3-Dimensional engineering parts and other objects, and lastly to give the analysis on the performance of the CNC 3-axis machine for the manufacturing industry and other fields. Also, as scholars, we are provided with access to computer software designing packages such as AutoCAD, Solid Works and Google Sketch for the purpose of creating drawings and animations.

Most industrial CNC equipment is complex and requires a serious investment. There are also simpler and less expensive variants that can be applied to simple machining operations. This chapter takes a closer look at the components used to construct a simple CNC router machine that can be a helpful first step along the path to understand a CNC machines. This machine is composed of parts that can be acquired through conventional means or crafted using commercially available products. There are three important components of the computer numerical control as shown in the figure below.

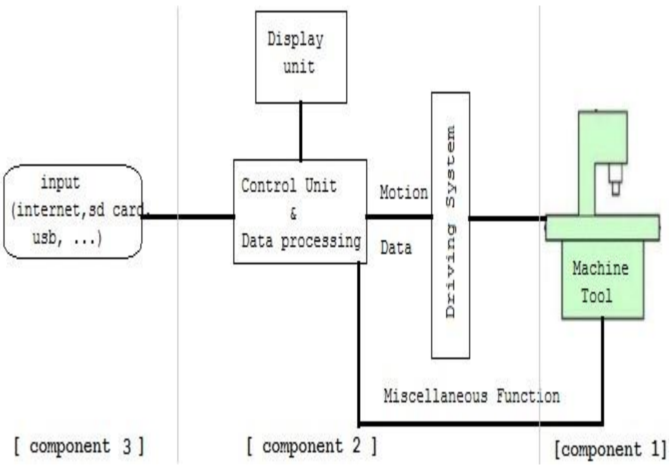

Figure 3-1*: CNC components*

Author: (Y.Uda, 2007)

3.1 DESIGN CONCEPT

3.1.1 Stepper Motor

The slides and spindles of the CNC machine are driven by stepper motors. A digital signal is sent from the controller to the motor in the form of pulses, which will cause the motor to rotate through a specified angle, which causes the slider to move by the required distance.

3.1.2 Part Program

This section consists of a series of coded instructions required to produce a part that controls the movement of the machine tool and on/off control of auxiliary functions such as spindle rotation and coolant. The coded instructions are composed of letters, numbers and symbols.

3.1.3 Program input device

The program input device is the means for part program to be entered into the CNC control. Three commonly used program input devices are punch tape reader, magnetic tape reader, and computer via RS-232-C communication but in this project a computer/laptop will be used.

3.1.4 Machine control unit

The machine control unit (MCU) is the heart of a CNC system. It is used to perform the following functions:

- To read the coded instructions.
- To decode the coded instructions.
- To implement interpolations (linear, circular, and helical) to generate axis motion commands.
- To feed the axis motion commands to the amplifier circuits for driving the axis mechanisms.
- To receive the feedback signals of position and speed for each drive axis.
- To implement auxiliary control functions such as coolant or spindle on/off and tool change.

To achieve all these objectives outlined above the Arduino is the component that will be used in this project.

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3.1.5 Machine tool

CNC controls are used to control various types of machine tools. Regardless of which type of machine tool is controlled, it always has a slide table and a spindle to control position and speed. The machine table is controlled in the X and Y axes, while the spindle runs along the Z axis.

3.1.6 Feed Back System

The feedback system is also referred to as the measuring system. It uses position and speed transducers to continuously monitor the position at which the cutting tool is located at any particular instant. The MCU uses the difference between reference signals and feedback signals to generate the control signals for correcting position and speed errors.

3.1.7 Drive System

Drives are used to provide controlled motion to CNC elements. A drive system consists of amplifier circuits, drive motors, and ball lead-screws. The MCU feeds the control signals (position and speed) of each axis to the amplifier circuits. The control signals are augmented to actuate drive motors which in turn rotate the ball lead-screws to position the machine table.

3.1.8 Power Drives

In machine tools, power is generally required for driving the main spindle, saddles and carriages and some auxiliary units. The motors used for CNC system are of two kinds:

- ✓ Electrical- AC, DC or Stepper motors
- ✓ Fluid – Hydraulic or Pneumatic

In this study the stepper motors are the main interest. Usually stepper and servo electrical drives are used in CNC machines. They exhibit favorable torque-speed characteristics and are relatively inexpensive.

3.1.9 Linear Motion Drives

Linear motion drives are mechanical transmission systems which are used to convert rotary motion into linear motion. The conventional thread forms like vee or square are not suitable in CNC because of their high wear and less efficiency. Therefore, CNC machines generally employ ball screw for driving their work piece carriages. These drives provide backlash free operation with low friction-wear characteristics. These are efficient and accurate in comparison with that of nut-and- screw drives. Most widely used linear motion drives are ball screws. The threaded rod will be used in this project to accomplish this task.

3.1.10 Key Component Selection

The key component selection is the function of the factors such as cost minimization, work to be performed, and availability of the material, precision and accuracy level. The recognition of the component required is an important step in designing and making any machine. After it has been recognized the selection for the proper material and its designing should be done. The process will follow:

- The identification of working condition.
- Calculation of the forces.
- Calculation for the dimensions.

3.1.11 Ball screw

The ball screw is a mechanical component consisting of an assembly that changes rotating motion of motor to linear motion of drive and vice versa. The ball screw assembly consists of a ball screw and ball nut with Re-circulating ball bearings inside. The linking between the screw and the nut is made by ball bearings that revolve in the matching forms in the screw and ball nut. The forces transferred over a great number of ball bearings, giving a comparatively low relative load per ball. Due to rolling ball bearings the ball screw Drive has a very less friction coefficient. Ball Screw drives typically provide mechanical efficiency of greater than 90% so their higher initial cost is compensated by less power requirements. Ball screws are often

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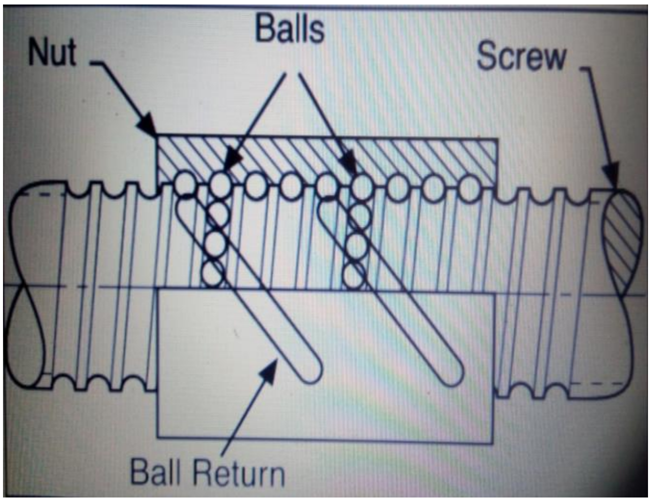
preloaded. Preload serves the following main purposes:

- It removes axial play between a screw shaft and a ball nut (i.e. Zero backlash).
- It reduces elastic deformation caused by outside force (i.e. Enhances rigidity).

Figure 3-2: Cut section of a ball screw nut.



Source:(Okwudire, 2011)

3.1.11.1Guide ways

To ensure that the machine tool components moves in its predetermined track Guide ways are used which along with moving the machine tool along the correct path reduces the friction of motion. Factors to be considered for slide selection:

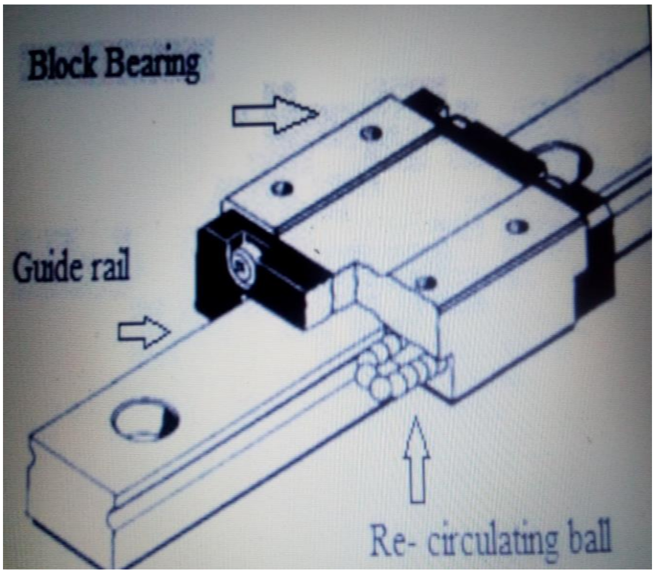
(i) Length of stroke and size
(ii) Mounting orientation.
(iii) Load to be carried out.
(iv) Maximum velocity.
(v) Acceleration and deceleration rate.
(vi) Service life.
(vii) Environment of work.

Broadly two types of guide ways are available as discussed below.

(a) Linear motion guide ways

A linear motion guide way guides the motion of machine tool components smoothly which is derived with the help of ball screw. They drive the motion in all the three direction with prescribed accuracy and confined motion. Co-efficient of friction for linear motion guide way is 0.02 as compared to traditional slide.

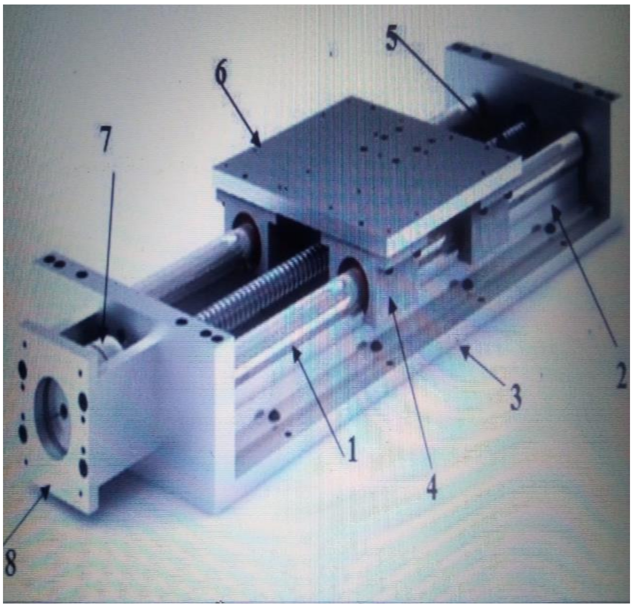
Figure 3-3: Linear motion guide way.



Source :(Otsuka, 2010)

The LM guide way mainly comprises of block bearing and guide rail. The Block bearing is composed of re-circulated ball bearings which provide smooth motion over the guide rails.

Figure 3-4: standard round shaft technology-based machine drive system with plain bearing.



Author: (Otsuka, 2010)

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(a) Round shaft guide ways

Round shaft guide ways are used for working in dusty environment without any risk of chip inclusion. The round shaft ways use the ball screw assembly to transmit the rotary motion from the drive motor to linear sliding motion of the slider mounted over the block bearings, whereas the block bearings are mounted over the round shafts. The figure below shows the various component of the standard round shaft technology-based machine drive system, which are namely:

1. Circular solid steel rod
2. Aluminium alloy support for round shaft
3. Frame for supporting two round shaft supports
4. Block bearings
5. Ball screw assembly
6. Slider plate
7. Coupling (for transmitting rotary motion from motor to ball screw)
8. Motor housing (built in the frame)

The three main components of the round shaft guide ways comprising of round shaft, bearing and supporting rail has been shown in the figure below with the markings 1,2 and 3 respectively.

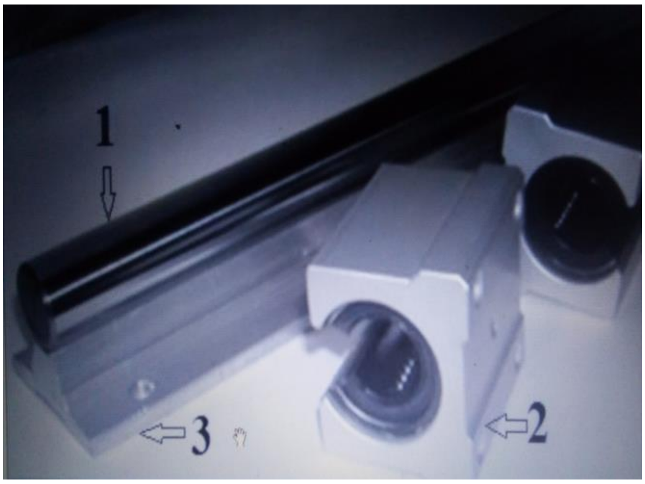


Figure 3-5: Main components of round shaft guide way.

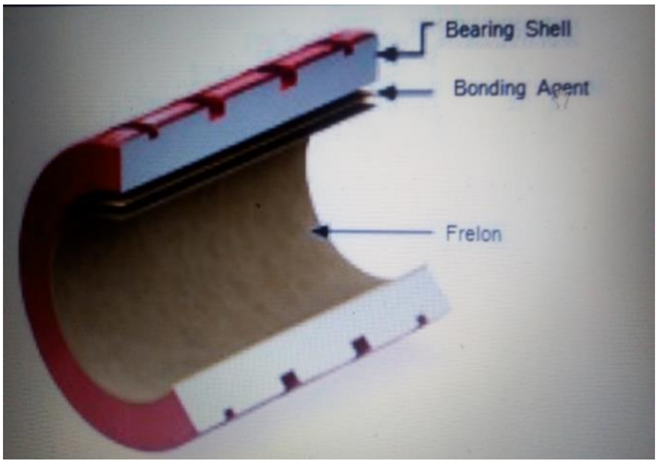
Source: (Otsuka, 2010)

The bearings are the most important part of the round shaft technology-based machine drive system which helps transmit the motion in linear direction by minimizing the friction. Generally, three types of bearings can be used with the round shaft technology-based machine drive units as given below:

1. Bearing with re-circulating ball.
2. Bearing with preloaded non-recirculating balls
3. Plain Bearing

The recirculating and non-recirculated ball bearings are not suited for working in dusty environment like wood carving. Out of the above-mentioned types the plain bearings have many advantages over linear ball bearing. These can be used in dirt, vibration, shock loading, welding, and foundry and wash down situations. These are made up of special liner material called Frelon, which is bonded to the bearing shaft which transfers the load and dissipates heat generated in the shaft. Frelon is a combination of Polytetrafluoroethylene (PTFE) with some filler materials. PTFE is a fiber material having self-lubricating properties mainly used in making non-stick house hold utensils and has good vibration damping properties. Whereas filler material is of high load capacity, low wear rate and high strength are used in plain bearings. One such example of plain bearing is shown in the figure below. The plain bearings do not need any lubrication and when lubricated can work up to very high speed. Backlash is not a problem with them. Therefore, they are not preloaded so have a longer life.

Figure 3-6: Construction of plain bearing.



Source:(Dimofte, 1995)

The round shaft guide ways are preferred over the LM guide ways for the work of wood carving because of the reason as compared in the table below.

Table 1: Comparison of plain and ball bearing.

Bearing type	Load	Moment Load	Linear Speed	Coefficient of friction	Precision	Environment
Plain bearing	Up to 20 times of ball bearing	Limited to 2:1 ratio	1.524 m/sec in dry run 4.19m/sec in lubrication.	0.125	Precision running clearance of 0.0127 mm per side	Excels in dry, contaminated, wet and clean room applications
Ball bearing	Limited due to point to point contact with shaft	Moderate to good	Up to 3m/sec always required lubrication	0.05	Can be preloaded. This shortens life	Will fail and corrode in contaminated conditions

The conclusion from the comparison between plain and ball bearing types as given above has been used as guideline to select the round shaft instead of linear guide ways.

The selection for the key dimensions of round shaft drive system for the present work is done on the basis of permissible bending moment for Z-axis and Y-axis motion. While for X-axis the selection depends upon the load carrying capacity required by the drive.

3.2 Design Interpretation

3.2.1 Mechanical side (Machine tool)

The mechanical subsystem of a CNC provides the means needed to cut and machine various materials for a given job. The choice of materials has a direct impact on performance, precision, repeatability, longevity, and mechanical noise transfer into the parts (Chen, 2014). The mechanical subsystem is comprised of the guide system, the drive system, and the frame housing structure.

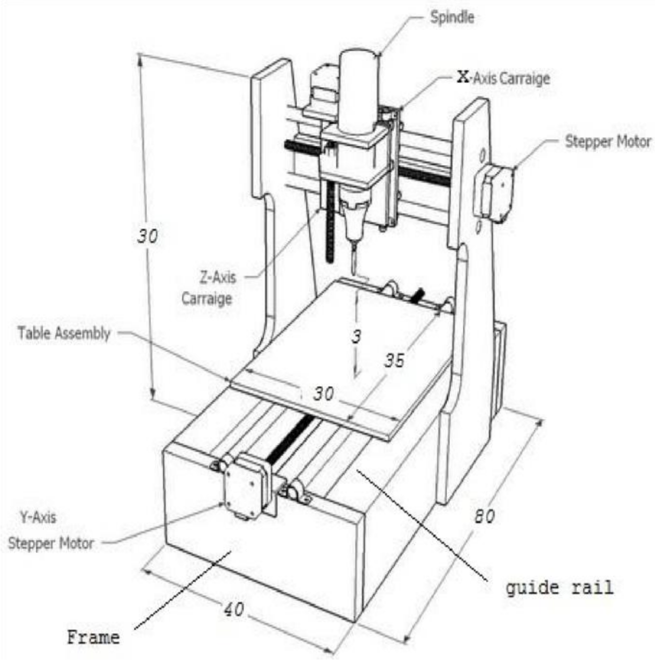


Figure 3-7*: Wireframe drawing of a CNC Router*

Source: Author 2019

3.2.2 CNC router mechanical parts

3.2.2.1 Guide Rail Design

The first frame subsystem design to consider would be a conventional railing system, which consists of a linear motion bearing and shaft assembly, which would simply allow unrestricted movement along their lengths (Lu, 2014). The most logical rail design to consider, given the design specifications and size requirements, would be the sort of railing that could be supported in some way to handle the loads applied to it without much deflection. For instance, the railing system shown in the figure below has a simple steel shaft railing system and is light weight. This system is capable of higher loading capacities with stability in handling off-balanced loads.

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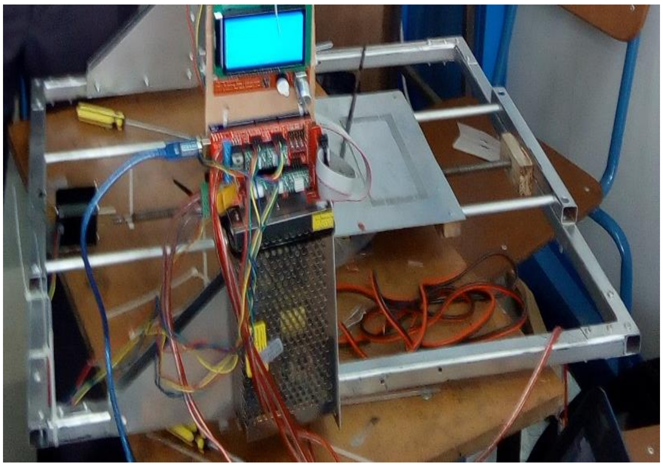
Figure 3-8*: Railing system used in this project*

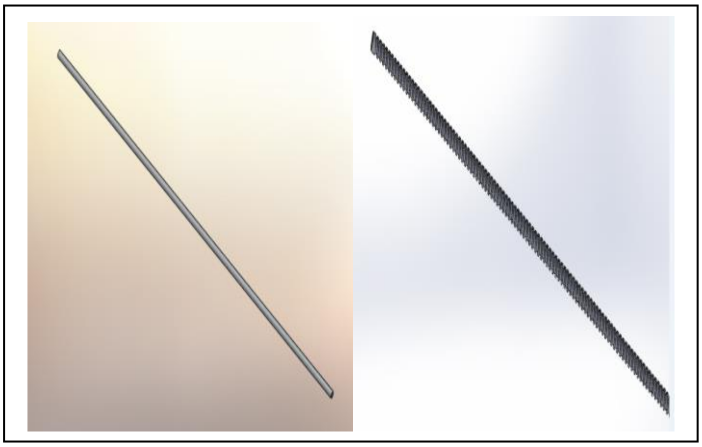


Source: Author 2019

3.2.2.2 Drive Designs

The purpose of the drive mechanics is to transfer the torque provided by the electric drive motors into linear motion to move the tool head. Since CNC machines require linear movement in multiple axes, drives will be used to accomplish this goal. These systems offer a simple and compact means of transmitting power and motion with excellent reliability. For these machines, the shafts/rods are turned by motors, generating linear motion. Threaded and Plain rods are used because they are low cost, less noise, self-lubricating if copper is the material used, less maintenance, higher efficiency. (Wu, 2014)

Figure 3-9*: Threaded rods and plain rods used for linear positioning*

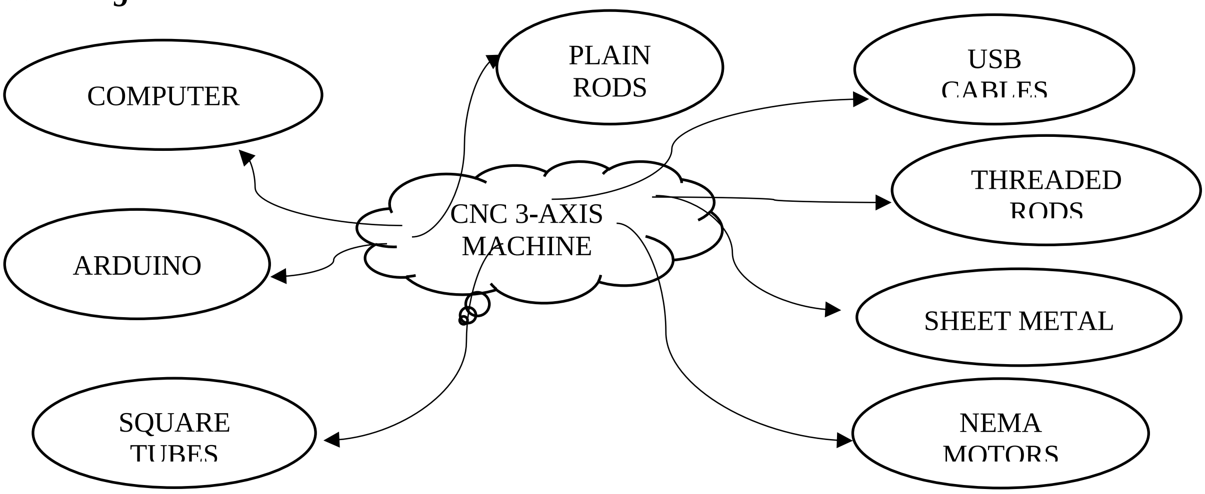


Source: Author 2019

3.2.2.3 Frame

CNC frame materials need to have some strength in order to support the weight of the gantry and the cutting head as well as with stand forces resulting from the routing process. Stiffness is also required to prevent any deflection due to both static forces and dynamic forces resulting from the acceleration of the tool head (Sun, 2011). Weight is also important because the mass of the frame contributes to both the static and acceleration forces. The best frame material would accomplish and offer excellent machinability and be available at a low cost.

3.3 Bubble Diagram



Source: Author 2019

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3.4 Material Selection

The structure of the CNC machine is designed to cope with the torsional forces and heavy duty cutting imposed on these machines. Therefore, the material from which they are made is of great essence when it comes to design. Wood is one of the materials in abundance and it is cheaper, but due to inconsistences they are not too reliable. If they stay for long, they start experiencing deformations due to temperature changes, and this leads to the compromise in the accuracy or precision of the products made. Due to these shortfalls in this project, steel proved to be suitable due to the outstanding properties it possesses. Even if it is not cheaper as compared to wood it is readily available and very affordable. Using this material will reduce on the cost of replacing the machine within the short period.

3.5 Material Specification

3.5.1 Spindle Motor Selection

The following points were considered while selecting the spindle motor for the machine:

(i) It should run at high Rpm to cut brittle material like wood.
(ii) Should be air cooled instead of water cooled to avoid any moisture on wood.
(iii) Depth and width of cut should be known.
(iv) Feed rate.
(v) Diameter of the cutting tool.

The selection of spindle power is followed by the calculation of tangential and axial force on work material required to make machining. And these forces depend on the specific cutting force of the material and method of machining. In vertical milling process the two types of forces tangential and axial occurs due to simple milling and plunging respectively. While machining wood the knowledge of specific cutting force becomes very difficult because of the following reasons:

1. Wood variety varies from very soft wood to very hard wood.
2. Seasoning of wood improves its material properties which depend upon time and method of seasoning.
3. Properties of wood are not the same in all directions.

Therefore, specific cutting force of Aluminium was considered instead of wood having similar machining properties. Both of the material shows brittle behavior while machining and for the design safety the value of Aluminium is safer to use instead of wood.

3.5.2 Selection of Ball Screw

A ball screw is the machine tool member which transmits rotary motion from the drive motor to the linear motion of the slide way.

(i) It is subjected to the thrust or axial force due to the load of work piece, cutting force, friction of the slide way and inertia force.

(ii) Torsion force to overcome this force.

When the nature of the stress is not unidirectional and combination of stresses are acting on a component it will be calculated from Von-mises stress formula (Anon., 2019). The equivalent von-mises stress is composed of axial and Torsional stress in case of ball screw which can be calculated by the relation given below

- Axial stress

$$\sigma_{axial} = \frac{F_a}{\pi {r_b}^2}$$

Where, σ_{axial} = axial stress in N/m^2

F_a = Axial load applied on the Ball Screw in N

r_b = Root Radius of the ball screw in m

- Torsional stress

$$\tau_{torsional} = \frac{2 \times T_t}{\pi {r_b}^3}$$

Where, $\tau_{torsional}$ =Torsional stress in N/m^2

T_t= Driving torque to obtain thrust force in N-m.

Therefore, Equivalent Von-mises stress

$$\sigma_{eq} = \sqrt{{\sigma_{axial}}^2 + 3{\tau_{torsional}}^2}$$

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Ball screw selection is based upon the parameters selected for the drive motor which runs the ball screw to transmit the motion.

3.5.3 Selection of Slide way.

The round shaft slide way was selected earlier for the purpose of wood carving CNC machine because of its properties discussed. The selection of the round shaft slide way depends upon the permissible value of the bending moment. The models for the round shaft slide ways were taken from the round shaft guide way technology. Calculation for the Bending Moment Produced:

Bending moment = (cutting force) × (Distance of cutting force from the center of gravity of the arrangement)

3.5.3.1 Z- axis Slide

The Z-axis slide way carries the spindle and the bracket arrangement and is in direct effect of the cutting force. The Z-axis slide has to move very rapidly and is under motion in every process. It is composed of the components such as the ball screw, drive motor, and coupling which is mounted on the slide way. Apart from that it also supports the spindle.

3.5.3.2Selection of the ball screw

Ball screw selection is based upon the parameters selected for the motor which runs the ball screw to transmit the motion.

Table 2: Drive motor parameters.

Parameter	Value	Unit
Minimum delay between two steps (commands)	5	ms
Step angle	1.8	degree
Steps required per rotation	200	
Rotations per minute	60	rpm

The material for the ball screw is taken as Chrome steel which is a suitable material under both types of loading i.e. axial and Torsional and its properties are as follows.

Table 3: Mechanical properties of Chrome Steel.

Density	7833 kg/m^3
Young's Modulus	234 Gpa
Poisson's ratio	0.29
Ultimate tensile strength	2650 Mpa
Ultimate Yield Strength	2070 Mpa

Ball screw at the same time is under two different type of loading i.e. is axial and Torsional, therefore Von-Mises stress criteria is used to determine the diameter of the ball screw. The permissible Von-Mises stress value for this material is 147 Mpa with a factor of safety taken as 7 for machine tool with vibration and impact (Anon., 2019).

The permissible range of bending moments according to the manufacturer of the round shaft in the Z-axis is given below in the table from which the safe model will be selected.

Table 4: Diameter of round shaft available against the bending moment in Z-axis drive.

Diameter of round shaft rod (mm)	F_{max}(N)	M_x(N-m)	M_y(N-m)
12.7	1157	163	169
15.875	1334	311	311
19.05	1334	325	325
25.4	2669	565	501
31.75	3003	1073	989
38.1	3158	1627	1424
50.8	4003	3649	3169

Therefore, shaft diameter of 12.7 mm is chosen from the above table.

3.5.3.3Y- axis Slide

Selection of Y-axis slide is most critical in terms of deflection because it is the case of simply supported beam with large span length. The selection of the Y-axis is done without considering the self-weight of the components whose analysis is done in solid works.

3.5.4 Frame

This being the base which anchors all the components of the machine, the material from which is made is of great essence. The yield strength of the material should be high to overcome all the reaction forces imposed by the components. For this reason, stainless steel is chosen for this study. Since wood is the main focus here for our work piece, issues of moisture should not be overlooked due to improper seasoning, therefore the material used for this machine should be resistant to corrosion.

3.5.5Selection of Driving Motor

For the selection of proper motor and its size the torque required should be calculated, for which the following points should be considered while calculating the required motor torque.

(i) Rate of acceleration, deceleration and required velocity for the desired motion.

(ii) Inertia, frictional and other load torques to be encountered.

(iii) Condition and Environment of operation.

Total peak torque can be calculated as the sum of all the torque which the machine has to overcome as given below:

$$T_p = T_a + T_f + T_\omega + T_g$$

Where,

T_a = Acceleration torque in N-m

T_f = Friction torque in N-m

T_ω = Viscous torque in N-m

T_g = Gravity torque in N-m

For the Z-axis drive motor Gravity Torque is considered because the motor has to work against the gravity in Z-axis drive motor. The standard available is the NEMA 23 model M1233021 having a value of the holding torque of 0.8 N-m.

3.5.6 Selection of the Coupling

The coupling is required for transmitting the torque from the drive motor to the ball screw shaft. Therefore, the coupling is designed to withstand the required and fluctuating torque.

For the Z-axis the selection of the coupling is based upon the rated torque according to the standard available couplings. The Standard available rated torque coupling available is of 5 N-m so it has been selected for this topic.

3.6 Electronics

3.6.1 Introduction

CNC electronics are a vital part of any CNC machine. Aside from the motors and CNC controllers, there are many electronic components that assist in the machine operation. This section will cover all the electronics and electrical components involved with a CNC router and help to understand how they come together with other components to create a working machine.

3.6.2 Stepper Motor

A stepper motor is an electromechanical device which converts electrical pulses into discrete mechanical movements (Akutain, 2005). The shaft of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence. The motors rotation has several direct relationships to these applied input pulses. The sequence of the applied pulses is directly related to the direction of motors shafts rotation. The speed of the motor shafts rotation is directly related to the frequency of the input pulses and the angular rotation is directly related to the number of input pulses applied (Pawliczek, 2017).

As most motors, the stepper motors consist of a stator and rotor. The rotor carries a set of permanent magnets, and the stator has the coils. The internal structure of a generic stepper motor is shown in the figure below.

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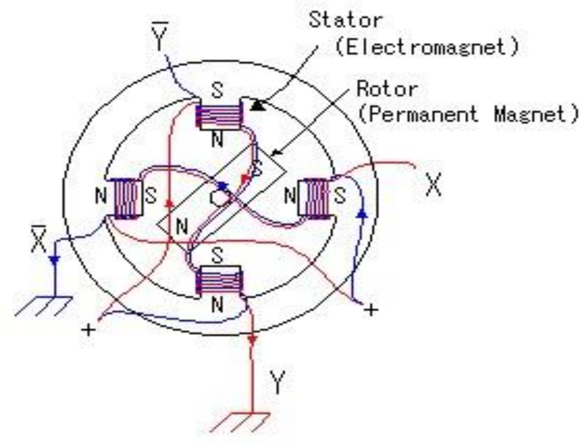
Figure 3-1*: Internal structure of a generic stepper motor.*



Source:(Chen, 2014)

The motors used in our project have a step angle of 1.8. The rotation of these motors is controlled by the electric current which pours into x coil, $\bar{X}$ coil, Y coil and $\bar{Y}$ coil using full- step mode as shown in the table below.

Table 5*:* Full Step Sequence of Stepper Motor

Step N°	X	$\bar{X}$	Y	$\bar{Y}$	Angle
1	0	1	0	1	0.0°
2	1	0	0	1	1.8°
3	1	0	1	0	3.6°
4	0	1	1	0	5.4°
5	0	1	0	1	7.2°

Table 2. 1 Full step sequence of stepper motor

In this project, the stepper motors shown below are characterized by:

- Drive system: Unipolar.
- Step angle: 1.8º full step/0.9ºhalf step.
- Voltage and current: 9V at 400mA
- Resistance per phase: 17 ohms.
- Ambient temperature: -10ºC to +55ºC.

Figure 3-2*: Stepper motors used to implement the CNC.*

Source: Author 2019

3.6.3 Stepper motor driver

A motor driver is a little current amplifier; the function of motor drivers is to take a low- current control signal and then turn it into a higher-current signal that can drive a motor (morar, 2014). There are many different kinds of motor drivers, used in this project is the TB6560.

3.6.3.1 TB6560 overview

The figure below illustrates the stepper motor driver TB6560 which is an excellent micro- stepping driver that uses TOSHIBA TB6560 Chip, based on pure-sine current control technology. Owing to the above technology and the self-adjustment technology (self –adjust current control parameters) according to different motors, the driven motors can run with smaller noise, lower heating, smoother movement and

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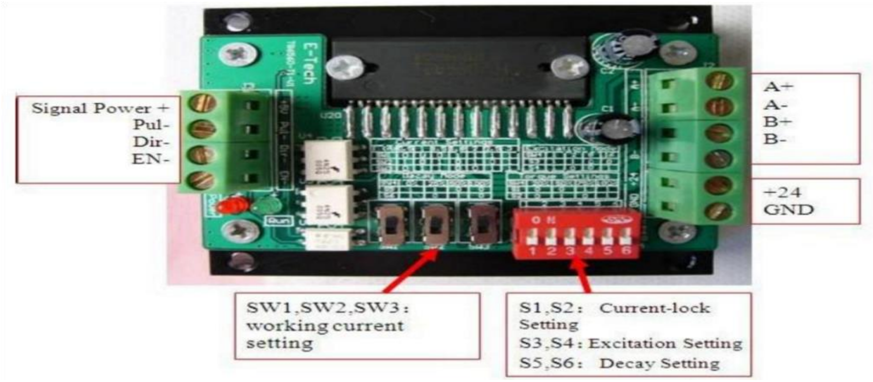
have better performances at higher speed than most of the drives in the markets (Basilio, 2010). It is suitable for driving 2-phase and 4-phase stepping motors.

Figure 3-3: TB6560 stepper motor driver. Source: Author 2019



3.6.3.2 TB6560 features

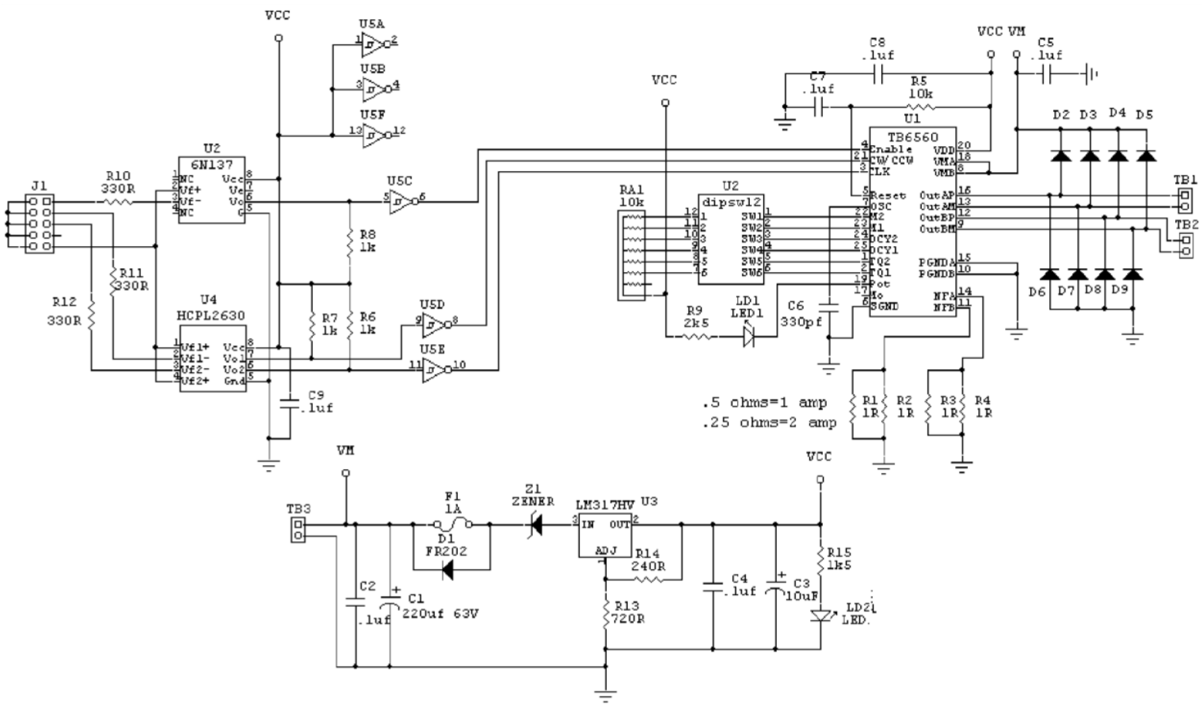
The TB6560 stepper motor driver has some features and characteristics.

- Low cost and good high-speed torque
- Supply voltage up to +32 VDC
- Output current up to 3.0A
- Pulse frequency up to 20 KHz
- Suitable for 2-phase and 4-phase motors
- Over-voltage and short-circuit protection
- 7 output current choices, max 3200 steps/rev
- Automatic idle-current reduction
- Slim size (96x61x37mm)

3.6.3.3 TB6560 Circuit

The main component of this circuit is the Toshiba TB6560AHQ, which is a PWM chopper-type sinusoidal micro-step bipolar stepping motor driver IC. It is capable of low-vibration, high-performance drive of 2-phase stepping motors using only a clock signal (Cho, 2015).

Figure 3-4: Stepper motor driver TB6560 circuit.



Source: Author, 2019

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3.6.4 Arduino

The Arduino is an open hardware microcontroller platform (Staff., 2018). It consists of a printed circuit board with a microcontroller and all the supporting hardware necessary to use the microcontroller mounted on it. All of the designs for the PCB (printed circuit board) layouts are freely available. A simple IDE (integrated development environment) has been created, uses a simplified version of C++, making it easier to program and many code libraries have been written. This has simplified working with microcontrollers, and has opened up the world of microcontrollers to people who would otherwise have been deterred by the complexity of working with them. The Arduino comes in many variations, and it is based either on an 8-bit Atmel AVR microcontroller or on a 32-bit Atmel ARM. An Arduino will be used to control the CNC router machine that will be built. The latest version is the Arduino UNO based on the 8-bit Atmel ATMEGA328 microcontroller. UNO does not need a separate piece of hardware (called a programmer) in order to load a new code onto it simply use a USB cable.

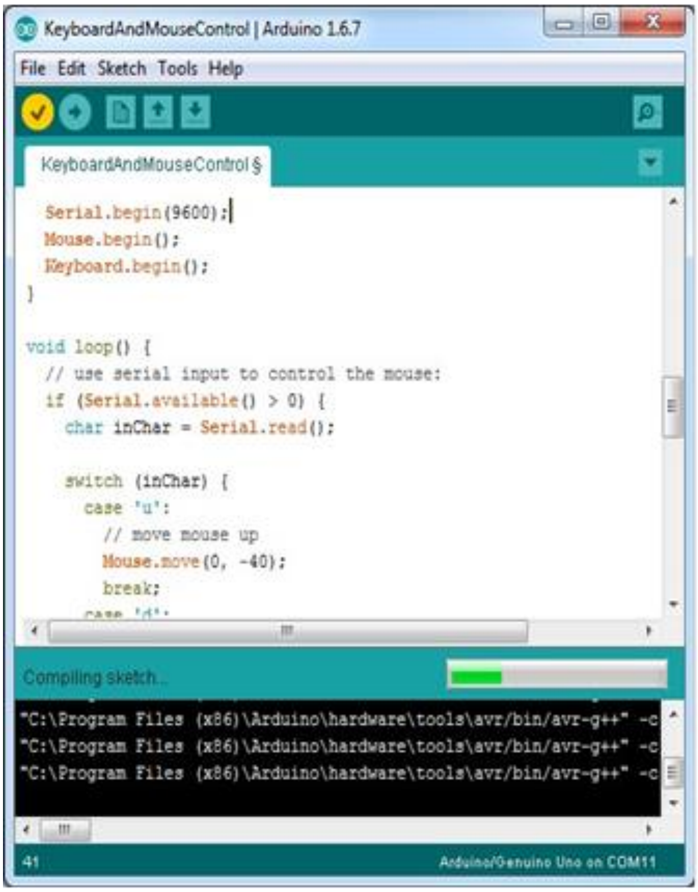

Figure - Arduino IDE on Windows OS **Figure - Arduino UNO board**

Figure 3-5*: Arduino IDE on Windows OS & Arduino UNO board.*

Source: Author, 2019

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3.6.4.1 Arduino UNO Specifications

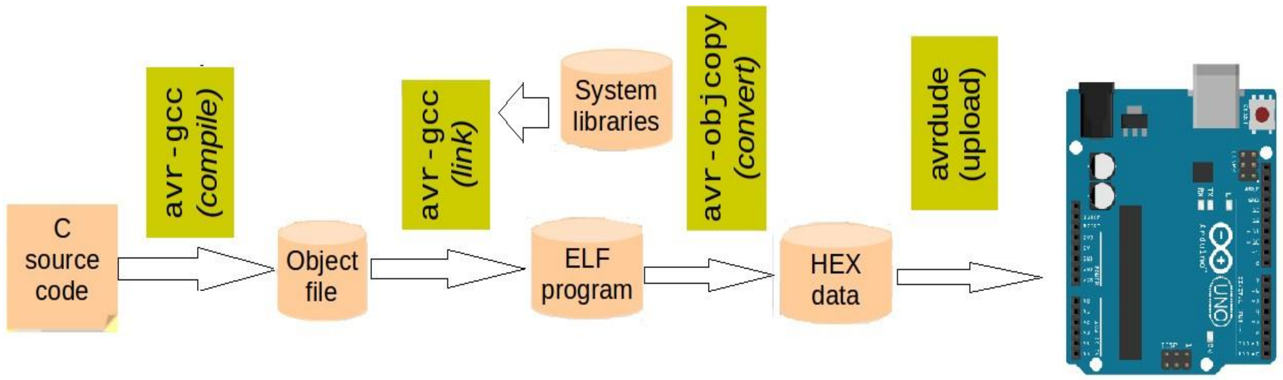
Table 6: shows the characteristics of the Uno board used in our project.

Microcontroller	ATmega 328	DC Current per I/O pin	40mA
Operating voltage	5V	DC current for 3.3V pin	50mA
Input voltage	7-12V	Flash memory	32KByte
Input voltage(limit)	6-20V	SRAM	2KByte
Digital I/O pins	14	EEPROM	1KByte
PWM Digital I/O pins	6	Clock Speed	16MHz
Analog input pins	6	Boot loader size	0.5KByte

3.6.4.2 Arduino Programming Language

Using C to program the Arduino means usually being able to create smaller programs, and with more fine-grained control of what happens (Bayle, 2013). C is adopted worldwide to program for small microprocessors because it gives a good trade-off between development effort and program efficiency, and because of its history there are well-optimized libraries, extensive guides and ways to solve problems. Arduino IDE uses the avr-gcc compiler and the avrdude uploading tool. The Arduino IDE preference contains verbosity options that have the effect of printing the commands that are run while the program is compiled and uploaded. This was very useful to understand what the graphical user interface is doing, which turns out is a common workflow for C and C++ builds.

Figure 3-6: Tool-chain flow from c code uploading to Arduino.



Source: Author, 2019

3.6.5 Communications

In order for the CNC to process any design implanted into it, the machine (motion controller that is Arduino board) must have a connection system between itself and the software being used by the CNC controller. Many connections used today are very common to people from using cable linking to add pictures to their computer hard drive or using a modern connection to log on to the internet. Two major types of communication systems between controllers and other hardware are discussed.

3.6.5.1 USB Ports

The USB ports, or universal serial bus ports, are most likely the simplest and one of the most widely available connection systems between computers and devices. The cable connector between the device and the computer uses either an ‘’A” connector which travels upstream to the computer or a “B” connector which travels downstream to the device as shown below.

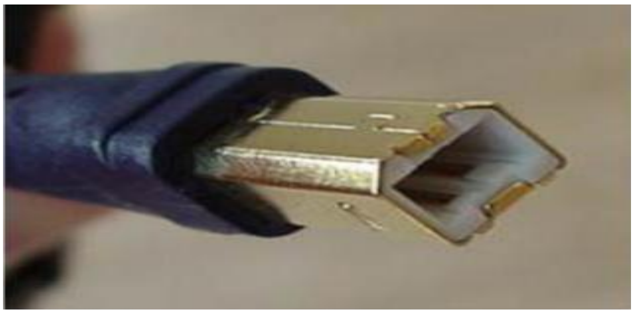


Figure- "A" Connector

Figure- "B" Connector .

Figure 3-7*: Shows two different types of USB connectors.*

Source: Author 2019

The Arduino UNO board used in this project has a FTDI FT232RL USB/Serial chip embedded in the head of it. The FT232R is the latest device to be added to FTDI's range of USB UART interface Integrated Circuit Devices. The FT232R is a USB to serial UART interface with optional clock generator output, and the new FTDIchip-ID™ security dongle feature. In addition, asynchronous and synchronous bit bang interface modes are available. USB to serial designs using the FT232R have been further simplified by fully integrating the external EEPROM, clock circuit and USB resistors onto the device. The FT232R is fully compliant with the USB 2.0 specification and has been given the USB-IF Test-ID (Pandey, 2016).

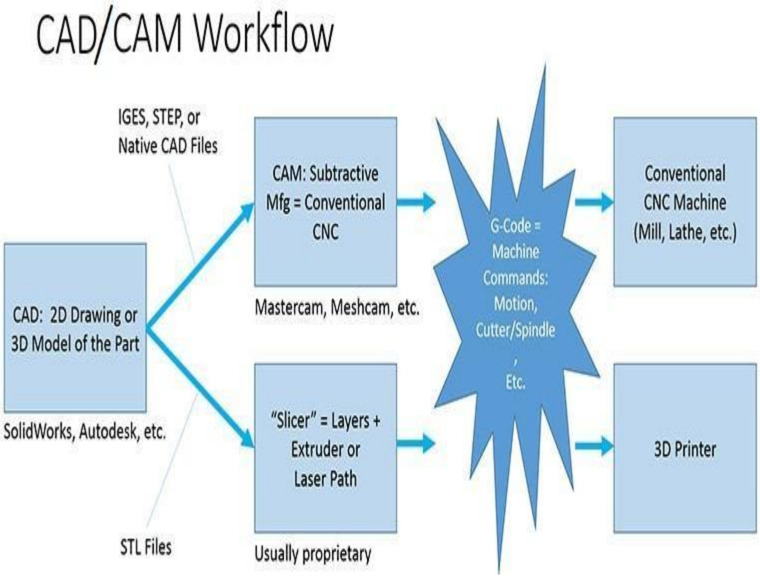
3.6.5.2 Ethernet

Ethernet is used greatly for networking over either short or long distances to many different devices for large and large amounts of information. It has a great advantage over other communication systems by allowing it to communicate with many devices at once and many different levels of distance. There are two major types of Ethernet networks, LAN (local area networks) and WAN (wide area network). LAN's are used to connect many devices over short distances while WAN's are used to connect a few devices over large area of up to many kilometers. Although WAN's carry information over long distances, they tend to be slower and less reliable than LAN's, but improvements in fiber optic cables may lessen this hindrance as the process improves. Ethernet is able to accommodate new devices once they become attached to the network by connecting to the single cable, which allows any device on the network to communicate with any other device without modifications to the devices. Unfortunately, for the devices to communicate effectively with each other, they must have knowledge of the network's protocol or language. The messages between the machines are sent over mediums that may meet at a shared medium or segment. The devices will interact with the segment by attaching at its nodes communicating in chunks of information called frames (Lajmi, 2015).

3.6.6 Program of instruction

When starting out with CNC, the first thing to do is creating some sort of model, drawing, or representation of the part or object to be machined. Most of the time this is a function of a CAD/CAM systems so they will generate g-code (machine commands) (Smid, 2000). Computer-aided design (CAD) involves creating computer models defined by geometrical parameters. These models typically appear on a computer monitor as a three- dimensional representation of a part or a system of parts, which can be readily altered by changing relevant parameters. CAD systems enable designers to view objects under a wide variety of representations and to test these objects by simulating real-world conditions. Computer-aided manufacturing (CAM) uses geometrical design data to control automated machinery. CAM systems are associated with computer numerical control (CNC) or direct numerical control (DNC) systems. The figure below shows the steps needed for generating a g-code.

Figure 3-8: CAD/CAM workflow



3.6.7 G-CODE

G-Code or Geometrical Code is the generic name for a control language for CNC machines. It is a way to tell the machine to move to various points at a desired speed, control the spindle speed, turn on and off various coolants, and all sorts of other things. It is fairly standard, and is a useful tool. The standard version of G-code is known as RS-274D. Since G-code are preparatory codes, in a CNC program they begin with the letter G and direct the machine. Typical actions G-code directs include:

- Changing a pallet
- Rapid movement
- A series of controlled feed moves, resulting in a workpiece cut, a bored hole, or a decorative profile shape
- Controlling feed movement, in an arc or a straight line
- Setting tool information

3.6.7.1 How G-Code Works

In order to achieve these particular kinds of movement, Numerical Control uses a block as its basic unit-when printed, it resembles a line of text. Each block carries one or more words (of sorts) each consisting of a letter- detailing the function to be performed-followed by a number that assigns value to the function (Read & nbsp & G-Code, 2019). Currently, a block of input is limited to a maximum of 256 characters. Below are some common individual codes, that when combined, guide a machine's movement.

- G00: Rapid positioning

This code causes the machine to operate at a high speed.

- G01: Linear interpolation

The machine will move in a straight line, performing the appropriate machining (milling, cutting, etc.).

- G02: Circular/Helical Interpolation

The machine will move clockwise in a circular or helical pattern, performing the appropriate machining process.

- G03: Circular/Helical Interpolation

This code is the same as G02, but enables counterclockwise movement.

- G17: X-Y plane selection
- G18: X-Z plane selection
- G19: Y-Z plane selection

These codes maneuver the machine onto different planes for coordinated motion.

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Table 7: Shows the list of G-codes

G00	Rapid Linear Positioning	G55	Work Coordinate System 2 Selection
G01	Linear Feed Interpolation	G56	Work Coordinate System 3 Selection
G02	CW Circular Interpolation	G57	Work Coordinate System 4 Selection
G03	CCW Circular Interpolation	G58	Work Coordinate System 5 Selection
G04	Dwell	G59	Work Coordinate System 6 Selection
G07	Imaginary Axis Designation	G60	Single Direction Positioning
G09	Exact Stop	G61	Exact Stop Mode
G10	Offset Value Setting	G64	Cutting Mode
G17	XY Plane Selection	G65	Custom Macro Simple Call
G18	ZX Plane Selection	G66	Custom Macro Modal Call
G19	YZ plane Selection	G67	Custom Macro Modal Call Cancel
G20	Input In Inches	G68	Coordinate System Rotation On
G21	Input In Millimeters	G69	Coordinate System Rotation Off
G22	Stored Stroke Limit On	G73	Peck Drilling Cycle
G23	Stored Stroke Limit Off	G74	Counter Tapping Cycle
G27	Reference Point Return Check	G76	Fine Boring
G28	Return To Reference Point	G80	Canned Cycle Cancel
G29	Return From Reference Point	G81	Drilling Cycle, Spot Boring
G30	Return To 2nd, 3rd and 4th Ref. Point	G82	Drilling Cycle, Counter Boring
G31	Skip Cutting	G83	Peck Drilling Cycle
G33	Thread Cutting	G84	Tapping Cycle
G40	Cutter Compensation Cancel	G85	Boring Cycle
G41	Cutter Compensation Left	G86	Boring Cycle
G42	Cutter Compensation Right	G87	Back Boring Cycle
G43	Tool Length Compensation + Direction	G88	Boring Cycle
G44	Tool Length Compensation - Direction	G89	Boring Cycle
G45	Tool Offset Increase	G90	Absolute Programming
G46	Tool Offset Double	G91	Incremental Programming
G47	Tool Offset Double Increase	G92	Programming Of Absolute Zero
G48	Tool Offset Double Decrease	G94	Feed Per Minute
G49	Tool Length Compensation Cancel	G95	Feed Per Revolution
G50	Scaling Off	G96	Constant Surface Speed Control
G51	Scaling On	G97	Constant Surface Speed Control Cancel
G52	Local Coordinate System Setting	G98	Return To Initial Point In Canned Cycles
G54	Work Coordinate System 1 Selection	G99	Return To R Point In Canned Cycles

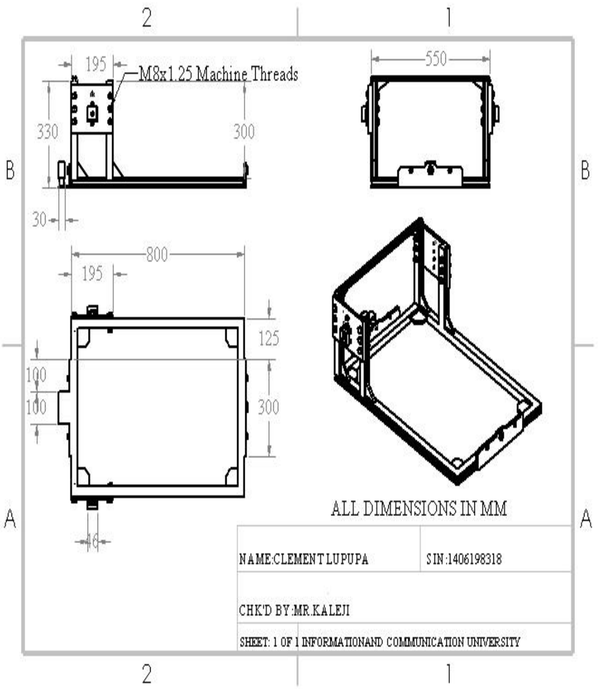
- G20: Programming in inches
- G21: Programming in mm

Changes in programming units occur short-term with these particular codes.

The above codes are the same for both milling and turning, but other units may vary. In terms of software specifications, most g-code files can be created using CAM, but certain CNC machines rely on ‘’conventional” programming, which either hides or bypasses the use of g-code completely.

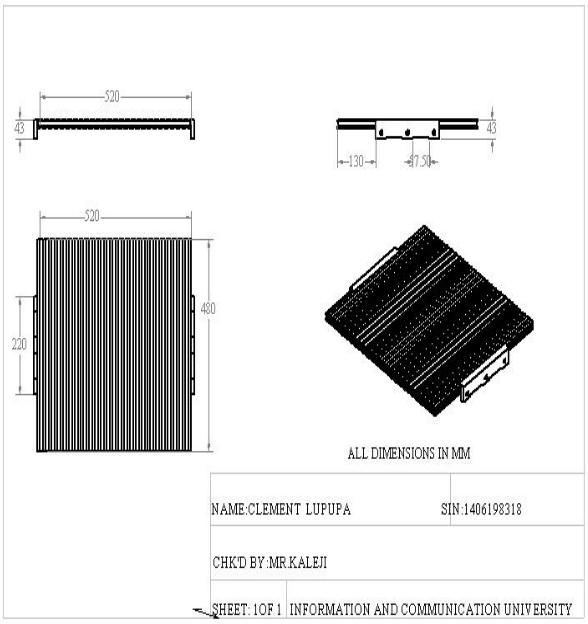
3.7 2-D Drawing of Parts

Figure 3-9*: Main frame views*



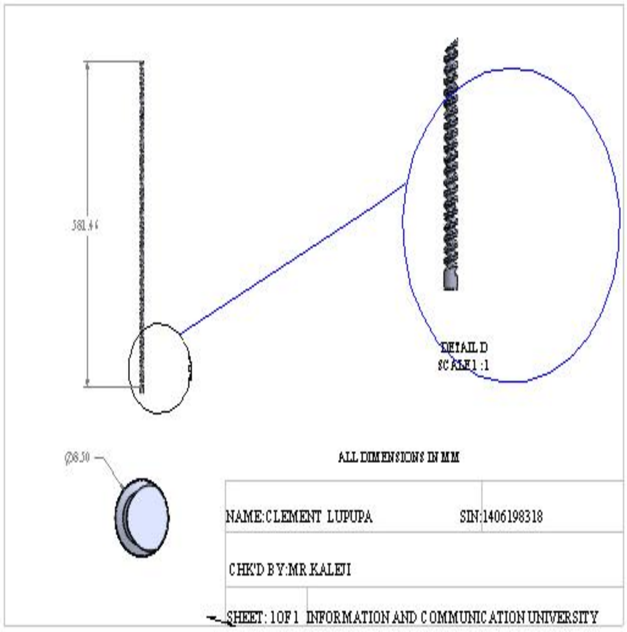
Source: Author, 2019

Figure 3-10: Plate/carriage.



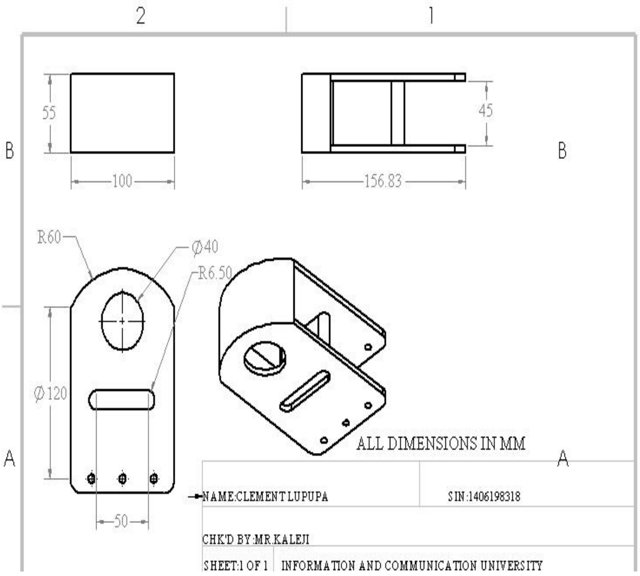
Source: Author, 2019

Figure 3-11*: Horizontal threaded rod*



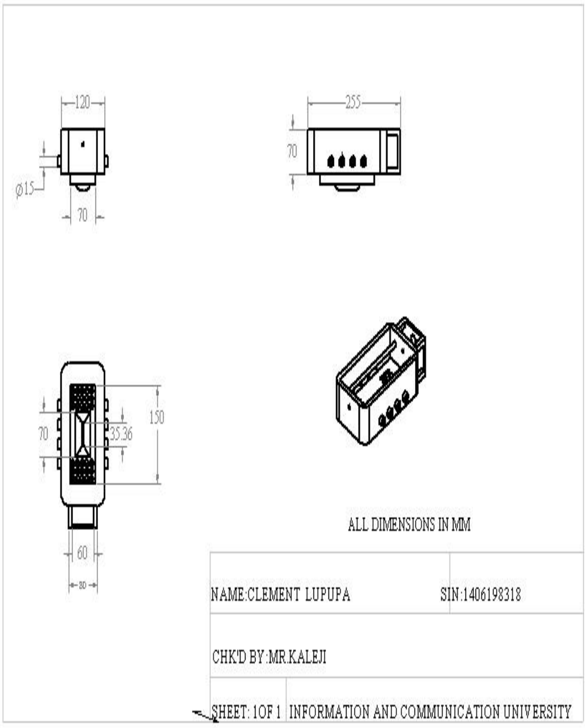
Source: Author, 2019

Figure 3-12*: Spindle.*



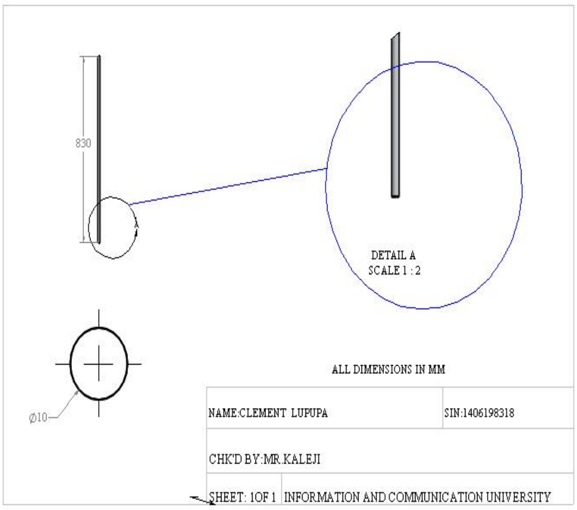
Source: Author, 2019

Figure 3-13*: Slider.*



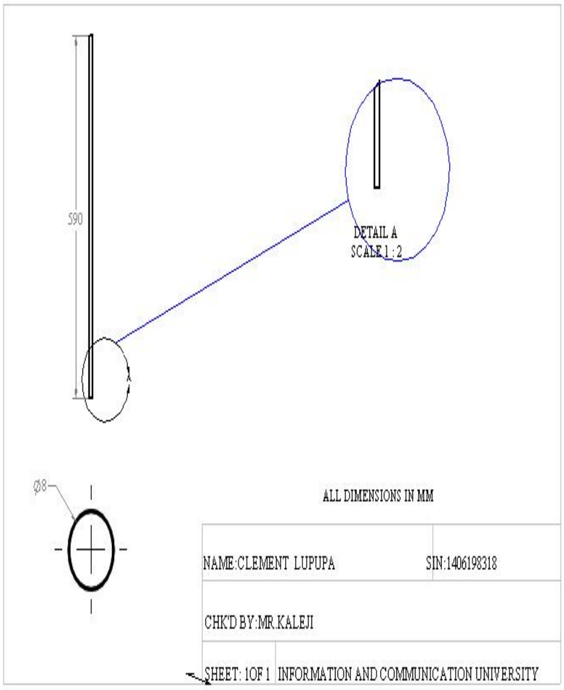
Source: Author, 2019

Figure 3-14*: X-axis Drive Plain rod*



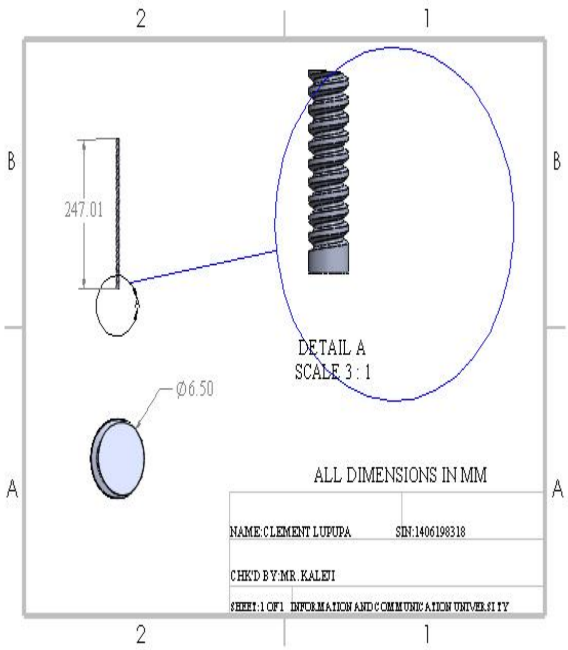
Source: Author, 2019

Figure 3-15: Y-axis Drive Plain rod.



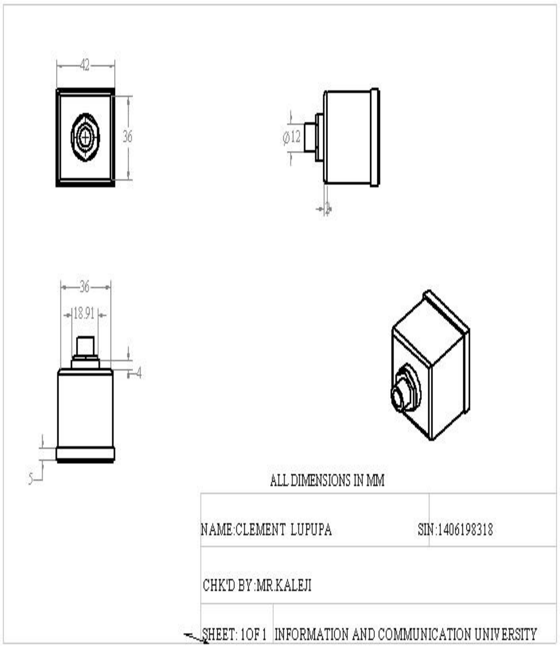
Source: Author 2019

Figure 3-16: Y-axis Drive threaded rod.



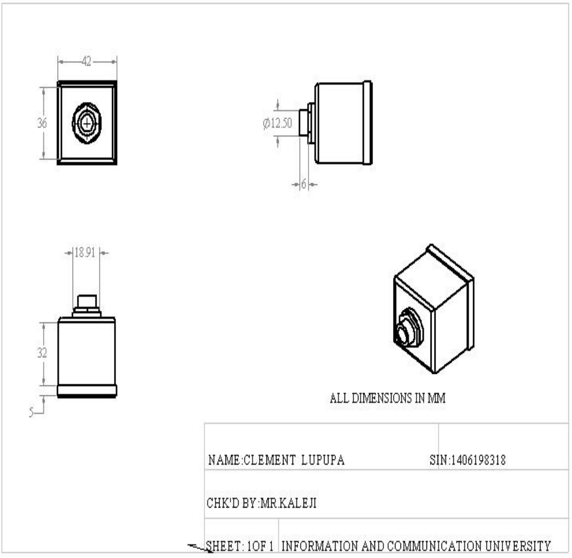
Source: Author, 2019

Figure 3-17: Motor slider



Source: Author, 2019

Figure 3-18*: Horizontal motor.*



Source: Author 2019

3.9 Isometric Drawing of Machine

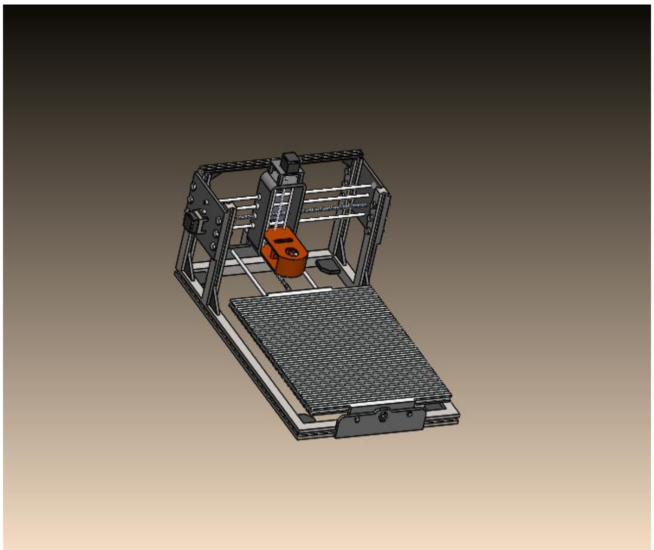


Figure 3-19*: CNC Assembled Machine.*

Source: Author, 2019

IV. CHAPTER FOUR: RESULTS AND DISCUSSION

4.0 INTRODUCTION

This chapter stipulates the results obtained and discussions from the simulations of the parts which are subjected to higher stresses. These regions of stress concentration, if they are not taken care of during the design process, the machine failure is inevitable. The material used for the entire structure is AISI 1020 Steel, with the Elastic Modulus of 2e+011 N/m^2, Poisson's Ratio of 0.29, Mass Density 7900 kg/m^3 and the Yield Strength of 351571000 N/m^2. The testing force used in this project is 2000N. The regions of interest considered in this study are the main frame, the plate/carriage and the slider along the y-axis. The software used is solid works to extract the intended results.

The other tests carried out on this CNC machine are cutting, engraving and marking into the wood board.

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4.1 Machine Testing Results

4.1.1 Meshing

Meshing is the subdividing of a continuous geometric space into discrete geometric and topological cells. The mesh generated for the main frame, the plate and the slider will be shown from the figures outlined below.

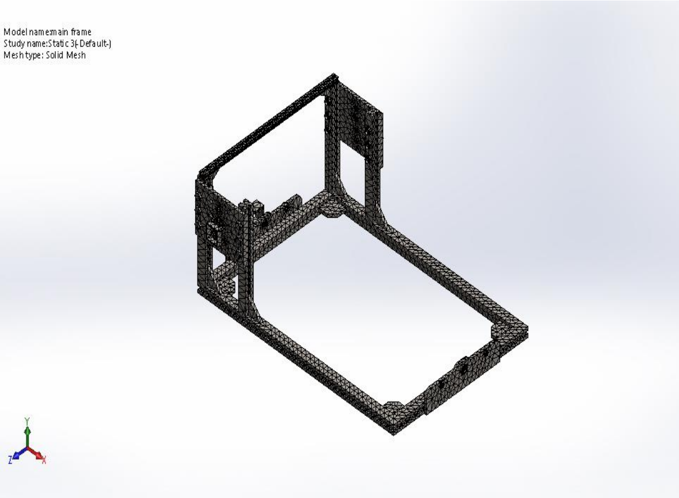


Figure 4-1: Meshed main frame.

Source: Author, 2019

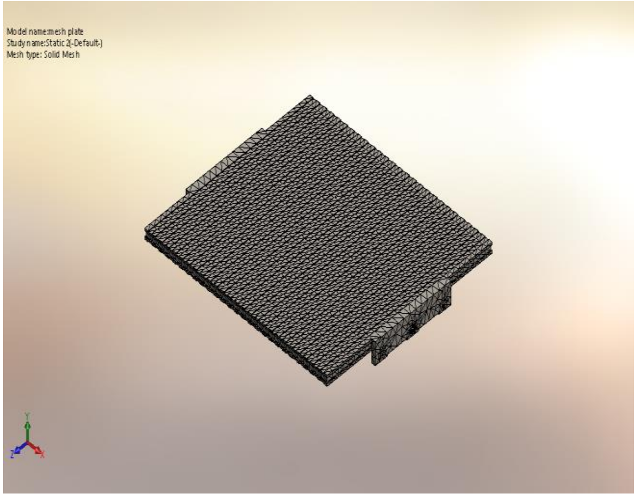


Figure 4-2: Meshed plate/carriage.

Source: Author 2019

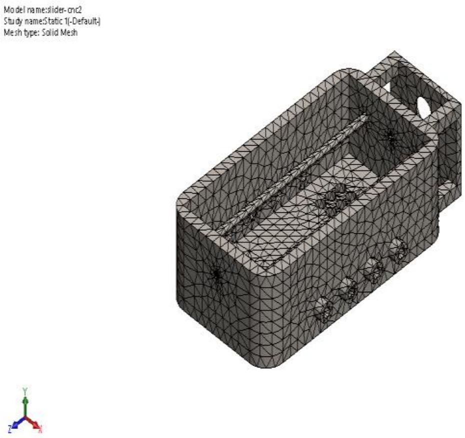


Figure 4-3: Meshed Slider.

Source: Author 2019

4.1.2 Von Mises Stress

These are stresses that are used in the prediction of yielding of materials under complex loading from the results of uniaxial tensile tests. Results obtained after simulations of the main frame, the plate and the slider are shown in the figures below.

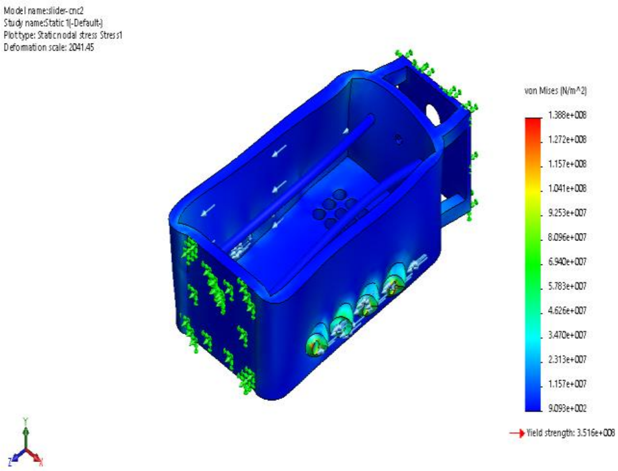


Figure 4-4: Slider displaying the Max. and Min. von mises stresses and the yield strength.

Source: Author 2019

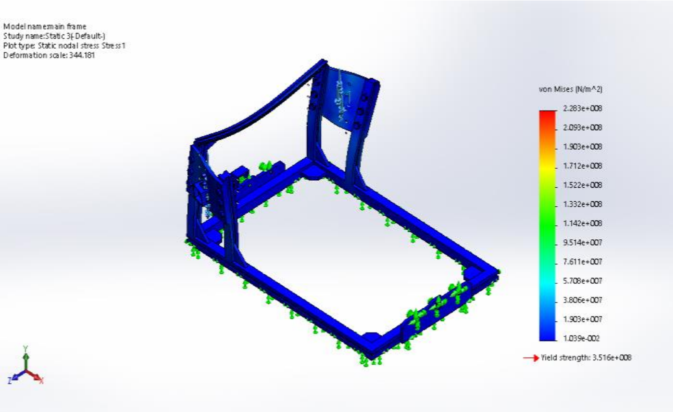


Figure 4-5: Main frame display of the Max. and Min. von mises stresses and the yield strength.

Source: Author 2019

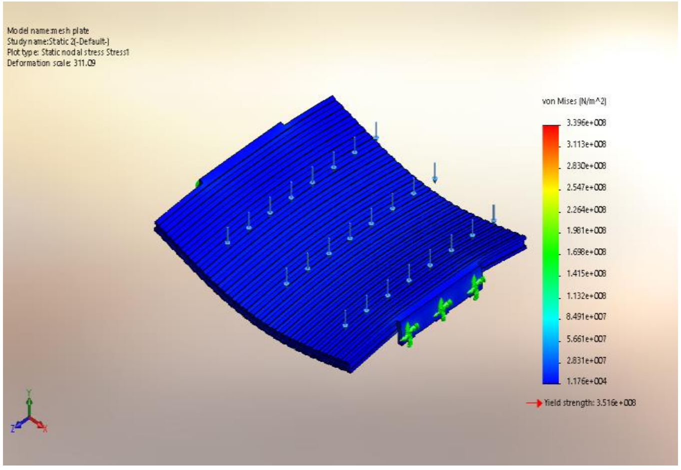


Figure 4-6: plate displaying the Max. and Min. von mises stresses and yield strength.

Source: Author 2019

4.1.3 Displacement

Displacement is a vector whose length is the shortest distance from the initial to the final position of the point. It quantifies both the distance and direction of an imaginary motion along a straight line from the initial position to the final position of the point. The figures below are the results obtained from simulations.

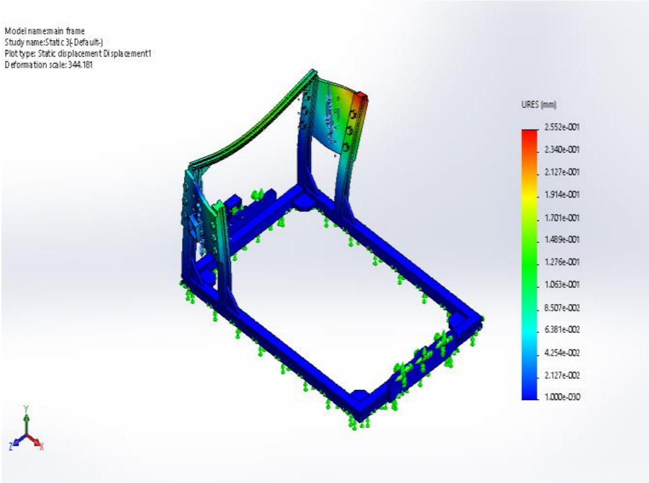


Figure 4-7: Main frame depicting the Max. and Min. displacement.

Source: Author 2019

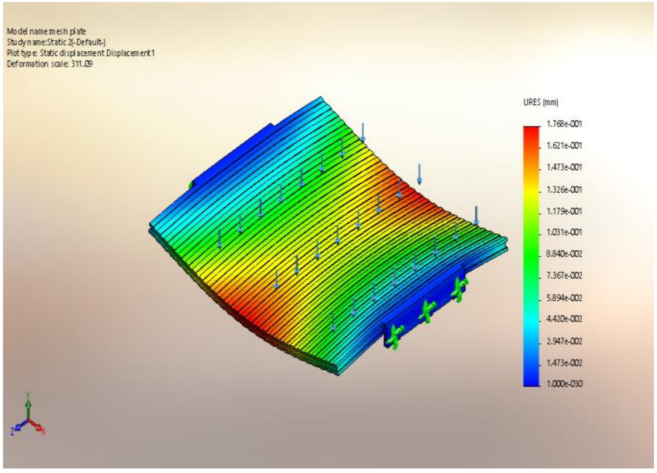


Figure 4-8: Plate display of the Max. and Min. displacement.

Source: Author 2019

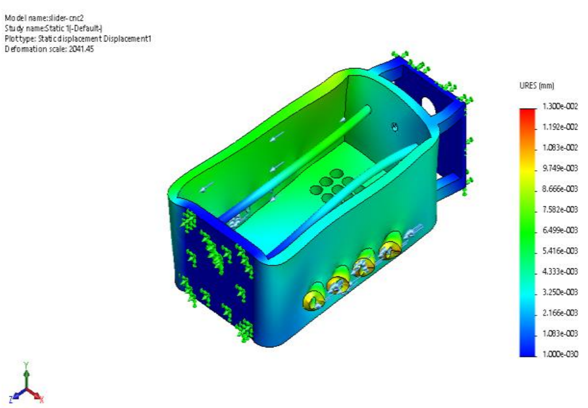
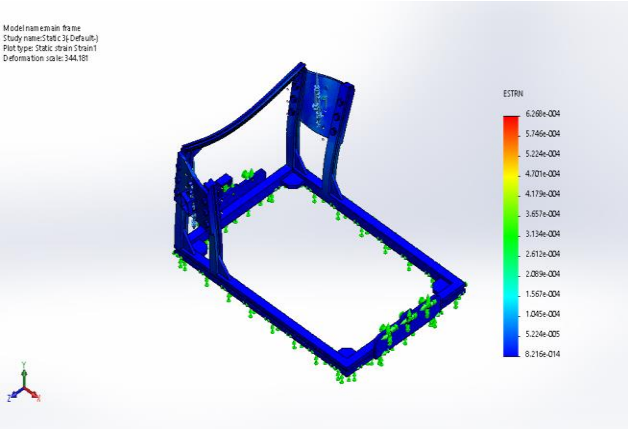


Figure 4-9: Slider display of Max. and Min. displacement. *Source: Author 2019*

4.1.4 Strain

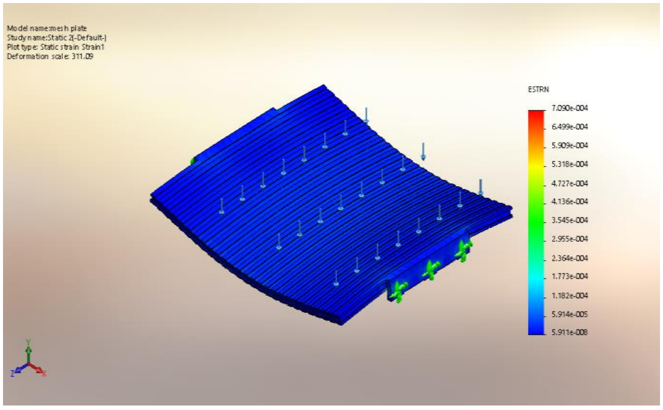
Strain is the relative change in shape or size of an object due to externally-applied forces. The results are shown from the figures below.

Figure 4-10: Main frame depicting Max. and Min. strain.



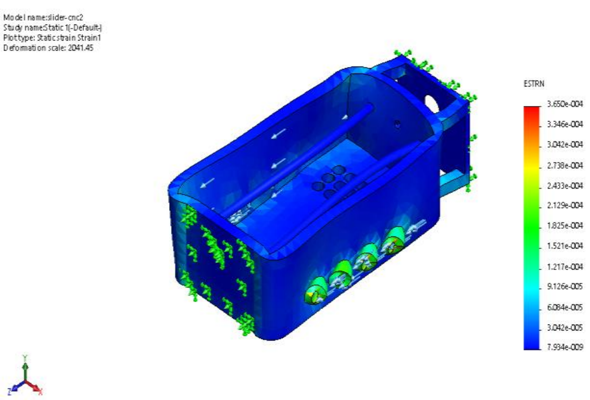
Source: Author 2019

Figure 4-11: Plate display of max. and min. strain.



Source: Author 2019

Figure 4-12: Slider display of the Max. and Min. strain.

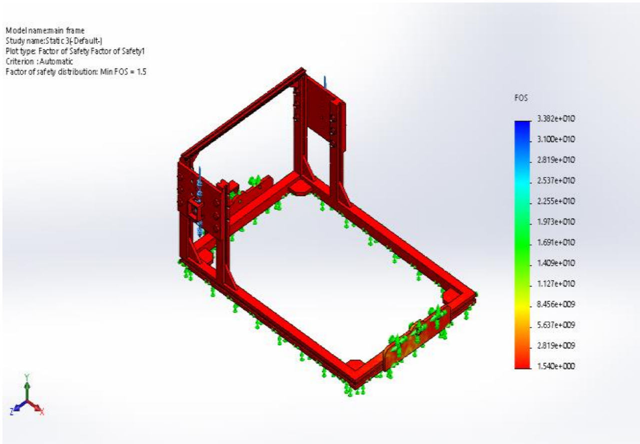


Source: Author 2019

4.1.5 Factor of Safety (FoS)

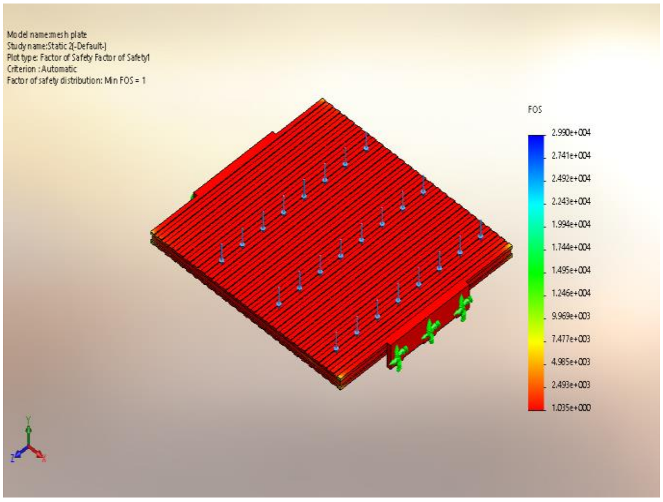
Factor of safety is the ability of a system's structural capacity to be viable beyond its expected or actual loads. It depends on the materials and use of an item. If the factor of safety is less than one, this means the component/part is likely to fail but if it is equal or greater than one predicts that the component is not likely to fail. The following figures shows the results obtained from the simulations.

Figure 4-13: Main frame displaying the Max. and Min. FoS.



Source: Author 2019

Figure 4-14: Plate display of Max. and Min. FoS.



Source: Author 2019

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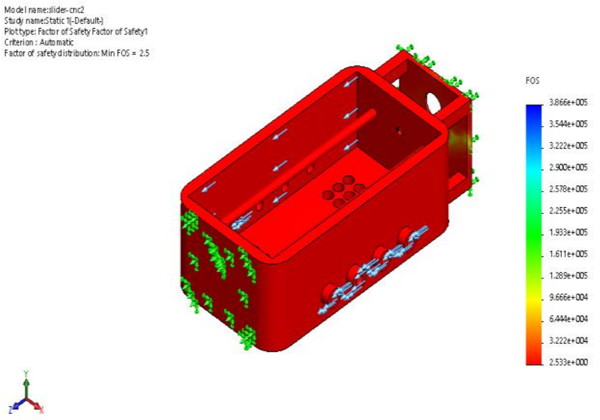
Figure 4-15: Slider display of the Max. and Min. FoS.



Source: Author 2019

4.2 Vibration

The vibration which occurs in most machines, vehicles, structures, building and dynamic systems is undesirable, not only because of the resulting unpleasant motions and the dynamic stresses which may lead to fatigue and failure of the structure or machine, and the energy losses and reduction in performance which accompany vibrations, but also because of the noise produced. Noise is generally considered to be unwanted sound, and since sound is produced by some source of motion or vibration causing pressure changes which propagate through the air or other transmitting medium, vibration control is of fundamental importance to sound attenuation. From the analysis of the machine which has been produced the following results were obtained:

1. The vibration in the axial direction is highest in comparison with the horizontal and vertical directions.
2. The type of metal or its hardness effects are directly on the vibration quantity.
3. Logically, with increase in Feed the vibration is increased.
4. Logically, with increase in Feed the power is increased.
5. The type of metal or its hardness effects are directly on the vibration than power.

4.3 Maintenance and Cleaning

4.3.1 Maintenance

The machine axes are greased with a Teflon grease. Only a Teflon base grease should be used to grease the axes, a small fat film is sufficient.

The machine plate is maintained in a perfect state, ensuring it does not oxide, lubricating it with a fatty rag. In cases where the plate gets damaged, it can be stopped by the use of a resin. A sand paper should be used after hardening to maintain the flatness.

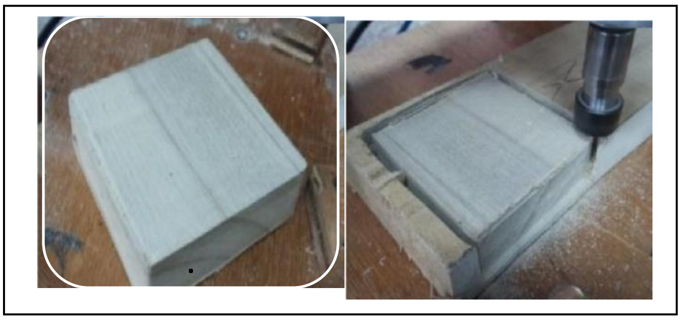
4.3.2 Cleaning

Etching a board makes many copper and epoxy dust. These are very abrasive, and there is need after each operation to clean the machine, with a brush or a vacuum cleaner dedicated to the machine.

4.4 Cutting System Test

Cutting is a technique for cutting wood using a drill bit with a shape according to the design. The cutting system was tested on a wood with 20mm thickness, using 3mm endmill drill bit, 1200 rpm spindle speed and 20mm cutting depth. Image design using *solid works* software, design example is a square shape with 6x6cm.

Figure 4-16: Cutting process and result.



4.5 Engraving System Test

Engraving is a technique of carving on wooden material surface with different depths, so images or letters can be recognized. The engraving system was tested on wood with 20mm thickness, using 3mm vbit60^{o} drill bit, 12000 rpm spindle speed and 7mm engraving depth. Image design using solid works software, design examples using writing combined with engraving pattern

Figure 4-17: Engraving process and results.

4.6 Marking System Test

Marking is a technique of carving on material surface with the same thin depths. Usually marking was used to put a mark or a brand on a metal or non-metallic material. The marking system was tested on a wood with 20mm thickness, using 3mm *vbit* 60° and *endmill* drill bit, 12000 rpm spindle speed and 1mm and 0.5mm marking depth. Image design using *solid works* software, sample design using writing combined with carving pattern.

Figure 4-18: Marking results on wood board.

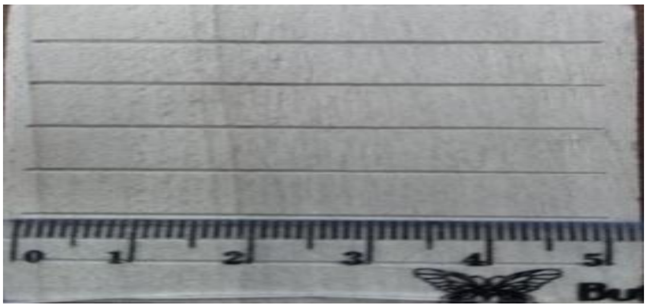
4.7 Accuracy Test

The accuracy test was conducted to determine the level of precision of CNC machine in making shape. This test input was a 6 lines design with 50mm length, which will be formed on a wood with 1mm depth, using 3mm *vbit* 60° drill bit, with 12000 rpm spindle speed.

Table 8: Accuracy Test

Line No	Design	Measurement Result	Accuracy (%)
1	50mm	50,5mm	99%
2	50mm	51mm	98%
3	50mm	50,5mm	99%
4	50mm	50,5mm	99%
5	50mm	51mm	98%
6	50mm	51mm	98%

Figure 4-19 Accuracy Measurement



From testing result on the table, test result in a form of 6 lines with 50,75mm length in average and 98.5% accuracy level was obtained.

4.8 Depth Measurement

The measurement was conducted to determine the level of precision on the depth of CNC machine when working. Testing in the figure shows that 7 lines each of which has 5cm length and 2mm depth using a 3mm *endmill* drill bit with a spindle speed of 12000 rpm were created.

Table 9: Depth Measurement

Line No	Depth in design	Measurement Result
1	2mm	2mm
2	2mm	2mm
3	2mm	2mm
4	2mm	2mm
5	2mm	2mm
6	2mm	2mm
7	2mm	2mm

The table above shows that the line carving produced by the CNC machine with 2mm depth has a precision accuracy of 100%.

Figure 4-19: Depth Measurement

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4.9 Speed Test

The speed test was conducted to determine the effect of angle on the speed in the object formation. The input for this test was a line design with 10cm length which will be formed to resemble some 2D shape. With 1mm engraving depth on wood using 3mm *endmill* drill bit. Uploaded designs were timed using a stopwatch to see how long it takes for each design to be made.

Table 10: Speed Test

No	Design	Time(s)
1	Line	7,1
2	Circle	10,9
3	Triangle	10,5
4	Square	12,2
5	Rectangle	13,4
6	Pentagon	13,5
7	Hexagon	13,6
8	Heptagon	13,7
9	Octagon	15,2
10	Nine Facet	15,4

The Table above shows that there is a time variation for the engraving process on a wide range of 10cm length 2D shapes. From the 10 tests in the table, it can be deduced that the more angles in the formation of the object will slow down the work process, because the X, Y and Z axes on CNC machine move more simultaneously resulting in slower movement of the axis.

4.10 Discussion

After doing all the necessary simulations the results obtained proved to be satisfactory/preferable in relation to the design of the machine considered in this project. The yield strength, von mises stresses, displacement, strain and the Factor of Safety values obtained fall in the safe regions, meaning that the structure is not likely to fail if the same conditions given earlier are applied to this machine. The force used is not the standard but just an approximate value in the sense that it might be less or more depending on the material of the blank/work piece being worked on.

V. CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.0 Introduction

The previous chapter presented and discussed the data analysis of the results obtained. It discussed the software used for the simulations of the machine parts.

This chapter presents a summary of the major findings of the study. It provides the objectives that were met, the conclusions and recommendations as well as areas for further research.

The research had the following objectives;

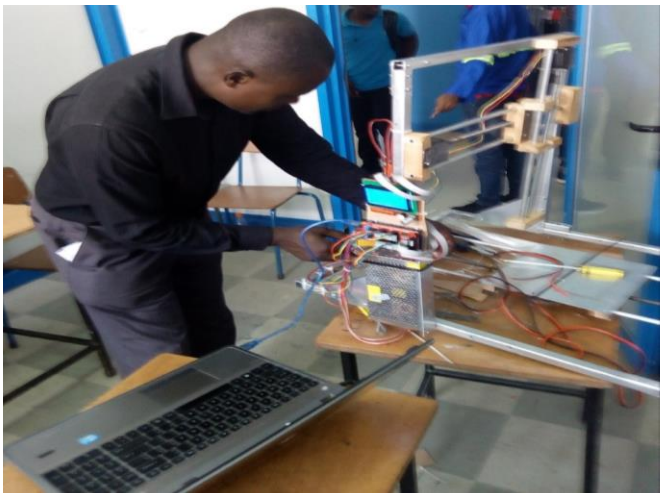
1. Design of the CNC 3-axis machine
2. Performance analysis of the CNC 3-axis machine
3. Fabrication of the CNC 3-axis machine using locally obtained materials

5.1 Conclusion of the Product

The design of the product was successful and the functions it was able to play were massive compared to conventional machines. This can be testified by the prototype which was made from the locally acquired and some imported materials.

The model of the machine produced in this work is shown in the figure below.

Figure 5-1: Shows the whole CNC system built in this project with its all components



Source: Author 2019.

5.2 Conclusion on the Results

After carrying out all the necessary simulations in solid works on parts which were subjected to concentrated forces, the results obtained were satisfactory based on the conditions stated earlier for the testing process of this study.

The CNC router machine was successfully built using ATmega328p and IC4988 microcontrollers combined with 3 Nema 17 stepper motors, with 20x20cm cross-sectional area and using 500-Watt Spindle Air Cooled drill type. The CNC machine can be used for cutting, engraving and marking on wood to form 2D or 3D objects with 98.5% carving accuracy and 100% depth accuracy. The process of synchronizing the 3 stepper motors was controlled using GRBL library and Universal Gcode Sender Software.

5.3 Recommendations

- Design being a process it requires more time, due to this factor this knowledge of software should be introduced in the early stages of learning for students, in order for them to be conversant enough.
- Trainings should be put in place to educate people in electrical installations for the CNC machines. When people are skilled in electrical installation or wiring then issues of maintenance would not be a problem.
- There should be much advocacy on the promotion of CAD packages in the Zambian school curriculum, so much that it is easily embraced at an early stage by scholars in the Design and Technology domain.
- Precision issues if this machine is implemented and put on the market will be a thing of the past due to the higher levels of automation characterized by this machine.

5.4 Future Works

Areas of further research is to find way to cut on the expenses especially for the imported parts to be incorporated to this machine by making sure that at least three quarters of the materials are obtained locally. This will contribute to a lot of small-scale designers countrywide to be able to purchase these machines at affordable prices. And if established manufacturing companies are engaged to invest into this project, not only will their business prosper but also increase on job opportunities for citizens in our country

VI. ACKNOWLEDGEMENTS

I believe and acknowledge that God the Almighty, the Most Merciful enabled me to perform this work and study smoothly and with the commitment it deserves. I offer my all humility to Him and a hearty gratitude to all those whom He deputed to help me during my study.

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