Sudan University of Science & Technology
College of Graduate Studies

Design of Wood Carving Computerized Numerical Control Machine

تصميم ماكينة ذات تحكم رقمي محوسب لنحت الخشب

A Thesis Submitted in Partial Fulfillment of the Requirements of Master Degree in Mechtronics

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وقل اعملوا فسيرى الله عملكم ورسوله والمؤمنون وستردون إلى عالم الغيب والشهادة فينبئكم بما كنتم تعملون

سورة التوبة الآية(105)

Dedication

إلى والدي الذي لم يبخل عليَ يوماً

إلى والدتي الحنونة قبيلة

إلى إخوتي الأعزاء معمر محمد سلمى ومؤيد

إلى زوجتي رفيقة دربي الغالية أم رسيل

إلى كل من علمني حرفاً

إلى أستاذي المرحوم والمغفور له بإذن الله حسن الطيب بسكوتة

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To my supervisor Dr. Al Hadi Badawy, without his support and encouragement, this project would not have been possible.

Abstract

CNC Router systems have been around for a while; their popularity is rapidly growing in all areas. This is probably due to the impressive capabilities of these machines. Offering the ability to create complex shapes that would take a skilled worker much longer time.

In the last years, there have been an increasing number of businesses and hobbyist invests in routers systems. Many people, however, are still in the dark as to what these machines do and how they work.

Router bed and gantry structure designed according to standard wood board size, stress and strains. Main items like spindle, stepper motors, encoders, gearboxes and screw shafts selection calculated according to suitable ratings to avoid over or under rating witch will increase the cost or cause machine failure.

Breakout board is designed to interface between computer and power board, spindle inverter, emergency stop button, feedback encoders and limit switches. power board designed to receive position, speed, acceleration and direction from breakout board and generate the suitable axes stepper motor poles magnetizing sequence. Feedback signal encoders installed in the design to send position, speed and direction to computer through breakout board to make the control system closed.

مستخلص البحث

الماكينات التي يتحكم بها الحاسوب موجودة منذ عقود، واستعمالها ينتشر بسرعة في جميع المجالات، هذا يرجع إلى قدراتها العالية التي توفر إمكانية عالية لصنع الأشكال المعقدة التي من شأنها أن تأخذ زمناً أطول بكثير بالعمالة اليدوية.

في السنوات الأخيرة، كان هناك عدد متزايد من الشركات الكبيرة والهواة يستثمر في مجال التحكم بالحاسوب التي شملت ماكينات الخراطة والقص والثني والقطع و التشكيل.

تم تصميم قاعدة ومنضدة الماكينة والجسر المتحرك إستناداً إلى أبعاد الألواح الخشبية القياسية,الإجهادات ومدى التشوه المرن. تم عمل الحسابات اللازمة لإختيار المكونات الرئيسية كمحرك النحت, محركات المحاور, صناديق التروس, حساسات قياس بعد الحركة وأعمدة نقل الحركة لتفادي القيم الزائدة التي تؤدي لزيادة التكلفة وتفادي القيم الأقل التي تؤدي لفشل الماكينة.

تم تصميم لوحة ال(Breakout) لتعمل كوسيط بين حاسوب التحكم الرئيسي ولوحة القدرة, محول موتور النحت, زر التوقف الطارئ, حساسات المسافة و حساسات تجاوز الحد الأقصى. تم تصميم لوحة القدرة لتلقى أوامر المسافة والسرعة والإتجاه الخاصة بموتورات المحاور من لوحة ال(Breakout) وتوليد التسلسل المناسب لأقطاب موتورات الخطوة المشغلة للمحاور. تم وضع حساسات في التصميم لقياس المسافة والسرعة والإتجاه بالنسبة للمحاور ليكون نظام التحكم نظام مغلق(close loop).

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List of Symbols and Abbreviations

A=cross section area at root diameter (mm^2)

a =*Gantry acceleration*

α=Safety factors (α=0.5)

C_{0a}=Basic static load rating

d_r=Screw shaft root diameter (mm)

E=elastic modulus (E=2.06×10^5 Mpa)

f: factor determined by the shaft supporting condition

F_a: Axial load (N).

F_a:Axial load (N)

F:Forces at axial direction such as cutting force

f_w: Load factor.

f_s=static permissible load factor

g :gravitational acceleration(9.80665 m/s^2)

I=Moment of inertia

L= Unsupported length (mm)

l: Lead(cm)

m,N= Buckling load supporting conditions factors

m= motile mass

m: mass of travelling section(gantry +spindle)

N_1:Number of teeth in gear 1

N_2: Number of teeth in gear 2

n_c:critical speed

σ=Maximum stress(=147 Mpa)

T_a:Drive torque at constant speed (N.cm)

μ : Friction coefficient of the guide way

η_1:Normal efficiency

T_{Pmax}:Upper limit of dynamic friction torque of ball screw (N.cm)

T_u:Friction torque of support bearing(N.cm)

J : Moment of inertia applied to the motor (Kg.m^2)

ώ : Motor angular acceleration (Rad/S^2)

CPT: Count per turn

NC: Numerical control

CAD: Computer-Aided Design

CAM: Computer-Aided manufacturing

CNC: Computer Numeric Control

EIA: Electronic industry association

EDM: Electric discharge machine

PWM: Pulse width modulation

IC: Integrated circuits

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Chapter 1
Introduction

1.1 Background

Numerical control (NC) is the automation of machine tools that are operated by precisely programmed commands encoded on a storage medium, as opposed to controlled manually via hand wheels or levers, or mechanically automated via cams alone. (Paul Tran 2015)

The first NC machines were built in the 1940s and 1950s, based on machines that were modified with actuators that moved the controls to follow path fed into the system on punched tape. These early NC machines were rapidly improved with analog and digital computers, creating the modern CNC machine tools that have transfigured the machining processes. Modern CNC systems highly automated using computer-aided design (CAD) and computer-aided manufacturing (CAM) programs. (Wikipedia)

There are many types of CNC machines like Milling machines, Lathes, Plasma cutters, Electric discharge machining(EDM), Water jet cutters, Drills, Embroidery machines, Wood routers, Sheet metal works (Turret punch), Wire bending machines, Hot-wire foam cutters, Plasma cutters, Water jet cutters, Laser cutting, Oxy-fuel, Surface grinders, Cylindrical grinders, 3D Printing, Induction hardening machines, submerged welding, knife cutting and glass cutters. (R.K Rajput 2012)

1.2 Importance of Study

to develop Furniture industry and give it a competitive position in regional and world market it must provided with three major characteristics, low cost, high quality and mass production , So the importance of this study is design CNC machines that's helps in carving and decorating wood pieces, which later be assembled to full products.

1.3 Problem Formulation

Manual woodcarving is a time consuming process and need a lot of skilled workers and this will increase the cost and decrease the quality and amount of production. The machine cost is important factor for the targeted market of workshops, So to avoid manual carving and reduce the initial cost of machine and continual cost of production, suitable CNC router should be designed and assembled.

1.4 Objectives

(i) Full Design of 4-axis, multiple drill heads and rotation axis CNC table.
(ii) Design a closed-loop control and interface circuit.

1.5 Scope

(i) Design a CNC table suitable for mass production of furniture woodcarving with multiple heads and able to work on 2D axis as router and 3Daxis for decorating and carving wood plates and 4D axis for carving the circular designs.
(ii) Design the interfacing with computer circuits and codes and human machine interface.

1.6 Methodology

First table dimensions would be defined, after that motion rails, pulleys, screw shafts and nuts are selected. Then selection of the Motors and encoders be carried out and design a suitable gearboxes for two of them.

Then selection of the limit switches, safety switches, electric protection, fault alarm and cooling system, and determine their positions.

Then design interface and control circuits and write the necessary codes for interfacing controllers.

The last step is calculating the machine characteristics like cutting bit moving and feedback resolution and also cutting acceleration and speed.

1.7 Definitions

Numerical control (NC) is the automation of machine tools that are operated by precisely programmed commands encoded on a storage medium, as opposed to controlled manually via hand wheels or levers, or mechanically automated via cams alone. Another definition of CNC given by Electronic Industry Association (EIA) is as follows:

A system in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data. (Charles Davis 2014)

1.8 CNC Concepts

An important advance in the philosophy of NC machine tools was the shift toward the use of computers instead of classic controller units in the NC system of the early 1970s. CNC is a self-contained NC system for a single machine tool including a dedicated minicomputer controlled by stored instructions to perform some or all of the basic NC functions. It has become widely used for manufacturing systems mainly because of its flexibility and less cost required.

most interpretation and interpolation functions can be replaced by proper software, the remaining hardware must contain at least servo amplifiers, transducer circuits, and interface components. The software portion of a CNC system must consist at least of three major programs: a part program, a service program, and a control program. The part program contains the geometry description of the part being produced and the cutting conditions such as spindle speed and feed rate. Computer Aided Manufacturing (CAM) software can be used to generate this part program. The service program is used to check and generate G-code . It usually has a user interface that allows the user to check design. The control program accepts the G-code as input data and produces signals to drive the axes of motion, It performs interpolation, feed rate control, acceleration and deceleration, and position counters showing the current axes position.

Most closed-loop CNC systems include both velocity and position control loops. The velocity feedback is usually provided by a tachometer and the position feedback is usually provided by an encoder or resolver. CNC software can also retrieve velocity feedback from encoder by differentiating the input signal. The computer output in CNC systems can be transmitted either as a sequence of reference pulses or as a binary word. The number of pulses represents position and the pulse frequency represents axis velocity. In an open-loop system, these pulses are the control signal of a stepper motor. In a closed-loop system, these pulses can be fed as a reference signal .

1.9 Description

Modern CNC mills differ little in concept from the original model built at MIT in 1952. Mills typically consist of a table that moves in the X and Y axes, and a tool spindle that moves in the Z (depth). The position of the tool is driven by motors through a series of step-down gears in order to provide highly accurate movements, or in modern designs, direct-drive stepper motor or servo motors. Open-loop control works as long as the forces are kept small enough and speeds are not too great. On commercial metalworking machines closed loop controls are standard and required in order to provide the accuracy, speed, and repeatability demanded. (N K Mehata 2016)

As the controller hardware evolved, the mills themselves also evolved. One change has been to enclose the entire mechanism in a large box as a safety measure, often with additional safety interlocks to ensure the operator is far enough from the working piece for safe operation. Most new CNC systems built today are completely electronically controlled.

CNC-like systems are now used for any process that can be described as a series of movements and operations. These include laser cutting, welding, friction stir welding, ultrasonic welding, flame and plasma cutting, bending, spinning, hole-punching, pinning, gluing, fabric cutting, sewing, tape and fiber placement, routing, picking and placing (PnP), and sawing. (Hong kong 2008)

1.10 Thesis Outlines:

Chapter one include background, importance, scope and description of the study, chapter two is literature review including elements, types, axes of motion and control loops, chapter three including CNC components review,, chapter four include design and component selection calculation.

Chapter 2

literature Review

2.1 Elements of a CNC System

A CNC system consists of the following 6 major elements as in figure (2.1) (P.Radhakrishnan 2014)

a. Input Device
b. Machine Control Unit
c. Machine Tool
d. Driving System
e. Feedback Devices
f. Display Unit

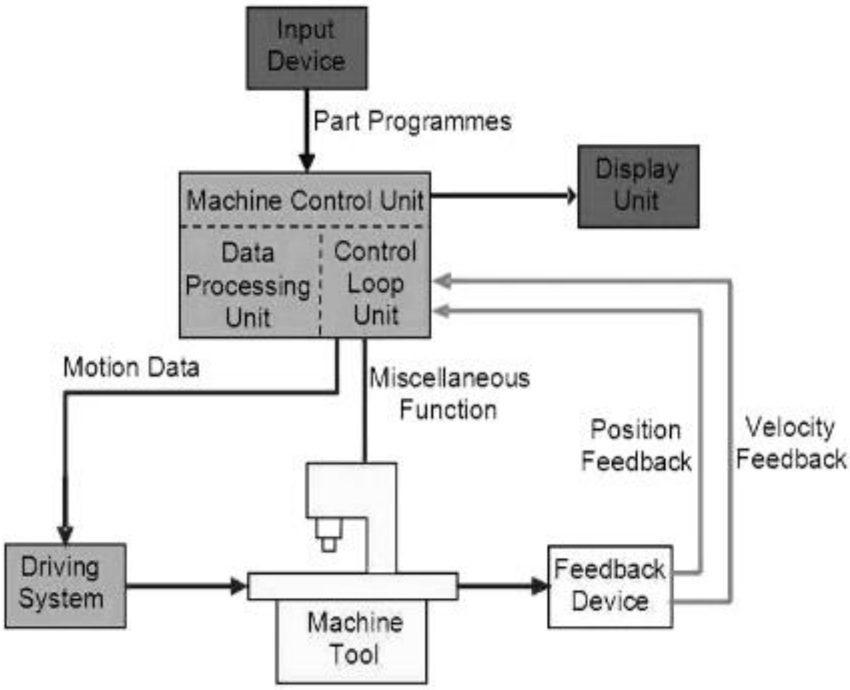


Figure 2.2 CNC system

2.2 Types of CNC Machines:

2.2.1 Mills and Routers

CNC mills and router use computer controls to cut different materials. They are able to translate programs consisting of specific number and letters to move the spindle to various locations and depths. Many use G-code, while others use proprietary languages created by their manufacturers. (Christian Rattat 2017)

Figure 2.2 CNC Mill

figure 2.3 CNC Router

2.2.2 Lathes

Lathes are machines that cut spinning pieces of metal. CNC lathes are able to make fast, precision cuts using indexable tools and drills with complicated programs for parts that normally cannot be cutted on manual lathes. These machines often include 12 tool holders and coolant pumps to cut down on tool wear. CNC lathes have similar control specifications to CNC mills and can often read G-code as well as the manufacturer's proprietary programming language. (N K Mehta 2016)

Figure 2.4 CNC Lathes

2.2.3 Plasma Cutters

Plasma cutting involves cutting a material using a plasma torch. It is commonly used to cut steel and other metals, but can be used on a variety of materials. In this process, gas (such as compressed air) is blown at high speed out of a nozzle; at the same time an electrical arc is formed through that gas from the nozzle to the surface being cut, turning some of that gas to plasma. The plasma is sufficiently hot to melt the material being cut and moves sufficiently fast to blow molten metal away from the cut. (M A Laughton 2013)

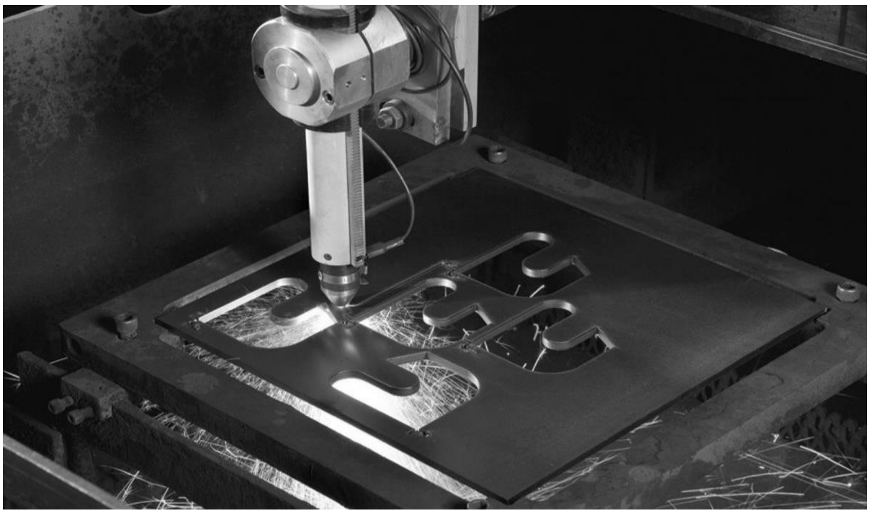


Figure 2.5 Plasma CNC

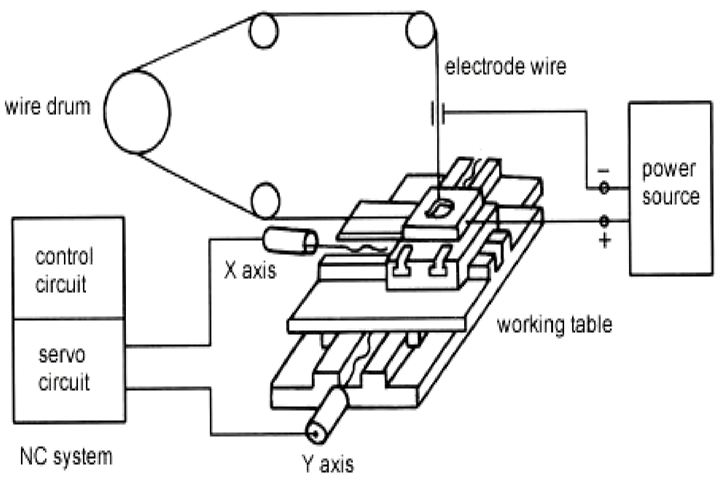
2.2.4 Electric Discharge Machining

Electric discharge machining (EDM), sometimes colloquially also referred to as spark machining, spark eroding, burning, die sinking, or wire erosion, is a manufacturing process in which a desired shape is obtained using electrical discharges (sparks). Material is removed from the workpiece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric fluid and subject to an electric voltage. One of the electrodes is called the tool-electrode, or simply the "tool" or "electrode," while the other is called the workpiece-electrode, or "workpiece".

Types of EDMs:

2.2.4.1 Wire EDM

Also known as wire cutting EDM, wire burning EDM, or traveling wire EDM, this process uses spark erosion to machine or remove material with a traveling wire electrode from any electrically conductive material. The wire electrode usually consists of brass or zinc-coated brass material.



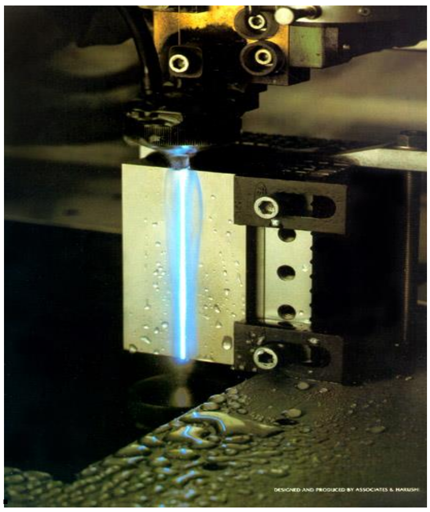


Figure 2.6 Wire EDM CNC

2.2.4.2 Sinker EDM

Sinker EDM, also called cavity type EDM or volume EDM, consists of an electrode and workpiece submerged in an insulating liquid—often oil but sometimes other dielectric fluids. The electrode and workpiece are connected to a suitable power supply, which generates an electrical potential between the two parts. As the electrode approaches the workpiece, dielectric breakdown occurs in the fluid forming a plasma channel) and a small spark jumps.

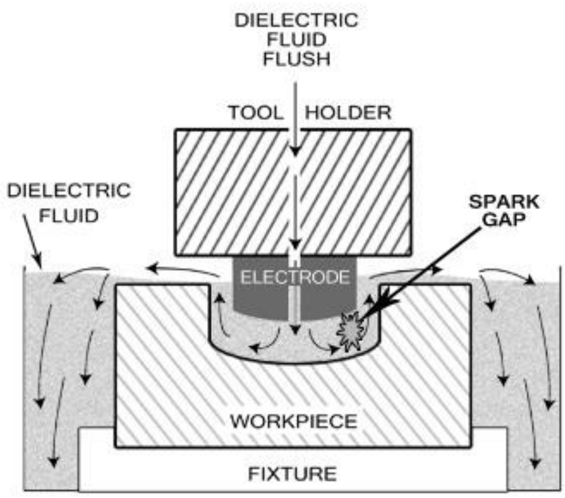


Figure 2.7 Sinker EDM CNC

2.2.5 Water Jet Cutters

A water jet cutter, also known as a water jet, is a tool capable of slicing into metal or other materials (such as granite) by using a jet of water at high velocity and pressure, or a mixture of water and an abrasive substance, such as sand. It is often used during fabrication or manufacture of parts for machinery and other devices. Water jet is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods. It has found applications in a diverse number of industries from mining to aerospace where it is used for operations such as cutting, shaping, carving, and reaming. (Larry Jaffus 2010)

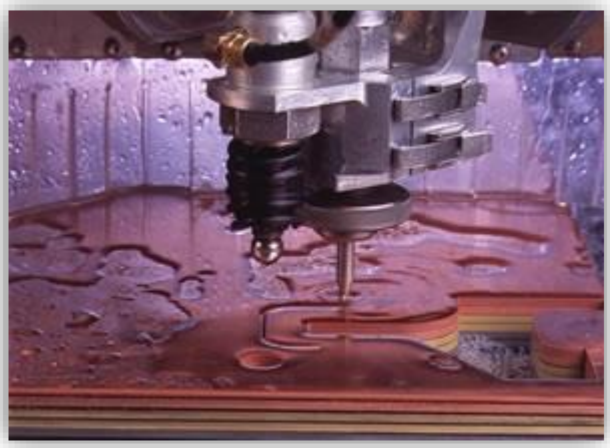


Figure 2.8 Water Jet Cutter CNC

2.3 Axes of Motion

In generally, all motions have 6 degrees of freedom. In other words, motion can be resolved into 6 axes, namely, 3 linear axes (X, Y and Z axis) and 3 rotational axes (A, B, and C axis). In this project only 4 axes needed X,Y,Z and the rotational axis A.(NSK motion and control)

Figure 2.9 CNC Axes Of Motion

2.4 Positioning Systems

2.4.1 Incremental System

This type of control always uses as a reference to the preceding point in a sequence of points. The disadvantage of this system is that if an error occurs, it will be accumulated. (NSK motion and control)

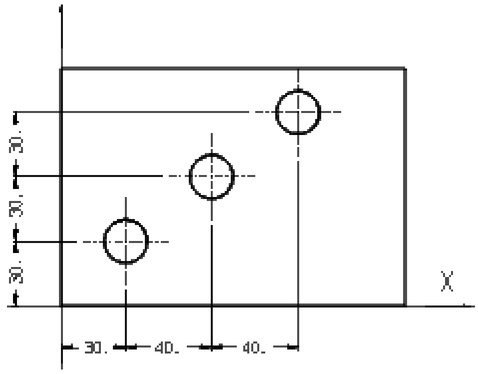


Figure 2.10 Incremental positioning System

2.4.2 Absolute System

In an absolute system, all references made to the origin of the coordinate system. All commands of motion defined by the absolute coordinate referred to the origin.

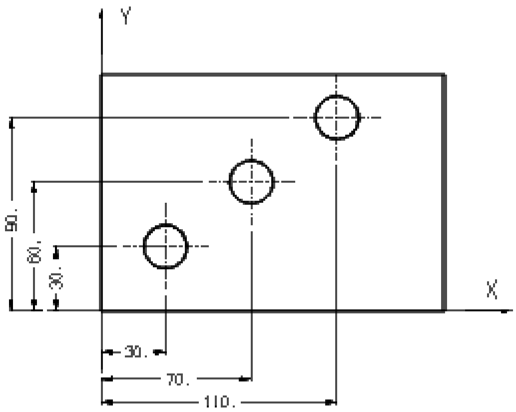


figure 2.11 Absolute positioning System

2.5 Control Loop Systems

2.5.1 Open Loop Systems

Open loop systems have no access to the real time data about the performance of the system and therefore no immediate corrective action can be taken in case of system disturbance. This system is normally applied only to the case where the output is almost constant and predictable. Therefore, an open loop system is unlikely to be used to control machine tools since the cutting force and loading of a machine tool is never a constant. The only exception is the wirecut machine for which some machine tool builders still prefer to use an open loop system because there is virtually no cutting force in wirecut machining. (NSK motion and control)

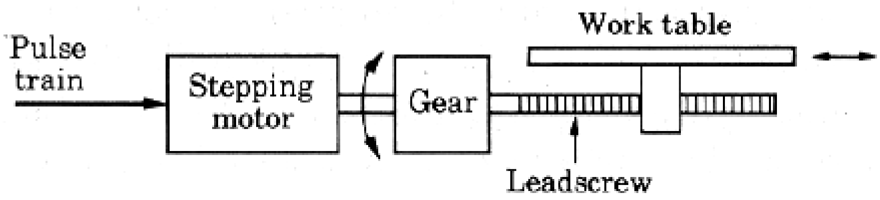


Figure 2.12 Open Loop Control System

2.5.2 Close Loop Systems

In a close loop system, feedback devices closely monitor the output and any disturbance will be corrected in the first instance. Therefore high system accuracy is achievable. This system is more powerful than the open loop system and can be applied to the case where the output is subjected to frequent change. Nowadays, almost all CNC machines use this control system.

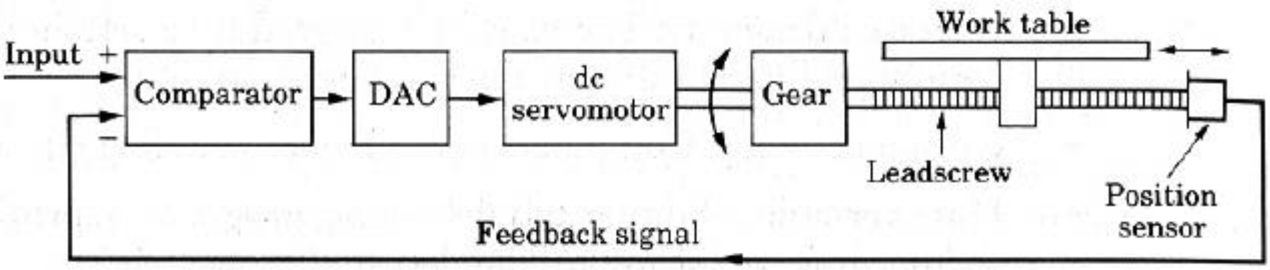


Figure 2.13 Close Loop Control System

Chapter three

CNC components review

3.1 Design Consideration of CNC Machine Tools

CNC machine tools must be better designed and constructed, and must be more accurate than conventional machine tools. It is necessary to minimize all non-cutting Machine time, by minimize idle motions by increasing the rapid traverse velocities to make the use of the machine tool more efficient. Digital control techniques and computers have undoubtedly contributed to better accuracy and higher productivity. the combined characteristics of the electric control as well as the mechanical design of the machine tool itself that determine the final accuracy and productivity of the CNC machine tool system. High productivity and accuracy might be contradictory, Because high productivity requires higher feed, speed and depth of cut, which increases the heat and cutting forces in the system. This will lead to higher deflections, thermal deformations and vibration of the machine, which results in accuracy deterioration. Therefore, to achieve high operating bandwidth while maintaining relatively high accuracy, the structure of CNC machine tool must be more rigid and stiff than its conventional counterpart. To achieve better stiffness and rigidity of structure, several factors should be considered in the design. The first concern is the material, Conventional machine tools are made of cast iron. However, the structures of CNC machines are usually all steel welded, constructed to achieve greater strength and rigidity for a given weight. In addition, better accuracy obtained in CNC machines by using low-friction moving parts, avoiding lost motions and isolating thermal sources. Regular sliding guides have higher static friction than the sliding friction. The force used to overcome the static friction grows too large when the guide starts to move. Due to inertia of the slide the position goes beyond the controlled position, adding overshoot and phase lag to the system response, and affects the accuracy and surface finish of the part. This can be avoided by using slides and lead screws in which the static friction is lower than the sliding friction. For example, rolling type parts such as ball-bearing lead screw and re circulating linear slides, as shown in figure (3.9) can be used.

Generally, the entire machine components must use rigid and solid materials. The clamp system should be strong enough to hold work piece when the machine faces a moveable part during the manufacturing process. In addition, clamping system should be efficiently moved, fast in clamping or unclamping the work piece with fast movement during the process. The choosing of cutting tools is important in order to make sure it will not break when cutting the work piece. (Charles Davis 2014)

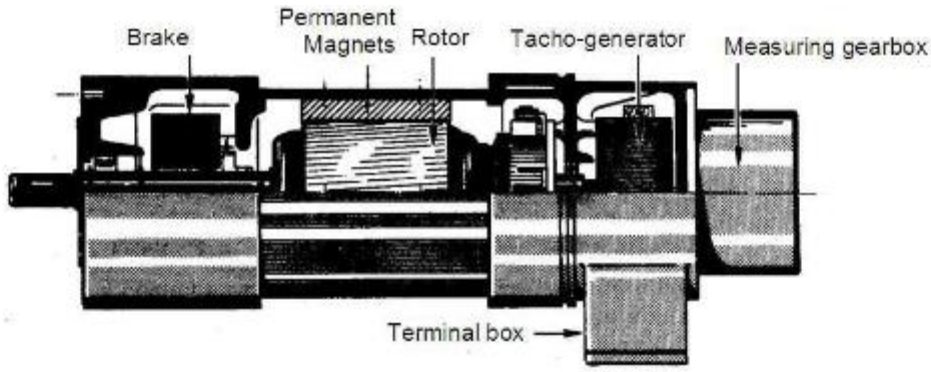
3.2 Motors

There are three electromechanical approaches that can be used to drive the mechanical system servo motor, stepper motor and linear motor.

3.2.1 DC Servo Motor

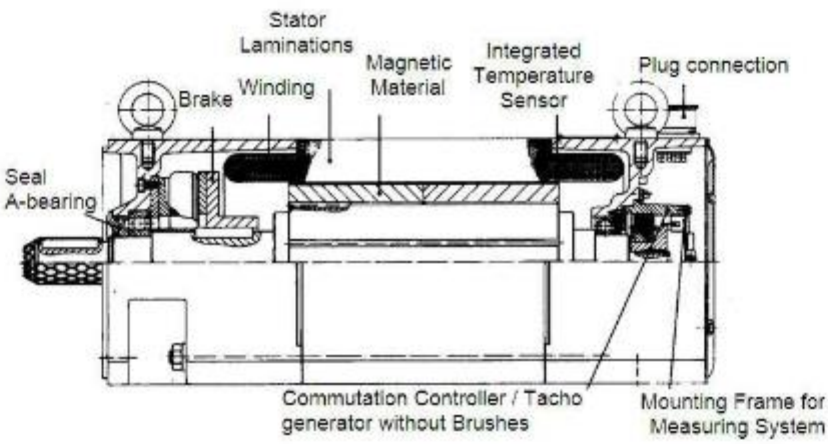
Most common type motors used in CNC machines. The principle of operation is based on the rotation of an armature winding in a permanently energized magnetic field, The armature winding is connected to a commutator. DC current is passed to the commutator through carbon brushes. The change of the motor speed is done by varying the armature voltage and the control of motor torque is achieved by controlling the motor's armature current. In order to achieve the necessary dynamic behavior it is operated in a closed loop system equipped with encoders to obtain the speed and position feedback signals. (Gerald B. Kaliman 2018)

3.2.2 AC Servo Motor



Figure(3.1) DC Servo Motor

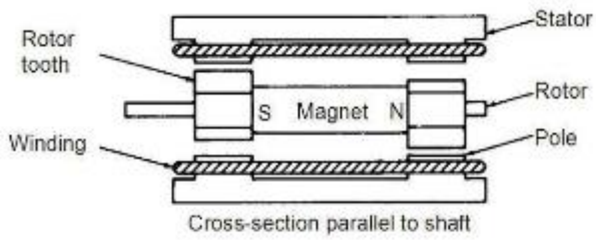
In an AC servomotor, the rotor is a permanent magnet while the stator is equipped with 3-phase windings. The speed of the rotor is equal to the rotational frequency of the magnetic field of the stator, which is regulated by the frequency converter. AC motors are gradually replacing DC servomotors. The main reason is that there is no commutator or brushes in AC servomotor so that maintenance is virtually not required. Furthermore, AC servos have a smaller power-to-weight ratio and faster response. (Austin Hughes and Bill Drury 2013)



Figure(3.2) AC Servo Motor

3.2.3 Stepper Motor

A stepping motor converts the electrical pulses into discrete mechanical rotational motions. This is the simplest device that can be applied to CNC machines since it can convert digital data into actual mechanical displacement. It is not necessary to have any analog-to-digital converter nor feedback device for the control system. They are ideally suited to open loop systems. (Matthew Svarpino 2015)



Figure(3.3) Stepper Motor

3.2.4 Linear Motor

A linear electric motor is an AC rotary motor laid out flat. The same principle used to produce torque in rotary motors is used to produce force in linear motors. the electrical energy is converted to linear mechanical energy to generate a linear motion. Linear motors have the advantages of high speeds, high precision and fast response. (Matthew Svarpino 2015)

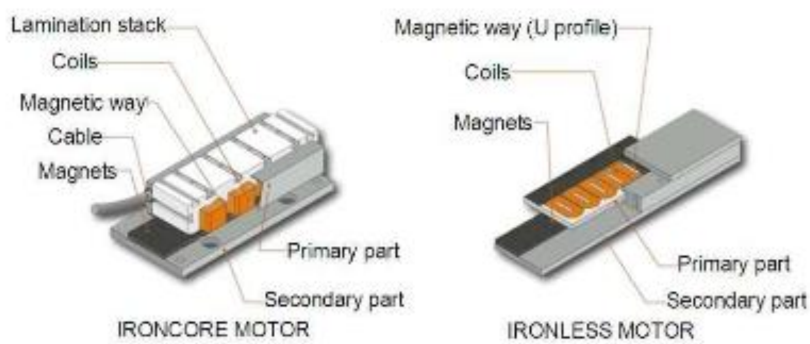


Fig.3.4 Iron core and Ironless Linear Motor

Servo and stepper motors are most widely used in CNC machines due to cost considerations, Cost of linear motors relatively higher so, choices narrowed to servo and stepper motors, following table compare between steppers and servos

Table 3. 5 Servo versus Stepper

Characteristics	Brushed Servo Motor	Stepper
Cost	Higher than stepper motor system with same power rating.	Cheaper than servomotors with same power rating.
Frame Sizes	wide variety of frame sizes, come in NEMA standard size	Do not have as many size selections as servo motors in the large sizes.
Reliability	It depends on the environment and how well the motor is protected.	Higher reliability because it does not require an encoder which may fail.
Motor Life	Brushes on servomotors must be replaced every 2000 hours of operation.	The bearing on stepper motors are the only wearing parts. That gives stepper motors a slight edge on life.
Setup Complexity	Require tuning of the (PID) closed loop variable circuit to obtain correct motor function.	Require only the motor wires wired to the stepper motor driver.
High speed High Torque	Maintain their rated torque to about 90% of their no load RPM.	Lose up to 80% of their maximum torque at 90% of their maximum RPM.
Overload Safety	May malfunction if overloaded mechanically.	Unlikely to be damages by mechanical overload.
Power to Weight/Size ratio	excellent power to weight ratio	Smaller power to weight/size ratio.
Efficiency	80-90% efficiency	usually about 70% efficient
Repeatability	very good repeatability if setup correctly	Very good repeatability with little or no tuning required.
Torque to Inertia Ratio	Capable of accelerating loads.	Less capability of accelerating loads. may stall and skip steps if the motor is not powerful enough.
Flexibility in motor resolution	Since the encoder on a servomotor determines the motor resolution servos have a wide range of resolutions available.	Usually have 1.8 or 0.9 degree resolution. With micro-stepping, steppers can obtain higher resolutions.
Reserve Power and Torque	Can supply about 200% of the continuous power for short periods.	Stepper motors do not have reserve power.
Noise	Servomotors produce very little noise.	Stepper motors produce a slight hum due to the control process.

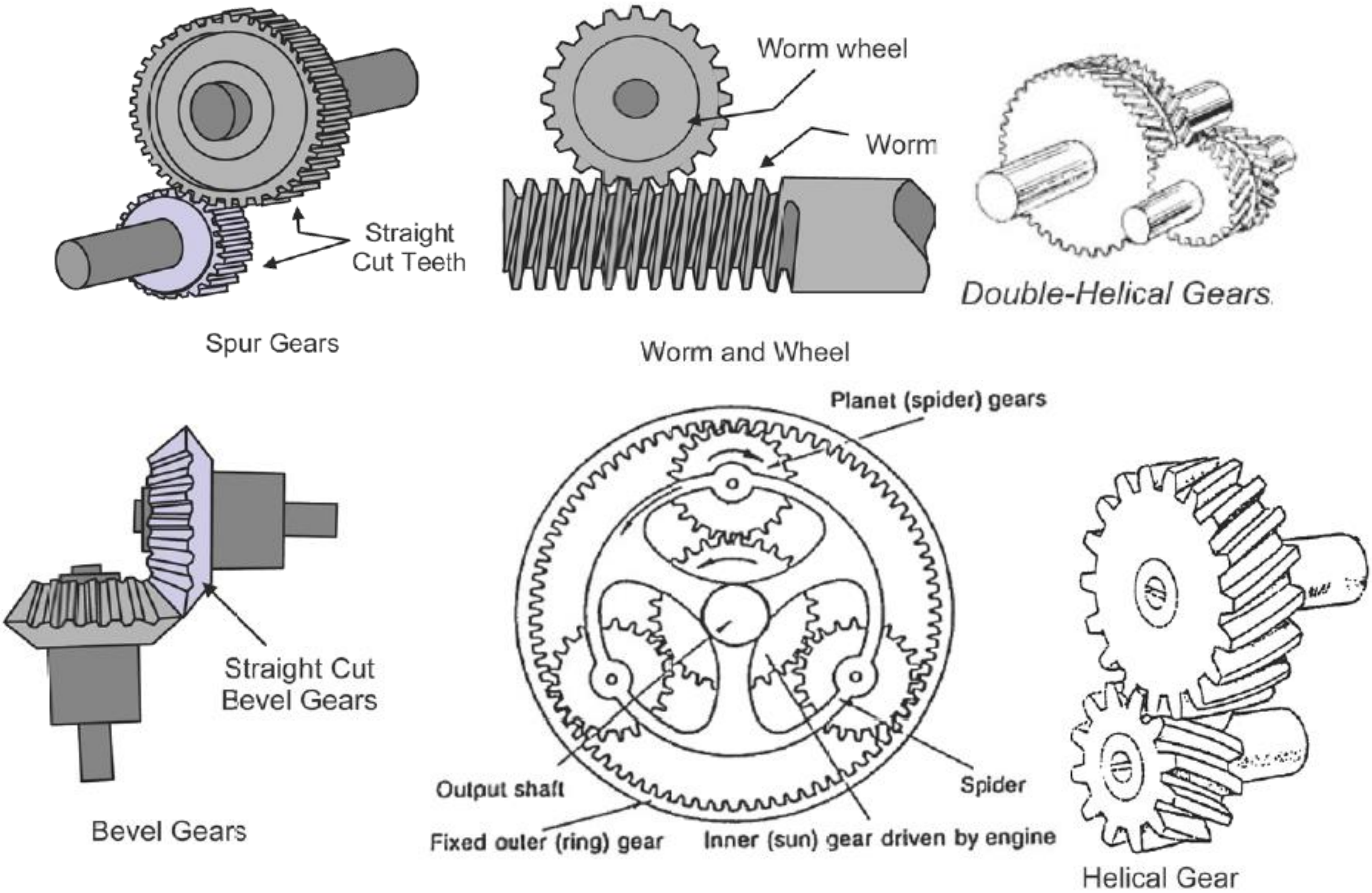
Least Heat production	Since the current draw of a servo motor is proportional to the load applied, heat production is very low.	Stepper motors draw excess current regardless of load. The excess power is dissipated as heat.
Resonance and Vibration	Do not vibrate or have resonance issues.	Vibrate slightly and have some resonance issues because of how the stepper motor operates.
Availability	Servomotors are not readily available to the masses.	Easier to find than quality servomotors.
Motor Simplicity	More mechanically complex.	Very simple in design with no consumable parts.
Direct Drive Capability	Usually require more gearing ratios due to their high RPM.	Stepper motors will work fine in direct drive mode.
Power Range	Because servomotors are available in DC and AC servo motors have a very wide power availability range.	The power availability range for stepper motors is less than servomotors.

3.3 Transmission

Transmission used to change speed, torque, shaft direction or direction of rotation between prime mover and driven machinery. Transmission types are gears, pulleys, belts and chains. (Michael M.Stanisc 2015)

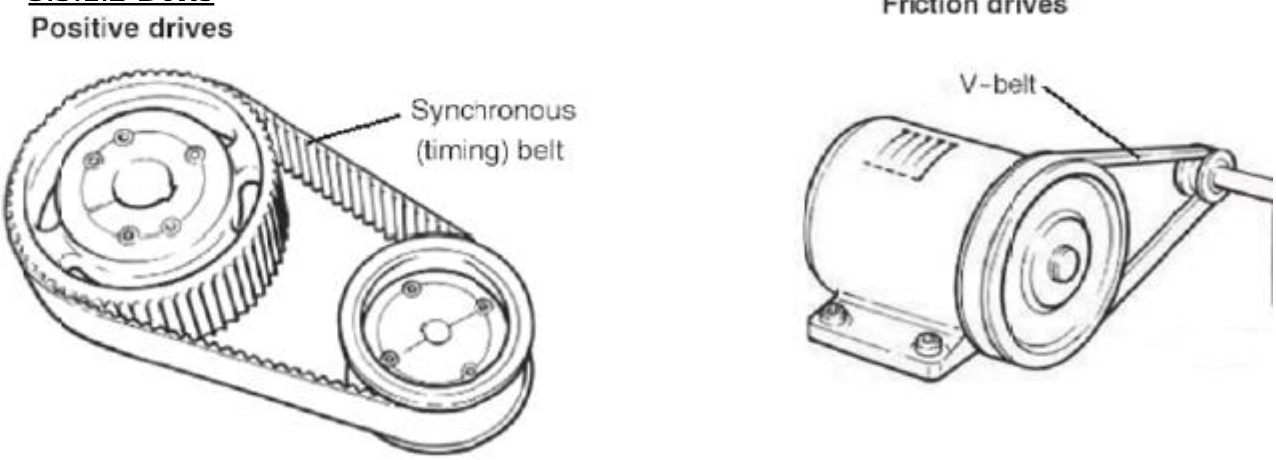
3.3.1 Transmission system types

3.3.1.1 Gears



Figure(3.5) Gear transmission systems

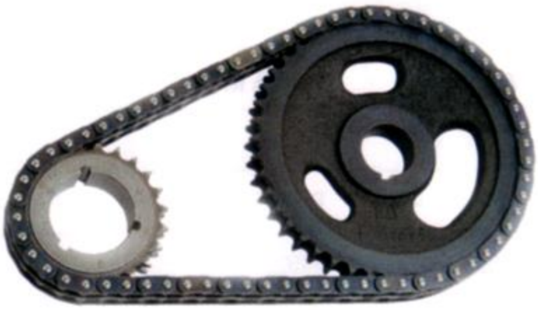
3.3.1.2 Belts



Figure(3.6) belt transmission systems

3.2.3 chains

Chain drive is a way of transmitting mechanical power from one place to another. It is often used to convey power to the wheels of a vehicle but It is also used in a wide variety of machines besides vehicles.



Figure(3.7) Chain transmission system

Chains Versus Belts

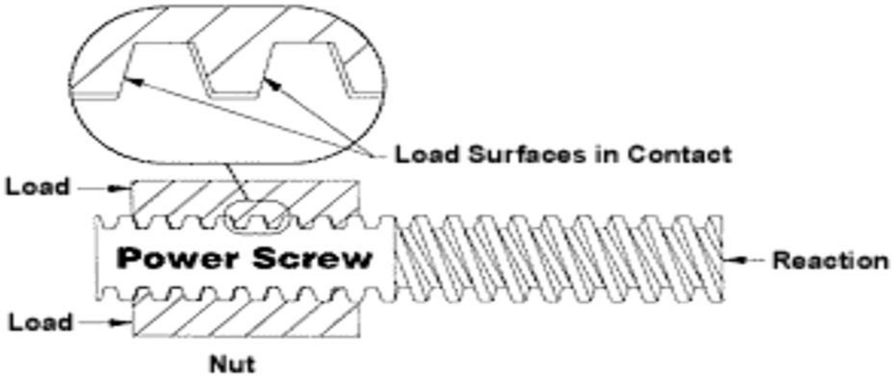
- Roller chain and sprockets is a very efficient compared to (friction-drive) belts, with far less frictional loss.
- chains can be made stronger than belts.
- Chains are often narrower than belts, and this can make it easier to shift them to larger or smaller gears in order to vary the gear ratio.
- conventional roller chain drives suffer the from vibration, as the effective radius of action in a chain and sprocket combination constantly changes during revolution.

3.4 Lead Screw Types

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, multiple screw systems are most often used to accomplish this goal, screws are turned by motors generating linear motion and thrust in the nut. There are two main types of screws:

3.4.1 ACME Power Screw

ACME uses a screw to nut contact resulting in sliding friction, the coefficient of friction depends on the part materials, the larger friction force allows the screw to self-lock and keep any thrust load from being converted to torque and back driving the motor. The trapezoid or squared thread shape allows for smoother rotation without the clapping force that is present in fastener threads. ACME lead screws have efficiencies that range from 20-30%. (Ferdinand P. Beer 1981)

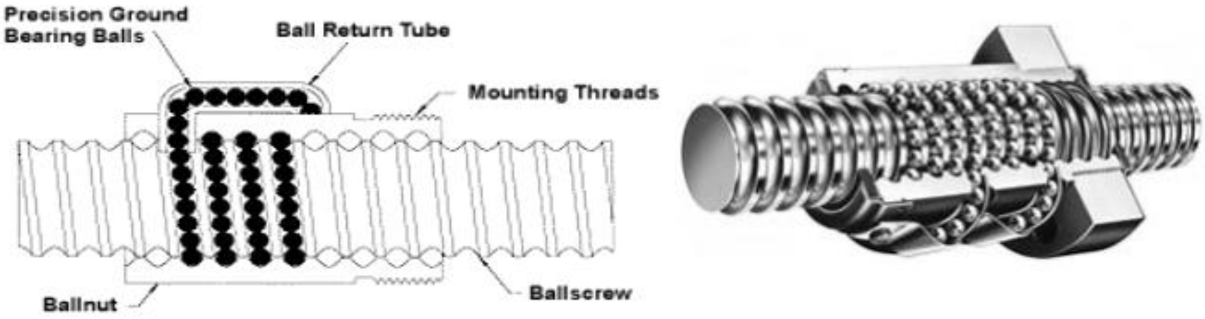


Figure(3.8) ACME Power screw

3.4.2 Ball Power Screw

ball screws use ball bearings between the threads of the nut and screw, These ball bearings travel a continuous path through the nut providing rolling contact and reducing friction. Some ball screws offer multiple ball circuits distributing the load and improving reliability. ball screws transmit motion with over 90% efficiency.

Ball screws will experience free linear motion of the nut, known as backlash, unless a preloaded nut or double nut or some type of brake is used , This can create complexity in the design and increase cost of the system. (SDP/SI)



Figure(3.9) Ball Power screw

3.5 Linear Guide Rails Types

Rails consists of a linear motion bearing and shaft assembly which would simply allow unrestricted movement along their lengths. the railing system shown down has a simple steel shaft railing system and is light weight ,types are:

3.5.1 Steel Rod

Steel shaft railing, as seen down is both a simple and efficient design for linear motion applications. The shaft provides support to loading applications along the shaft with forces generated from linear motion. (Charles Davis 2014)

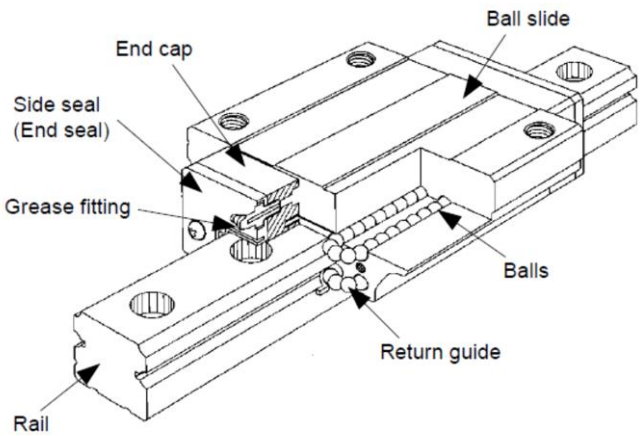
Figure(3.10) Steel Rod

This shaft and support system in this can come in a ceramic material that provides enhanced properties of the system. The enhanced properties include a reduction of vibration while also reducing deflection of the shaft during loading cases to help increase the life of the shaft.

Figure(3.11) Steel rod

3.5.2 Versa-Mount

This system is capable of higher loading capacities with stability in handling off-balanced loads.



Figure(3.12)Figure Versa-Mount

3.5.3 V-notch Rail

The V-notch rail system uses a notch in the rail and V-grooved wheel riding on the railing surface to carry the load and support linear motion.

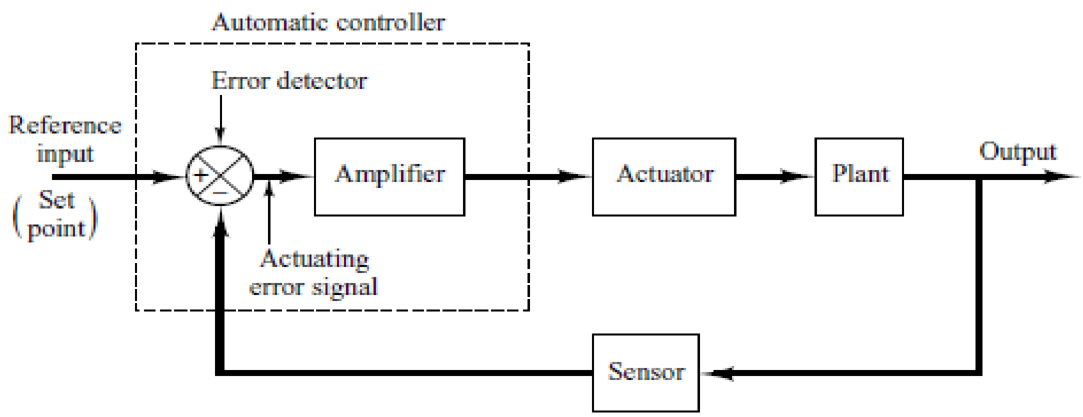
Figure(3.13) V-Notch Rail

The V-notch rail can be more complex by notching the top and bottom of the rail which can be used for rails suspended above the ground. (NSK motion and control)

3.6 Controller Hardware System

Control hardware system consist of

1. Main control unit: it is the heart of control hardware system and has the following functions:
   i. receive the instructions from computer and send the suitable signals to the motor drivers.
   ii. Receive feedback sensors signals and send it to the computer after conditioning and processing it.
   iii. Receive and send signals like limit switch, emergency buttons and spindle relay and act in suitable way.
2. Motors drivers: it receive control signals from Main control unit and amplify them to operate Motors.
3. Feedback units: feedback used to ensure that no error between input instructions and actual position.
4. Power supply: to supply motors with the required power.
5. Limit switches, emergency buttons, spindle relay and coolant relay.



Figure(3.34) Controller hardware system

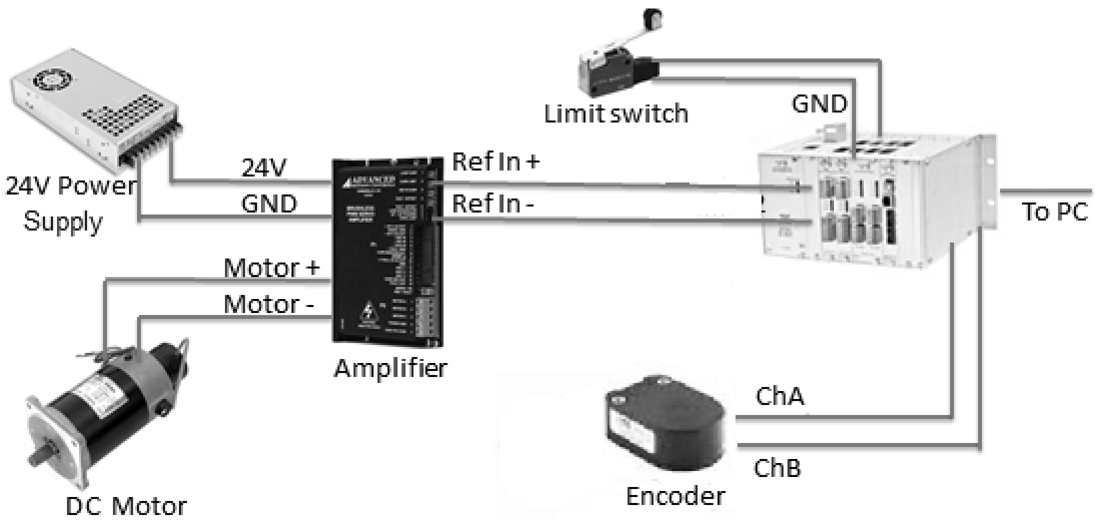
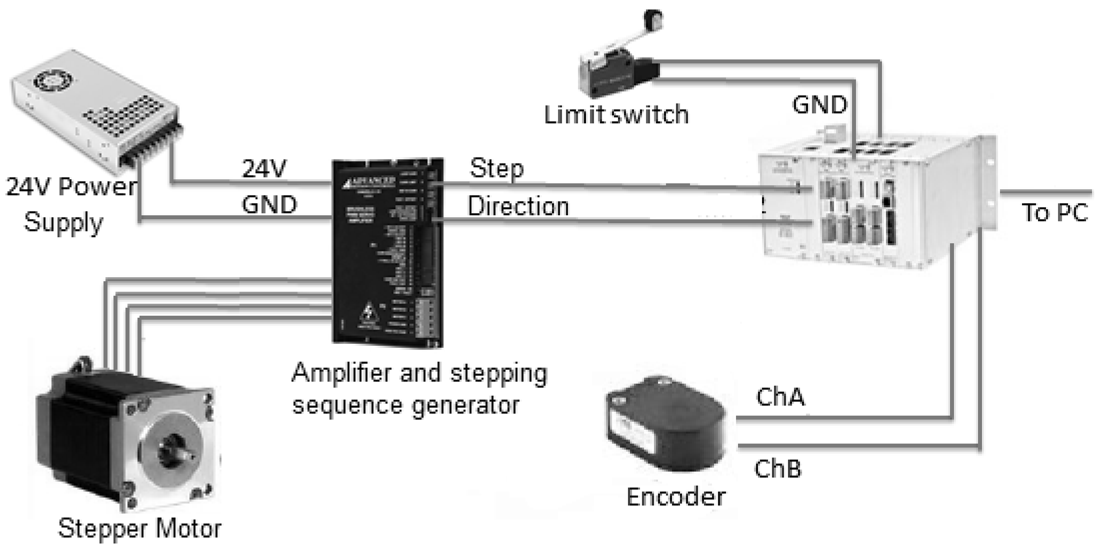


Figure (3.15) control hardware for CNC drived by DC motor

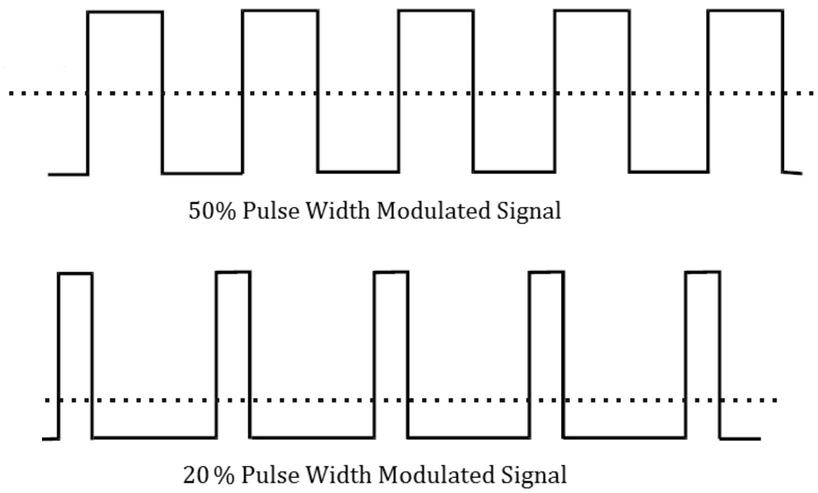


Figure(3.16)) control hardware for CNC drived by stepper motor

3.7 Motors Driving Techniques

3.7.1 DC Motor

Pulse width modulation (PWM) is a motor speed control technique, it output a pulse width modulated signal whose duty cycle is the percentage of full cycle, for example, duty cycle of PWM signal on for 0% of time gives 0 volts, 25% gives 2.5 volts, 50% gives 5 volts, up to 100% gives 10 volts. PWM signal could be used to trigger a triac in a simple DC speed controller.



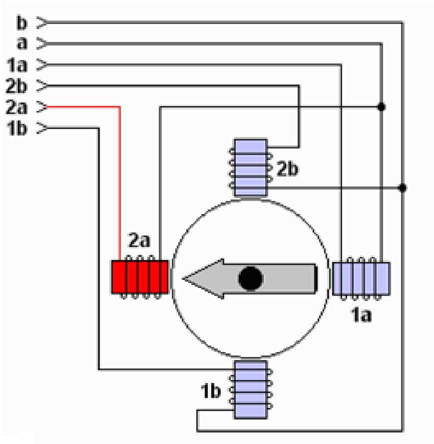
Figure(3.17) Pulse width modulation (PWM)

3.7.2 Stepper Motor

Stepper motor has three types of step driving as:

3.7.2.1 Full Step

Full stepping, illustrated in Figure (3.18), is the simplest of the driving techniques. In full step operation, the motor steps through the normal step angle i.e. 200 step/revolution motors take 1.8-degree steps. Single-phase full-step excitation is where the motor is operated with only one phase energized at a time.



Clockwise Rotation

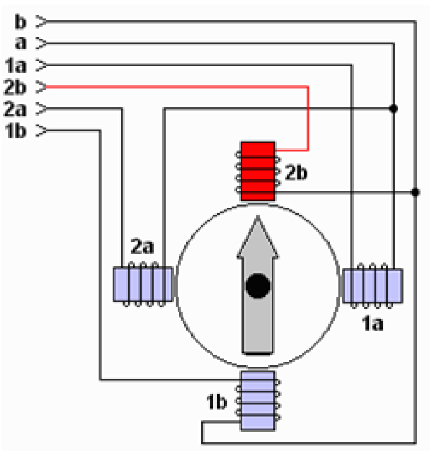
Index	1a	1b	2a	2b
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	1
5	1	0	0	0
6	0	1	0	0
7	0	0	1	0
8	0	0	0	1

Figure 3.18 Full step sequence of stepper motor

3.7.2.2 Half Step

Half-stepping, illustrated in Figure(3.19), is a technique by which both phases are energized, followed by only one phase being energized resulting in steps one half the normal step size. This increases the amount of steps by double compared to full-stepping.

Figure 3.18 Full step sequence of stepper motor



Clockwise Rotation

Index	1a	1b	2a	2b
1	1	0	0	0
2	1	1	0	0
3	0	1	0	0
4	0	1	1	0
5	0	0	1	0
6	0	0	1	1
7	0	0	0	1
8	1	0	0	1
9	1	0	0	0
10	1	1	0	0
11	0	1	0	0
12	0	1	1	0
13	0	0	1	0
14	0	0	1	1
15	0	0	0	1
16	1	0	0	1

Figure(3.19) Half step sequence of stepper motor

3.7.2.3 Micro-stepping

Micro-stepping is produced by proportioning the current in the two windings according to sine and cosine functions. Micro-stepping is a way of moving the stator flux of a stepper more smoothly than in full or half step drive modes. For practical methods, the current in one winding is kept constant over half of the complete step and current in the other winding is varied as a function of sin(θ) to maximize the motor torque.

Table 3. 6 Stepping Techniques -Advantages/Disadvantages

Stepping technique	Advantages	Disadvantages
Full	Good torque and speed with minimum resonance problems. Provides 50% more torque that Wave stepping.	Requires twice the power compared with wave. Increase noise and vibrations at resonant frequency.
Half	Little resonance problems. Larger speed range Can drive almost any load.	Requires more power. Complex drive electronics Reduced precision at electrical angles.
Micro	Smooth movement at low speeds Increased step position resolution Maximum torque at both low and high speeds	Low performance at higher speeds Increased cost Most complex of all stepper drive techniques

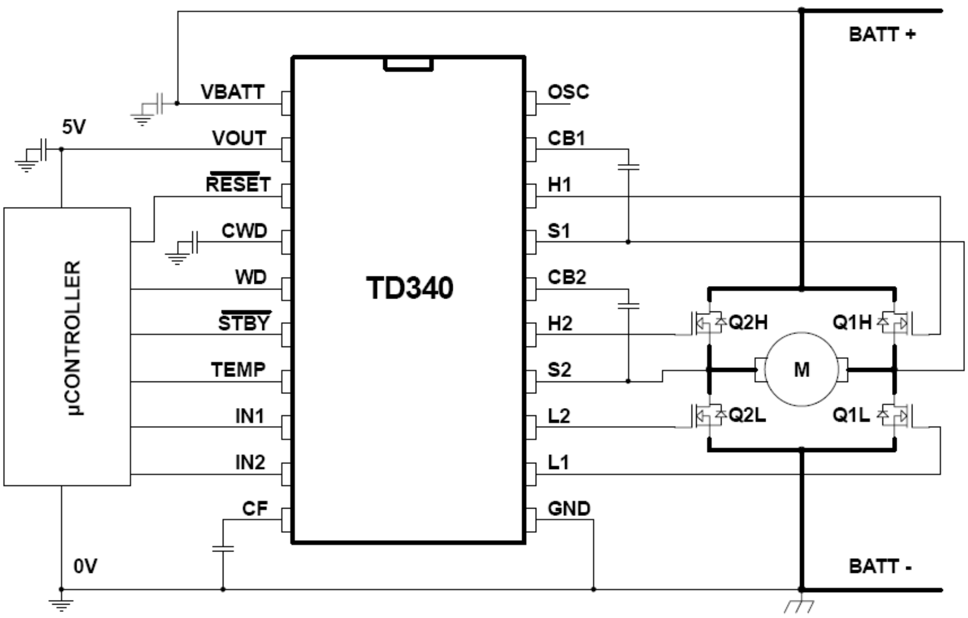
3.7.3 Stepper Motor Drivers

The function of the driver is to supply the rated amount of current to the motor in the shortest time possible. The driver voltage is very important to the operation and performance of the stepper motor. The motors' winding have a certain resistance and inductive reactance thus a certain time constant. This is the time taken to supply the rated current to the motor. At high motor speeds, this significantly reduces the torque supplied by the motor. The reduction in torque can be overcome by increasing the drive voltage to the motor, normally called overdriven the motor. (ST Inc)

3.8 Motors Drivers And Power Electronics

Motor drivers are internally generate Motor phases, this will reduce burden on the microprocessor, and the programmer. Some ICs generate weak signals just enough to trig a power amplifier.

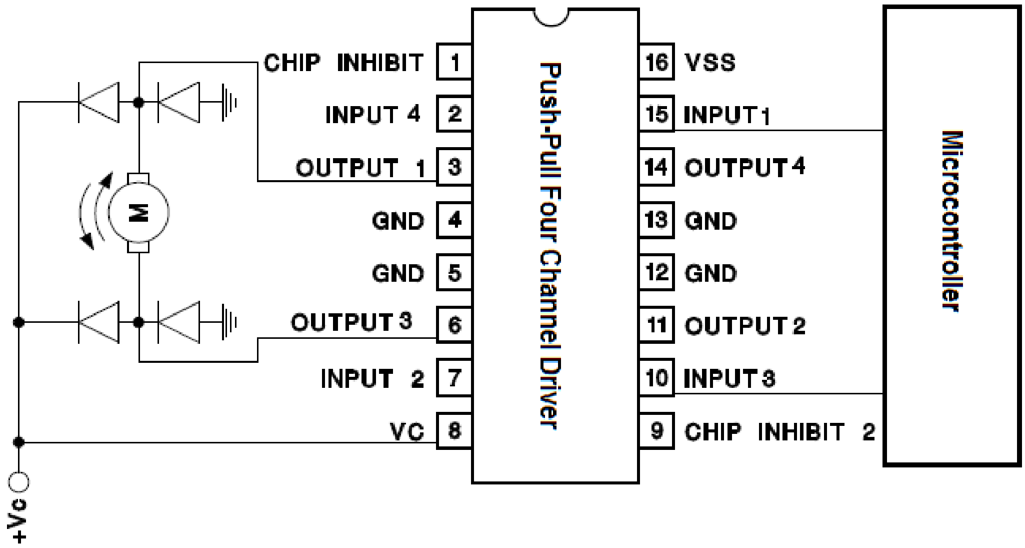
3.8.1 DC Motor



Figure(3.40) TD340 DC Motor driver

The TD340 integrated circuit allows N-Channel Power MOSFETs driving in a full H-bridge configured for DC Motor Control Applications. The four drivers outputs are designed to allow 25kHz MOSFET switching frequency.

The speed and direction of the motor are to be set by two pins. Voltage across the motor is controlled by low side Pulse Width Modulation (PWM). This PWM feature can be made internally when the input pin is connected to an analog signal, or it can be given directly from a digital source.



Figure(3.21) L293 DC Motor driver

The L293 are quad push-pull drivers capable of delivering output currents to 1A or 600mA per channel respectively. Each channel is controlled by a TTL compatible logic input and each pair of driver outputs is a full bridge circuit.

3.8.2 Stepper Motor

The L297 integrated circuit (IC) Stepper Motor Controller generates four phase drive signals for two phase bipolar and four phase unipolar stepper motor. The motor able to driven in half step and full step drive modes and on-chip PWM chopper circuits permit switch mode control of the current in the windings. L297 IC is coupled with L298 IC, the function of L298 IC is to amplify the current of L297 signal.

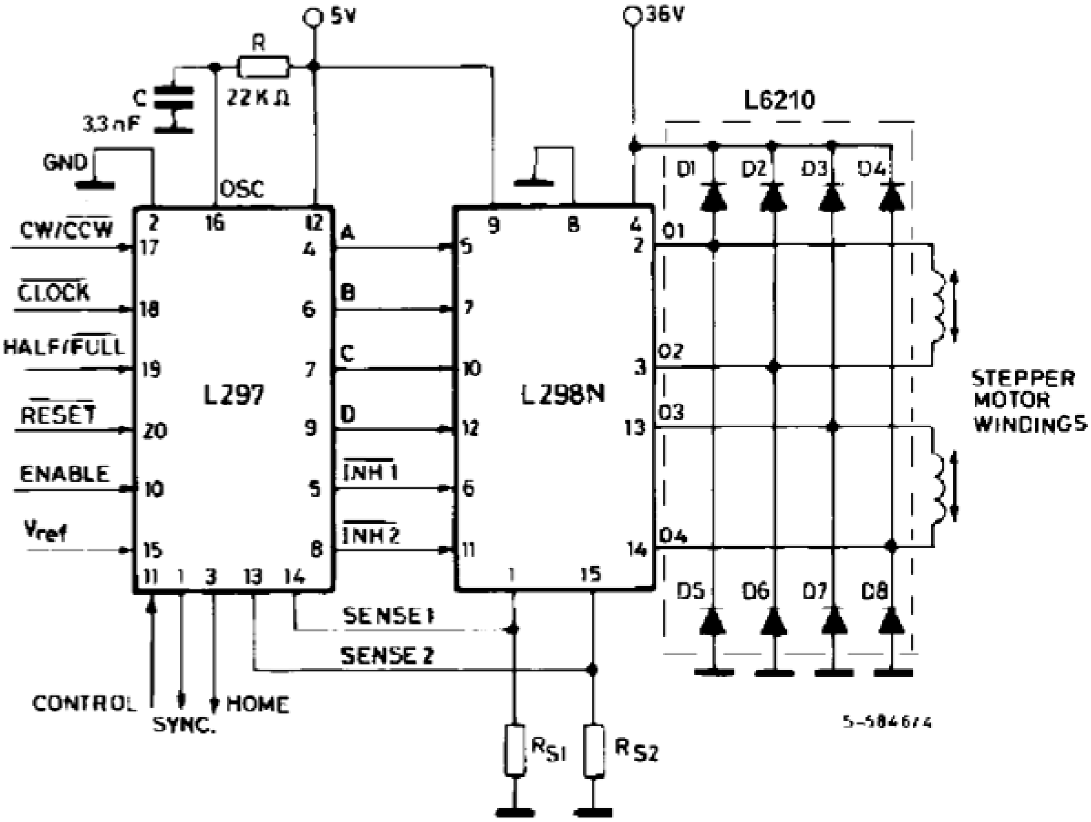


Figure (3.22) L297 Stepper Motor driver

The L6474 IC Stepper Motor Controller generates and amplify four phase drive signals for two phase bipolar and four phase unipolar stepper motor. The motor can be driven in half step, full step and micro step drive modes and on-chip PWM chopper circuits permit switch mode control of the current in the windings.

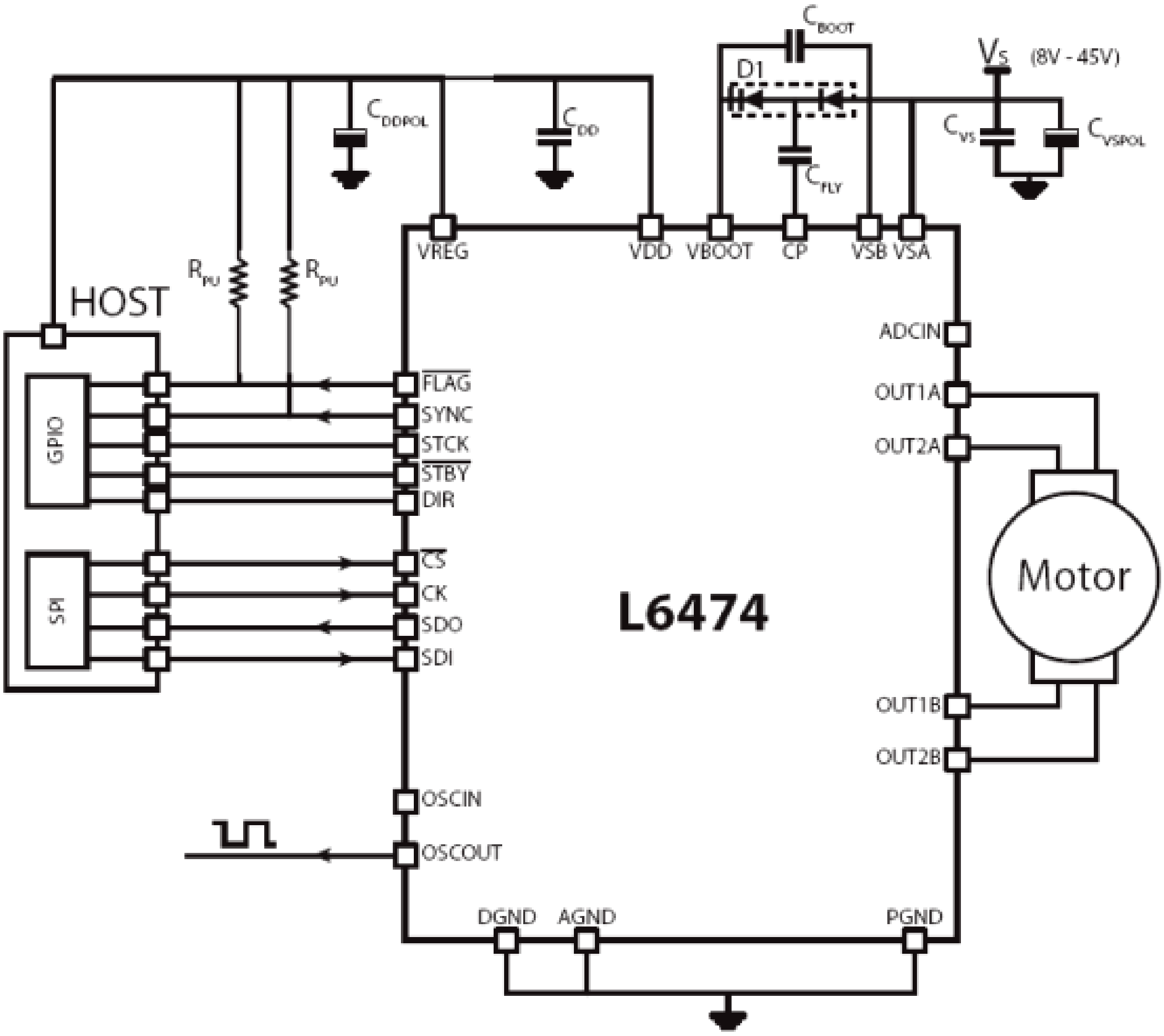


Figure 3.23 L6474 Stepper Motor driver

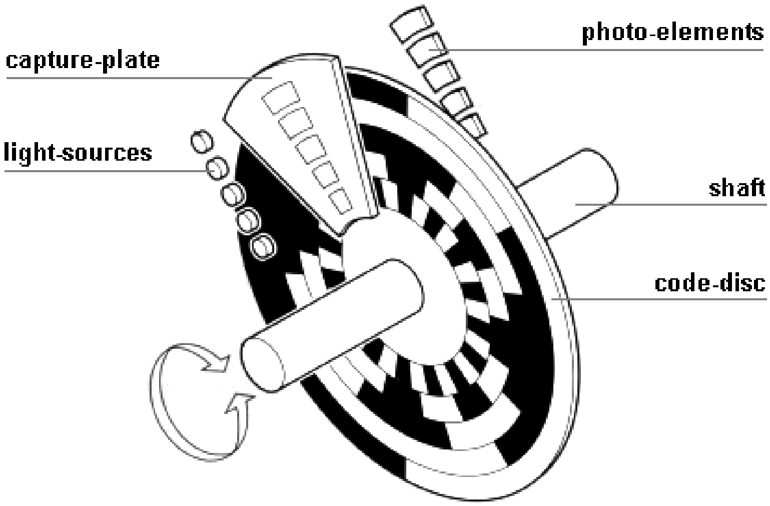
3.9 Encoders

Encoder is an electro-mechanical device that converts the position or motion to an analog or digital code, and used as feedback for position, speed acceleration and direction.

There are two main types: Rotary and linear, each of them has two types, absolute and incremental.

3.9.1 Rotary encoders

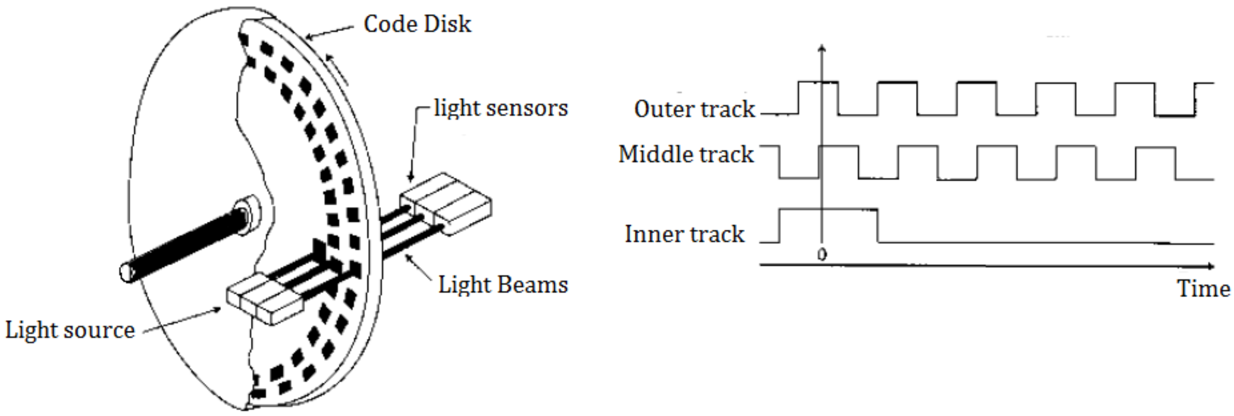
3.9.1.1 absolute encoder



Figure(3.24) absolute encoder

The optical encoder's disc is made of glass or plastic with transparent and opaque areas. A light source and photo detector array reads the optical pattern that results from the disc's position at any one time. This code can be read by a controlling device, such as a microprocessor or microcontroller to determine the angle of the shaft.

3.9.1.2 incremental encoder



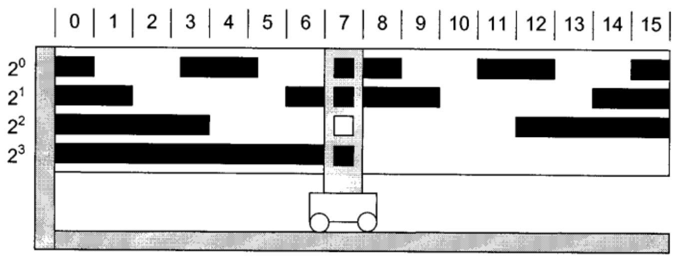
Figure(3.25) incremental encoder

An incremental rotary encoder provides cyclical outputs (only) when the encoder is rotated. They can be either mechanical or optical. The mechanical type requires de-bouncing and limited in the rotational speeds. The incremental rotary encoder is the most widely used of all rotary encoders due to its low cost and simple interpretation to provide position and motion related information such as velocity and acceleration. (Bela G. Liptak 2018)

3.9.2 Linear Encoders

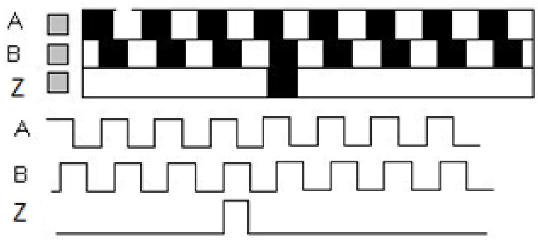
Principle of operation same to the rotary encoders

3.9.2.1 absolute encoder



Figure(3.26) Linear absolute encoder

3.9.2.2 Incremental encoder



Figure(3.27) Linear Incremental encoder

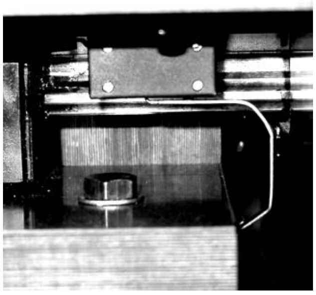
3.10 Limit Switches and Emergency Stop

Limit switches are used to prevent any linear axis from moving too far and causing damage to the structure of the machine. machine can be operated without them, but slightest mistake in setting up or programming can cause a lot of expensive damage.

3.10.1 Limit Switches Types

a. *Mechanical limit switch*

A mechanical cam trips a mechanical plunger, which actuates an electro-mechanical switch element through a sealed membrane. They function under conditions of vibration, shock, rapid temperature fluctuations, aggressive coolants, and heavy presence of chips.



Figure(3.28) Mechanical Limit Switch

b. *Optical limit switch*

Optical limit switch detect without direct contact object. It uses a light-beam generator, a photo detector, a special amplifier. The light beam obstructed by object and this change the state of photo detector. The light beam modulated at a specific frequency, and the detector has a frequency-sensitive amplifier that responds only to light modulated at that frequency.

Figure(3.29) Optical limit switch

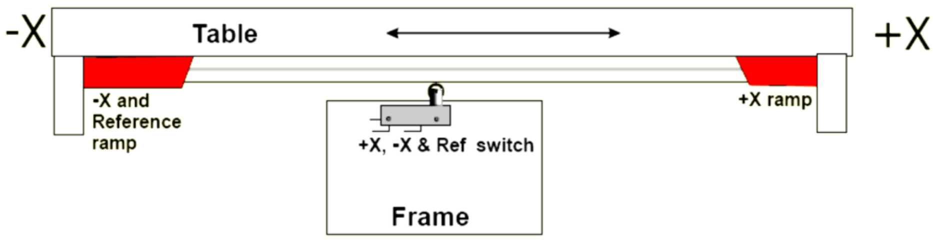
c. *Hall effect limit switch*

Hall Effect proximity sensors is used to detect the proximity, presence or absence of a magnetic object using a critical distance. They function via an electrical potential that developed across an axis transverse to an applied current flow in the presence of a magnetic field. As a magnetic target approaches the sensor the electrical potential increases and passes a threshold that marks a critical distance locating the target. (A. M. P. Brookes 2017)

Figure(3.30) Hall effect limit switch

3.10.2 Where to Mount the Switches

The choice of mounting position for switches is often a compromise between keeping them away from swarf and dust and having to use flexible rather than fixed wiring. For example the switches in Figure(3.31) mounted under the table even though they need a flexible cable, as they are much better protected there. X and Y axes of a gantry router could have switches on the gantry itself and a very short cable loop for the Z axis could then join the other two.



Figure(3.31) Limit switches positioning

Each axis could therefore need three switches (i.e. two Limit switches at the two ends of travel and a Home switch). Even a basic CNC machine would require nine parallel port inputs for them. This is not efficient This can be solved in three ways:

1. Connect the limit switches to external logic (perhaps in the drive electronics), and use this logic to switch off the drives when a limit is reached rather than interfacing them to control software.

2. Use one pin to share all the inputs for an axis, and make control program responsible for controlling both limits and detecting Home. For example, if control program instructed to "move to Home" on a milling machine, it could move the X axis to the left until a switch was triggered. In context, that would be interpreted as "Home." If that same switch was triggered while machining, however, it would be interpreted as "exceeded Limit."

3. Interface the switches by a keyboard emulator to be defined by the machine operator. (NSK motion and control)

3.10.3 Emergency Stop System

Every machine tool should have one or more Emergency Stop buttons, usually with a big red mushroom head. They should be fitted so that you can easily reach one from wherever you might be when you are operating the machine. This is particularly vital on a CNC machine. Each Emergency Stop button should stop all activity in the machine as quickly as is safely possible. The spindle should stop rotating and the axes should stop moving, This should happen without relying on software.

3.11 Software

Single CNC machine software consist of three parts:

I- CAD software used to Design and edit draws.

II- G-Code Generator convert the CAD file to G-Code file

III- G-Code interpreter interpret G-Code commands to machine control signals

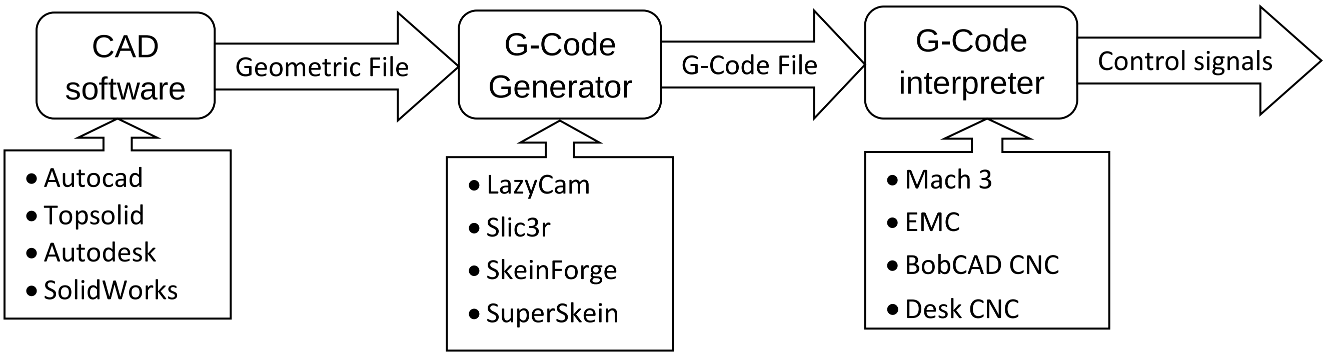


Figure 3.32 Software structure

3.12 G-code

G-code is where all the machining data are compiled and where the data are translated into a standard language which can be understood by the control Program of the machine tool. The machining data is as follows:

I. Machining sequence classification of process, tool start up point, cutting depth, tool path etc.

II. Cutting conditions spindle speed, feed rate, coolant, etc.

III. Selection of cutting tools.

3.12.1 G-Code Program Structure

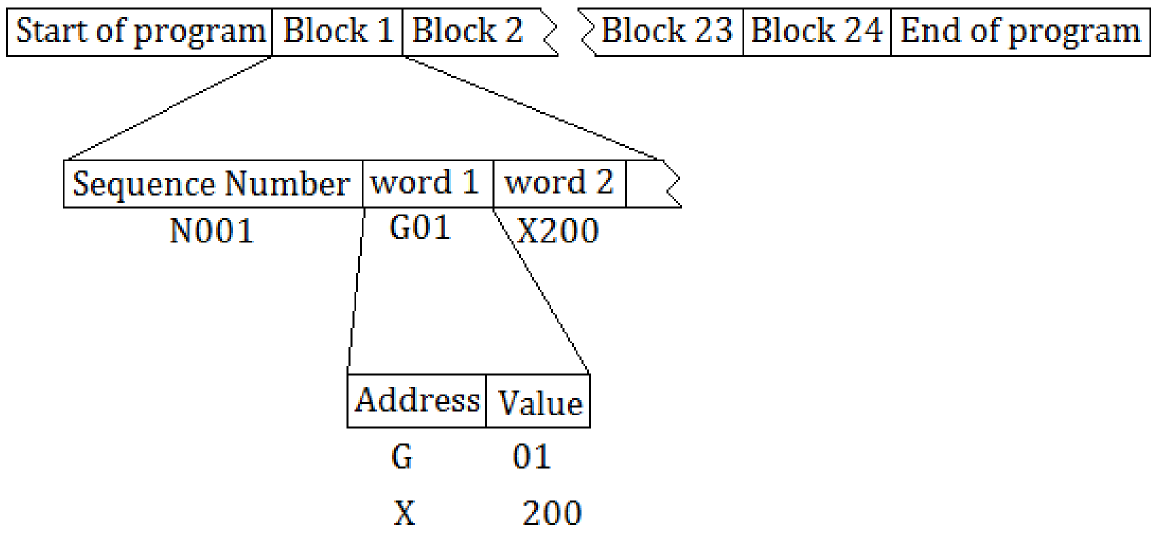


Figure 3.33 G-code structure

3.12.2 G-Code Block Components:

3.12.2.1 Sequence Number (N Address)

A sequence number is used to identify the block. It can be regarded as the name of the block. The execution sequence of the program is according to the actual sequence of the block and not the sequence of the number. (Seong Kyoon Kang 2008)

3.12.2.2 Preparatory Function (G Address)

A preparatory function determines how the tool is to move to the programmed target. The most common G addresses are listed below:

Code	Function
G00	Point to point position at rapid feed
G01	Linear interpolation
G02	Circular interpolation, clockwise
G03	Circular interpolation, anti clockwise
G40	Cutter compensation cancel

```
G41      Cutter compensation, Left
G42      Cutter compensation, Right
G45-G48  Other cutter compensation, if used
G70-G79  Milling and turning cycle
G80-G89  Drilling and tapping cycle
G90      Absolute dimensioning
G91      Incremental dimensioning
```

3.12.2.3 Co-ordinate Word (X/Y/Z Address)

A co-ordinate word specifies the target point of the tool movement (absolute dimension system) or the distance to be moved (incremental dimension). The word is composed of the address of the axis to be moved and the value and direction of the movement.

3.12.2.4 Spindle Function (S Address)

The spindle speed is commanded under an S address and is always in revolution per minute. It can be calculated by the following formula:

$$\text{SpindleSpeed} == \frac{\text{SurfaceCuttingSpeed (m/min)}1000}{\pi * \text{Cutter Diameter(mm)}}$$

The following table gives the surface cutting speeds for some common materials:

Table 3. 7 Common materials cutting speeds

Cutting tool material	**Workpiece material**			
	Al alloy	Brass	Cast Iron	Mild steel
HSS	120	75	18	30
Carbide	500	180	120	200

Example: S2000 represents a spindle speed of 2000rpm

3.12.2.5 Feed Function (F Address)

The feed is programmed under an F address except for rapid traverse. The unit is (mm per minute). The unit of the feed rate has to be defined at the beginning of the program. The feed rate can be calculated by the following formula:

Feed Rate =Chip Load/tooth x No of Tooth x Spindle Speed

The following table gives the chip load per tooth of milling cutters cutting some common materials:

Table 3. 8 Common materials chiploads

Milling Cutter material	Chip load per tooth (mm/rev)			
	Al alloy	Brass	Cast Iron	Mild steel
HSS	0.28	0.18	0.20	0.13
Sintered Carbide	0.25	0.15	0.25	0.25

Example: F200 represents a feed rate of 200mm/min

3.12.2.6 Tool Function (T Address)

The selection of tool in multi tool machines is commanded under a T address.

```
Example:  T02 represents tool number 2
```

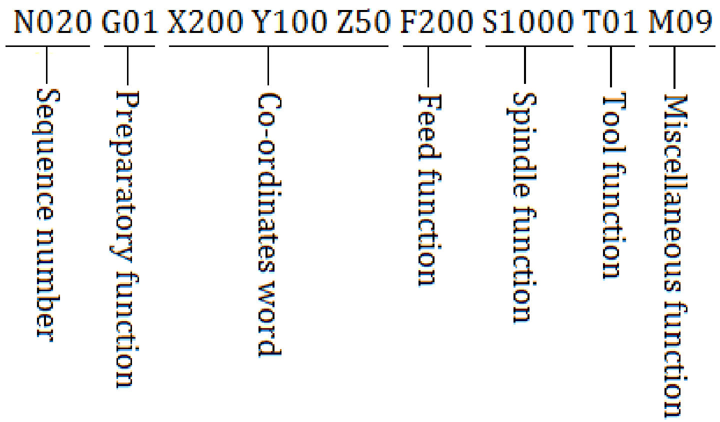
3.12.2.7 Miscellaneous Function (M Address)

The miscellaneous function is programmed to control the machine operation other than for co ordinate movement. The most common M functions are as follows:

```
Code   Function

M00    Program stop
M03    Spindle rotation clockwise
M04    Spindle rotation counterclockwise
M05    Spindle STOP
M06    Change of Tool
M08    Coolant ON
M09    Coolant OFF
M10    Clamp
M11    Unclamp
M30    Program end and ready for another start
```

G-code block example:



3.13 Communications

In order for the CNC to process any design implanted into it, the machine must have a connection system between itself and the software being used by the computer. Many connections used today are very common, the four major types of communication systems between computers and other hardware are:

- USB Ports
- Serial Ports
- Parallel Ports
- Ethernet

3.13.1 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 computer will act as the host once the connection is made, The computer will then use enumeration to provide an address to the device depending upon what other types of USB connections are attached at the same time. The device will respond to the host and describe what kind of data transfer it wants to perform.

Figure(3.34) USB port

3.13.2 Serial Ports

The serial port was the most widely used connection system until the use of USB connectors and parallel ports were integrated into most computers. Although not as widely used, serial ports are still used by some devices and most computers still allow for the connection of about two serial ports at a time. It is basically composed of a standard connector and a protocol to attach to outside devices .It is given the name serial because of its ability to serialize or take a byte of data and transmit the bits one at a time over just one wire.

Figure(3.35) Serial port

3.13.3 Parallel Ports

Parallel ports are the most common way of connecting bulk transfer devices to a computer although they are slowly being replaced by USB ports. Unlike the serial port, the parallel port is able to send a byte of information at one time which allows the standard parallel port to send 50 to 100 kilobytes of data per second. The most common use for parallel ports is for printing purposes. There are two major types of parallel ports for printing: the DB-25 and the Centronics 36 shown in Figure (3.36). Each pin has a specific task to allow the connection between the device and the computer.

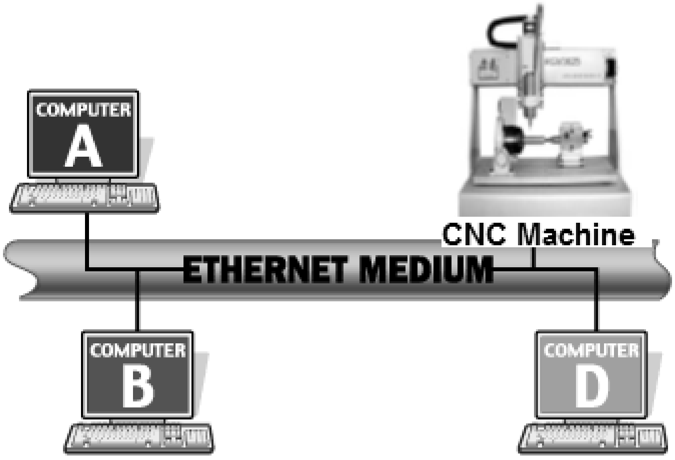
Parallel port is using transistor-transistor logic (TTL) voltage range, any voltage between 0 and 0.8 volts is called “low” and any voltage between 2.4 and 5 volts is called “hi.” Connecting a negative voltage or anything above 5 volts to a TTL input will produce smoke.

Figure(3.36)) Paralell port

3.13.4 Ethernet

Ethernet is used greatly for networking over either short or long distances to many different devices and large amounts of information. It has a great advantage over other communication systems by allowing it to communicate with many devices at one time 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. (Bela G. Liptak 2018)

Figure(3.37) Ethernet Port



Figure(3.38) Ethernet network

Chapter Four

Machine Design

4.1 Table Dimensions

Table are designed to work for single and multi-spindle. Single spindle mode intended for two dimension 2D and three-dimension 3D board routing in three linear degree of freedom, 1220×2440 mm standard board dimensions are selected, vertical axis is 300 mm.

Multi spindle mode intended for three-dimension carving in four degree of freedom, three degrees are linear plus one rotational degree. Gantry are including four spindles; every spindle has 2440×300 mm work area at the horizontal plane and 300 mm at vertical axis.

4.2 Structure Design

Machine structure requirements:

1- support axial, bending and torsion loads.
2- Insure stable, efficient and smooth operation.
3- Keep elastic deformation under permissible values.

For purpose of reducing designing calculations complexity, only the elastic deformations, operation stability and efficient are considered. if the machine structure kept the elastic deformation under permissible values, this inevitably prove that the structure will support axial, bending and torsion loads.

4.2.1 Gantry Structure:

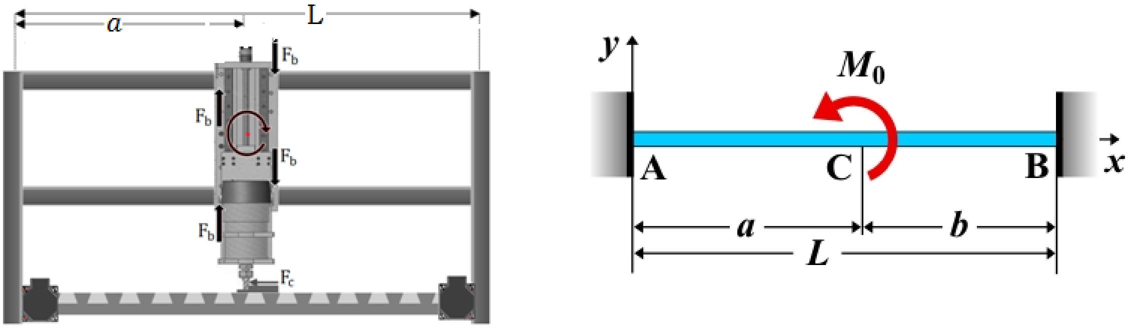


Figure 4.4 gantry structure

Shear:

$$V_{AB} = \frac{6M_0ab}{L^3} \tag{1}$$

Moment:

$$M_{AC} = \frac{-M_0b}{L^3}(2aL - 6ax - bL) \quad M_{CB} = \frac{M_0a}{L^3}(6bx - 4bL - aL) \tag{2}$$

Slope:

$$\theta_{AC} = \frac{-M_0bx}{L^3EI}(2aL - 3ax - bL) \quad \theta_{CB} = \frac{M_0a(L-x)}{L^3EI}(L^2 - 3bx) \tag{3}$$

Deflection:

$$y_{AC} = \frac{-M_0bx^2}{2L^3EI}(2aL - 2ax - bL) \quad y_{CB} = \frac{M_0a(L-x)^2}{2L^3EI}(2bx - aL) \tag{4}$$

The spindle holder installed in two horizontal square tubes, with 80×40 mm dimension, 3 mm thickness $3.68584\times10^{-7}\ m^4$, 1500 mm length, 8.27 kg weight and 0.0006 mm deflection at middle. And six vertical square tubes with 80×40 mm, 3 mm thickness 1000 mm height and 16.532 kg weight.

4.2.2 Spindle Holder

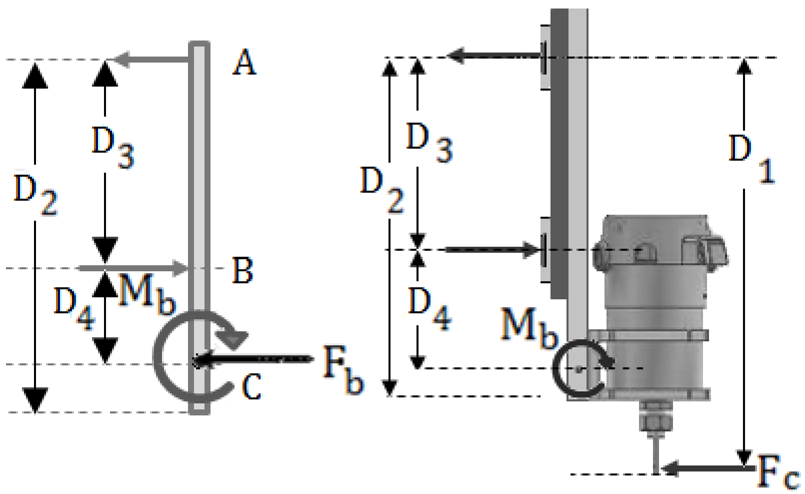


Figure 4.5 Spindle holder including fixture plate

Moment:

$$-F_b(a - x_1) + M_b \tag{5}$$

$x_1 = x - D_3$

Deflection:

$$y_{BC} = \frac{1}{6EI}[3(M_b - F_b a)x_1^2 + F_b x_1^3] \qquad (6)$$

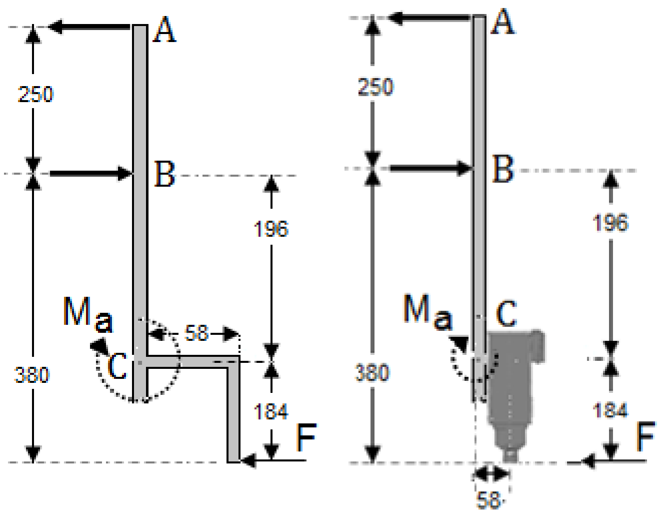


Figure 4.6 Spindle holder

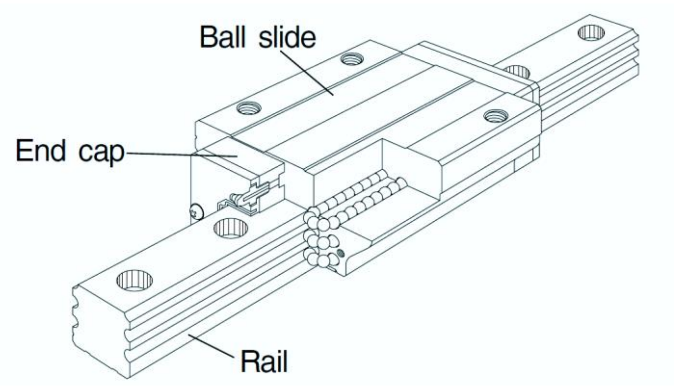
F= 100 N $\qquad M_a = F_a \times 0.184 = 100 \times 0.184 = 18.4\ N.m$

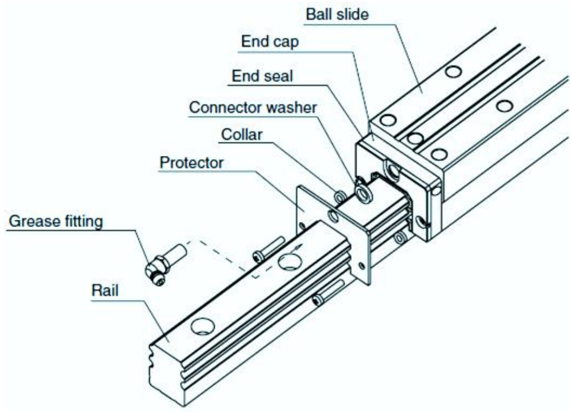
The spindle installed in two square tubes, with 70×70 mm dimension, 2 mm thickness, $8.39211\times10^{-7}\ m^4$ second moment of inertia , 556 mm length, 2.409 kg weight and 0.0006 mm deflection at bit tip.

Total weight for the main parts of single spindle gantry is 41.6, more weight are expected by 30% for accessories like rails, cables, fixtures and motors. Total weight of gantry will be about 55 kg. The total weight for 4 spindles gantry will be about 130 kg.(Ferdinand P. Beer 1981)

4.3 Linear Guide Rails Selection

NSK linear guides with ball rolling element are selected





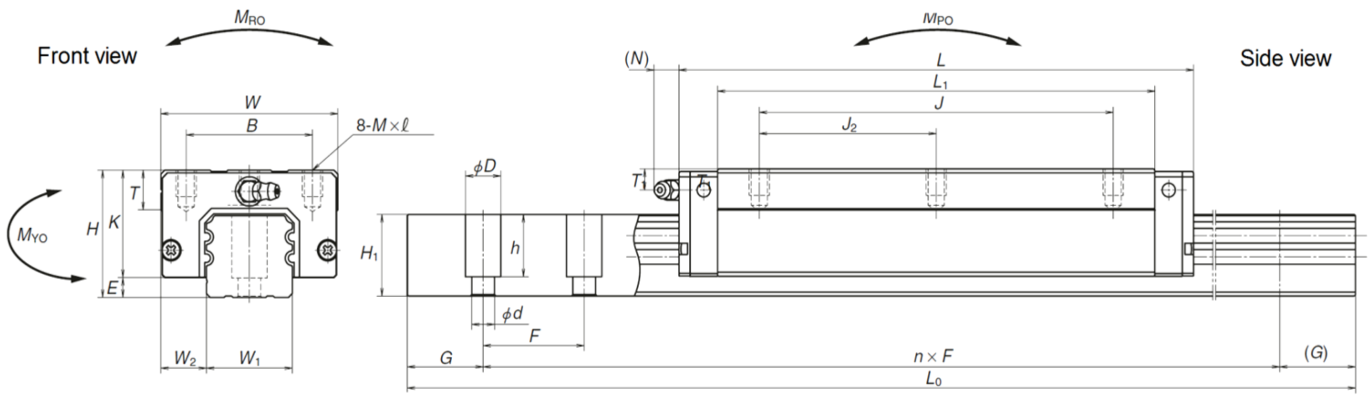


Figure 7.4 linear guide

Table 4.1 Linear guides dimensions

Axis	Model	Assembly			Ball slide												Rail	
		H	E	W_2	W	L	Mounting hole				L_1	K	T	Grease fitting			W_1	H_1
							B	J	J_2	M×Pitch×l				Hole size	T_1	N		
Z	**HA30AN**	45	7.5	16	60	177.2	40	120	60	M8×1.25×11	149	37.5	14	M6×0.75	9.5	11	28	28
Y	**HA35AN**	55	7.5	18	70	203.6	50	140	70	M8×1.25×12	173	47.5	15	M6×0.75	15	11	34	30.4
X	**HA55AN**	80	12	23.5	100	284.4	75	206	103	M12×1.75×18	245	68	18	Rc1/8	21	13	53	43.2

Table 4.2 Linear guides properties

Axis	Model	Rail				*Basic load rating*(1)								weight	
		F	$d{\times}D{\times}h$	G	L_0	Dynamic		Static	Static moment (N.m)					Ball slide kg	Rail (kg/m)
						[50km] C_{50}(N)	[100km] C_{100}(N)	C_0 (N)	M_{RO}	M_{PO} One slide	M_{PO} two slide	M_{YO} One slide	M_{YO} two slide		
Z	**HA30AN**	40	9×14×21	20	4000	79,500	63,500	166,000	1140	3550	17400	3550	17400	1.8	5.8
Y	**HA35AN**	40	9×14×23.5	20	4000	111,000	88,000	226,000	1950	5650	27100	5650	27100	3	12
X	**HA55AN**	60	16×23×32.5	30	3960	232,000	184,000	445,000	6500	15400	75000	15400	75000	9.4	17.2

(1)The basic load rating are comply with ISO standard (ISO 14728-1, 14728-2)

C_{50}; The basic dynamic load rating for 50 km rated fatigue life, C_{100}; The basic dynamic load rating for 100 km rated fatigue life

4.3.1 Fatigue Life

$$Fatigue\ life = 100 \times \left(\frac{C_{100}}{F_{rail}}\right)^3 \quad (7)$$

$$X\ axis\ Fatigue\ life = 100 \times \left(\frac{C_{100}}{F_{X\ rail}}\right)^3 = 100 \times \left(\frac{184000}{1275}\right)^3 = 300{,}554{,}278$$

Km

$$Y\ axis\ Fatigue\ life = 100 \times \left(\frac{C_{100}}{F_{Y\ rail}}\right)^3 = 100 \times \left(\frac{88000}{784}\right)^3 = 141{,}416{,}416$$

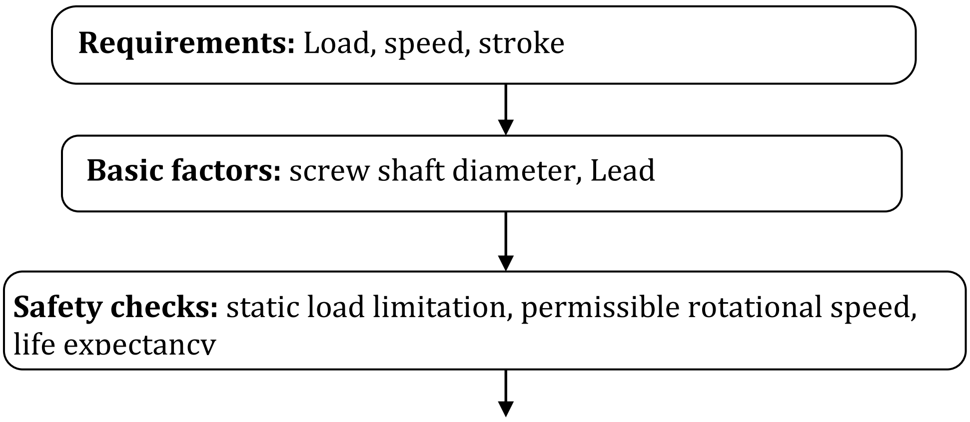
Km

$$Z\ axis\ Fatigue\ life = 100 \times \left(\frac{C_{100}}{F_{Z\ rail}}\right)^3 = 100 \times \left(\frac{63500}{100}\right)^3 =$$

25,604,787,500Km

4.4 Ball Screw Selection

NSK ball screw brand are selected and their selection procedure are applied (G. Johnson Oct 2012)



Factors to be checked to satisfy a need:

- Drive torque

Figure 4.5 screw selection procedure

4.4.1 Requirements:

4.4.1.1 Speed

Feed speed required for all axes is 15 m/s

4.4.1.2 Stroke

CNC has 2.5 meter stroke for X axis, 1.3 meter stroke for Y axis and 0.3 meter stroke for Z axis.

4.4.1.3 Loads

There are two types of Loads affecting on the lead screw:

i. Force due to acceleration.

ii. Cutting force.

Acceleration

$$a = \frac{V_f}{60 * t} = \frac{15}{60 * 1} = 0.25\ m/sec^2$$

V_f = feed rate velocity (meter/minute)
t= time to reach feed rate velocity (sec)

Motile mass accentuation by X-axis linear screw is about 130 Kg, Y axis about 70 Kg and Z axis about 60 Kg.

Force due to acceleration

$$F_{aX} = m * a = 0.25 * 130 = 32.5\ N$$

$$F_{aY} = m * a = 0.25 * 70 = 17.5\ N$$

$$F_{aZ} = m * a = 0.25 * 60 = 15\ N$$

m= motile mass
a =Gantry acceleration

By comparison, to homologue CNCs, cutting force estimated by 50 N.

4.4.2 Basic Factors:

Screw shaft diameter and lead selected from NSK company datasheet tables according to table size and loads.

Table 4.3 screw shaft properties

Screw axis	Model	Mass (Kg)	Screw length	Screw diameter	Lead	C_{0a}(N)	C_a (N)	T_{Pmax} (N.cm)
X axis	W3227FA-1P-C5z25	19.1	2.5 m	32 mm	25 mm	20900	11300	31.5
Y axis	W2012FA-1P-C5Z10	3.7	1.3 m	20 mm	10 mm	10800	6880	11.8
Z axis	W1002MA-3PY-C3Z2	0.22	0.3 m	10 mm	2 mm	2850	1490	2.4

4.4.3 Safety Checks:

Safety checks are including:

a. Static Load Limitation

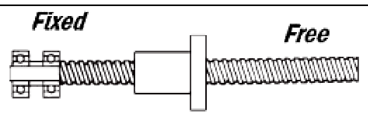
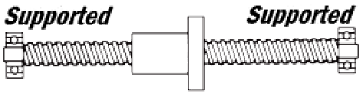
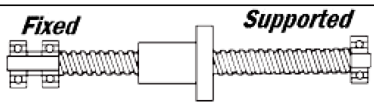
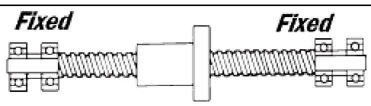
Static load limitation including:

i. Buckling load

$$\text{Buckling load} = \alpha \frac{N.\pi^2.E.I}{L^2} = m \frac{d_r^4}{L^2} \times 10^4 \qquad (8)$$

α=Safety factors (α=0.5)
E=elastic modulus (E=2.06×10^5 Mpa)
I=Moment of inertia
d_r=Screw shaft root diameter (mm)
L= Unsupported length (mm)
m,N= *Buckling load supporting conditions factors*

Table 4.4 Static load properties of screw shaft

Type	M	N
	1.5	0.25
	5	1
	10	2
	19.9	4

ii. Yield stress

$$\text{Yield stress} = \sigma . A = 1.15 . d_r^2 \times 10^2 \qquad (9)$$

σ=Maximum stress(=147 Mpa)
A=cross section area at root diameter (mm^2)

iii. Permanent deformation stress at the ball contact point ($P_\circ$)

$$P_\circ = \frac{C_{0a}}{f_s} \qquad (10)$$

C_{0a}=Basic static load rating: axial load that results a permanent deformation equal to 0.01% of ball diameter at the ball and ball groove.
f_s=static permissible load factor(1-2 normal operation) (1.5-3 with vibration and impact).

b. Permissible Rotational Speed

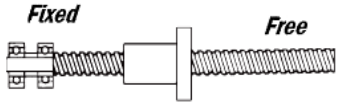
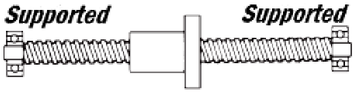
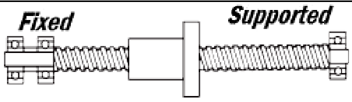
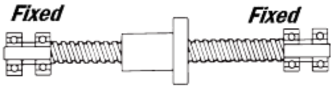
to calculate the ball screw permissible rotational speed it is necessary to calculate two items bellow, and witch smaller is the permissible rotational speed

i. critical speed: which the resonance vibration of the shaft.

$$n_c = f \frac{d_r}{L^2} \times 10^7 \text{ (RPM)} \qquad (11)$$

n_c:critical speed
f: factor determined by the shaft supporting condition

Table 4.5 rotational speed properties of screw shaft

Type	**f**	**λ**
	3.4	1.875
	9.7	π
	15.1	3.927
	21.9	4.730

ii. d.n value: which involved in damaging the ball recirculation components. It is calculated from NSK datasheet tables.

c. Life Expectancy(Dynamic Load Limitation) (L).

Life of ball screw can be estimated by basic dynamic load rating (C_a). dynamic load rating is the axial that allows a 90% of a group of the same ball screws to rotate 1 million time under the condition without causing flaking by rolling contact fatigue.

$$L = \left(\frac{C_a}{F_a . f_w}\right)^3 . 10^6 \qquad (12)$$

F_a: Axial load (N).
f_w: Load factor. (1.2-1.5 normal operation) (1.5-3 with vibration and impact).

Table 4.6 Screw shaft results

Screw axis	**static load limitation**			**permissible rotational speed(n_c)**	**life expectancy**
	Buckling load	**Yield stress**	**Permanent deformation stress($P_\circ$)**		
X axis	33387	117760	13933	1121	1.25E+12
Y axis	18840	46000	7200	2591	4.47E+11
Z axis	22111	11500	1900	24333	5.89E+09

4.5 Motor sizing

This section is insight into how to approach the selection of a suitable motor size according to required torque.

Geared stepper motors are selected because of cost, Reliability, simple setup, long life, Repeatability, Overload Safety and Availability.

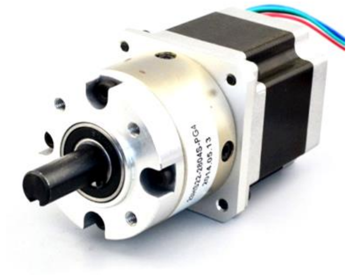


Figure 4.6 Planetary Geared stepprt motor

Drive torque consist of:

- Drive torque at constant speed
- Drive torque at acceleration

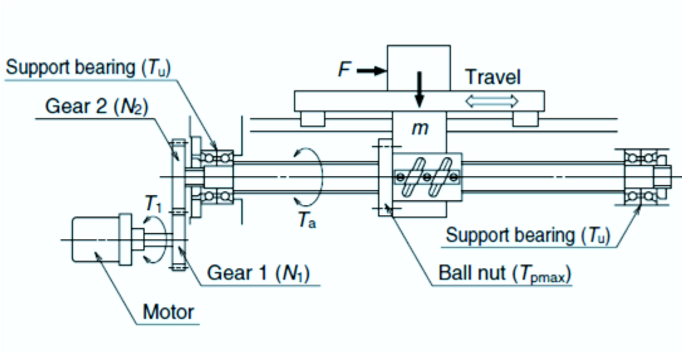


Figure 4.7 screw drive components

A. Drive torque at constant speed (T_1):

$$T_1 = (T_a + T_{Pmax} + T_u) \times \frac{N_1}{N_2} \quad (13)$$

$$T_a = \frac{(F+\mu.m.g).l}{2\pi.\eta_1} \quad (14)$$

T_a:Drive torque at constant speed (N.cm)
F_a:Axial load (N)
F:Forces at axial direction such as cutting force

μ : Friction coefficient of the guide way
l: Lead(cm)
η_1:Normal efficiency
m:mass of travelling section(gantry +spindle)
g :gravitational acceleration(9.80665 m/s^2)
T_{Pmax}:Upper limit of dynamic friction torque of ball screw (N.cm)
T_u:Friction torque of support bearing(N.cm)
N_1:Number of teeth in gear 1
N_2: Number of teeth in gear 2

Generally T_1 should kept under 30% of the motor rating torque.

B. Drive torque at acceleration(T_2):

$$T_2 = T_1 + J.\acute{\omega} \qquad (15)$$

J : Moment of inertia applied to the motor (Kg.m^2)
$\acute{\omega}$: Motor angular acceleration (Rad/S^2)

Table 4.7 screw shaft torques

Screw axis	T_1(N.cm)	T_2(N.cm)
X axis	2.22	6.50
Y axis	1.21	3.41
Z axis	0.49	11.49

Stepper motors models selected according to drive torque, required resolution and availability.

Table 4.8 axes motors properties

axis	Motor model	Motor Holding torque	Gear ratio	Current (A)	Resistance (Ohm)	Step angle °
X axis	OMC 17HS13-0404S-PG27	26	26.85	0.4	30	1.8
Y axis	OMC 14HS13-0804S-PG19	18	19.19	0.8	6.8	1.8
Z axis	OMC 14HS13-0804S-PG19	18	19.19	0.8	6.8	1.8

4.6 Transmission System Selection

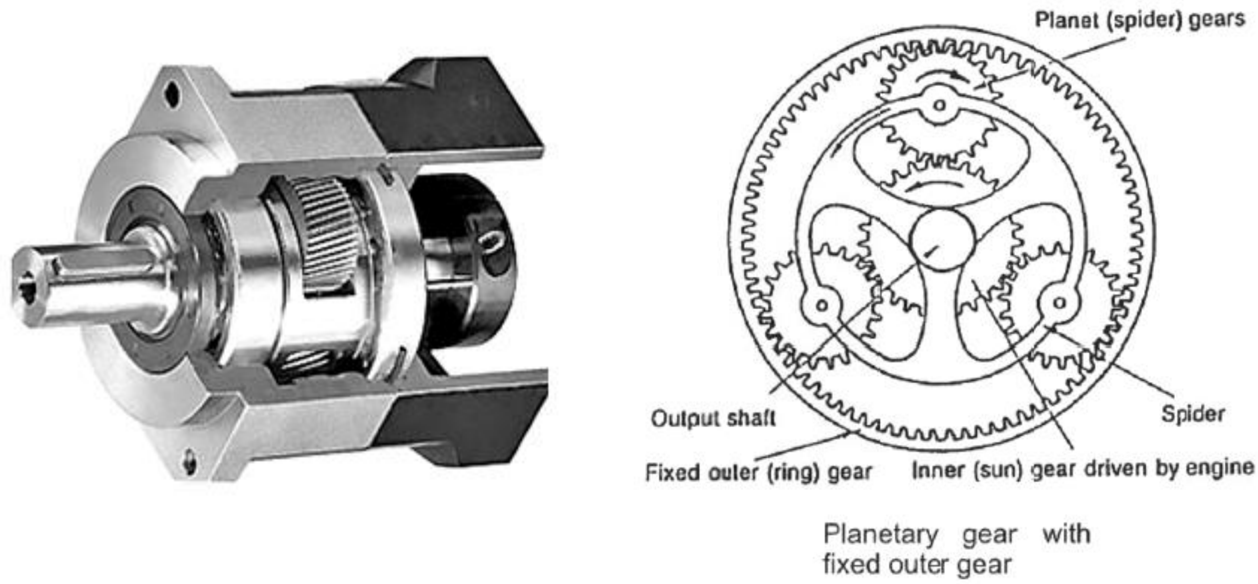


Figure 4.8 Planetary gearbox

Planetary gearboxes are selected due to the following benefits:

a. Compact size and low weight – as much as 50% reduction with same torque output.
b. High power density – several planets share the load rather than one gear, the more planets the more sharing.
c. Longer gear life at similar loads.
d. Gearing can be very accurate with virtually no backlash.
e. High efficiency – 95% per stage is common.
f. Very high gear ratio can be achieved when multi stage gearing used.
g. Coaxial arrangement – no offset output shaft

Table 4.9 Planetary gearboxes properties

axis	Gear ratio	Max torque (N.m)	Max moment torque (N.m)	Maximum shaft radial torque(N.m)	Maximum shaft axial torque(N.m)
X axis	26.85	3	5	100	50
Y axis	19.19	3	5	5	25
Z axis	19.19	3	5	5	25

4.7 Resolution Calculations

The resolution depends on:

1. The mechanical drive (e.g. pitch of lead screw, gearing between the motor and the screw).
2. The properties of the stepper motor or the encoder on the servo motor.
3. The micro-stepping or electronic gearing in the motor drive electronics.

$$\text{Resolution} = \frac{lead}{\left(\frac{360}{step\ angle}\right)\times\frac{N_1}{N_2}} \qquad (16)$$

Minimum required resolution at all axes is 0.005 millimeter

Table 4.10 Axes resolution

axis	Resolution (mm)	Motor steps/mm
X axis	0.00466	214.8
Y axis	0.00261	383.8
Z axis	0.00052	1919

4.8 Encoders Selection And Calculations

Incremental encoder selected due to its low cost and simple interpretation to provide position and motion related information such as direction, velocity and acceleration.

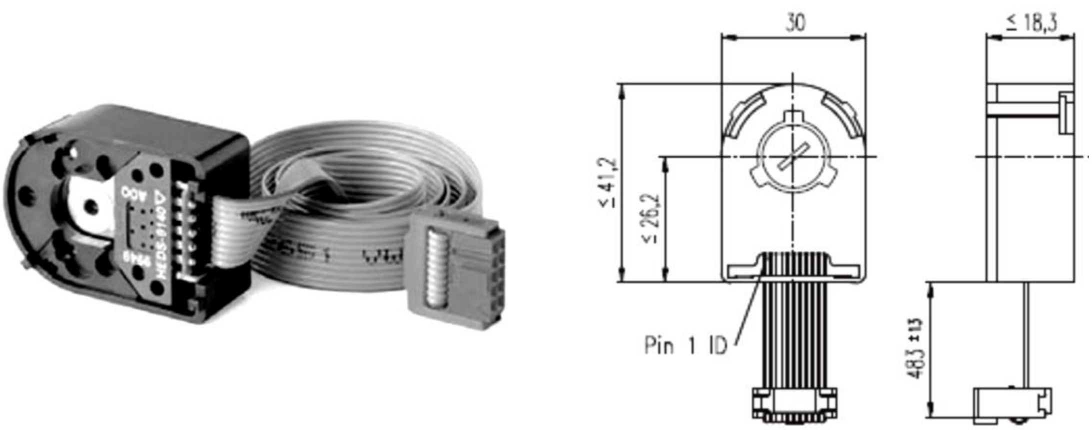


Figure 4.9 incremental encoder

Encoder has 5 pins as follows:

- Ground
- Power
- Channel A
- Channel B
- index pin (pulse/revolution) often used as a calibration reference.

Table 4.11 encoders properties

axis	Model	Supply voltage (V)	Phase shift	Max speed (RPM)	Max acceleration (RPM)	Shaft diameter (mm)	Count/turn
X axis	HEDL 55408	5	90°	12000	39800	8	500
Y axis	HEDL 55406	5	90°	12000	39800	6	500
Z axis	HEDL 55406	5	90°	12000	39800	6	500

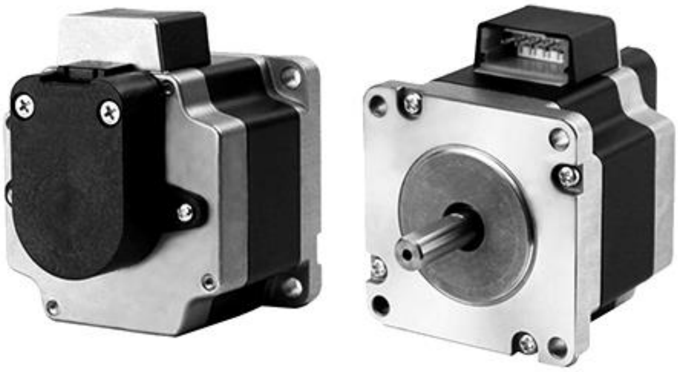


Figure 4.10 encoder installation

Encoder installed in the back of stepper motor, and rotate with same speed

$$\text{Resolution} = \frac{lead}{CPT \times \frac{N_1}{N_2}} \qquad (17)$$

CPT: Count per turn

Table 4.12 Motors CPT

axis	Resolution (mm)	Motor steps/mm
X axis	0.00186	537
Y axis	0.00104	959.5
Z axis	0.00021	4797.5

4.9 Breakout Board Design

Breakout board is an electronic circuit used to condition input and output signals to computer ports, and generate auxiliary control signals to the motors drivers.

Breakout board consist of:

a. **Two male DB25 parallel ports (J8, J9).**

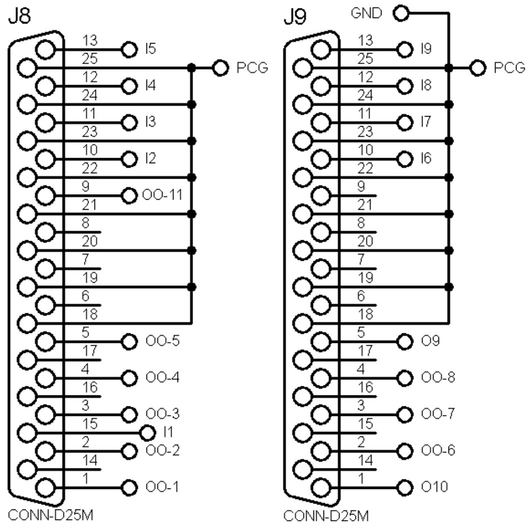


Figure 4.11 DB25 parallel port pinout

DB25 port used for Communication between computer and breakout board

b. **Two 74HCT241 output signal buffer integrated circuits (ICs) (U13, U18) with input pull up resistors.**

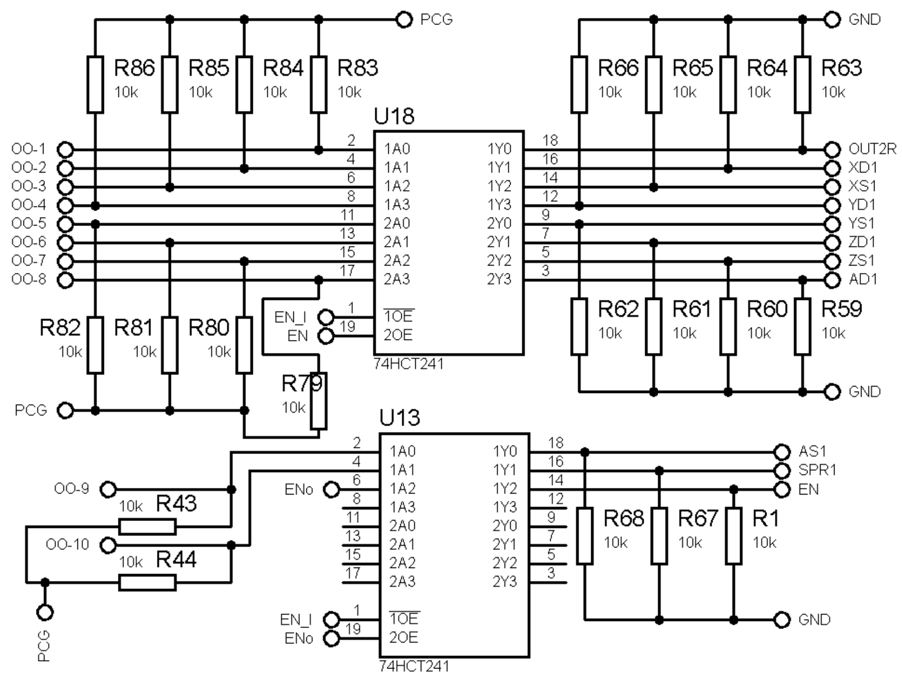


Figure 4.12 74HCT241 output signal buffer

The 74HC/HCT241 IC are octal non-inverting buffer/line drivers with 3-state outputs. The 3-state outputs are controlled by the output enable inputs 1 OE and 2OE. The signals current from computer is not sufficient, 74HC241 function is buffer signal current.

c. 74HCT241 input signals buffer (U16) with input pull up resistors.

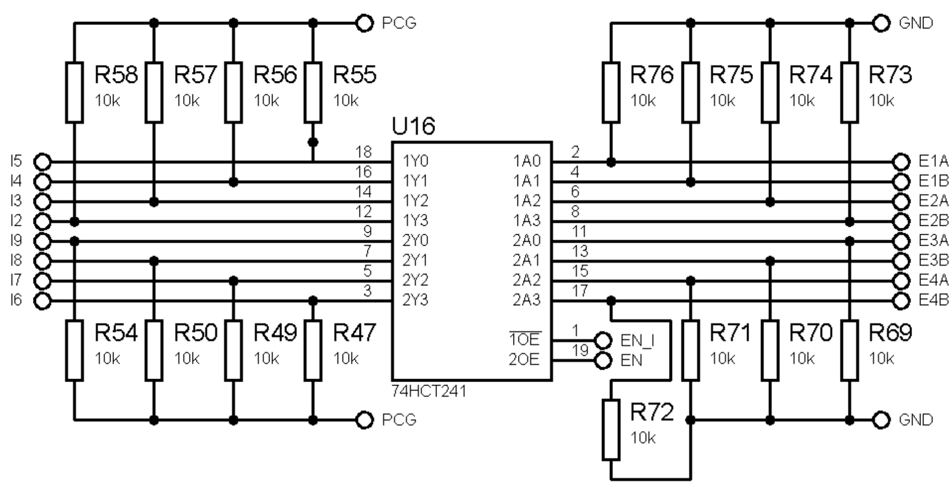


Figure 4.13 Input signals buffer

The function of 74HC241 IC in input is ensure the input signals has sufficient current to computer

d. Emergency stop signal optical isolator (U19).

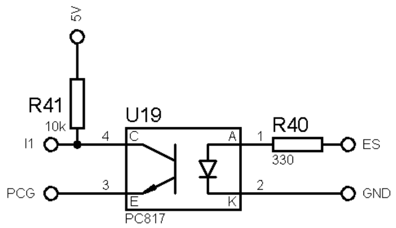


Figure 4.14 isolation photo coupler

PC817 photo coupler used as isolation element; it is isolate the computer from push button circuit.

e. Charge pump IC

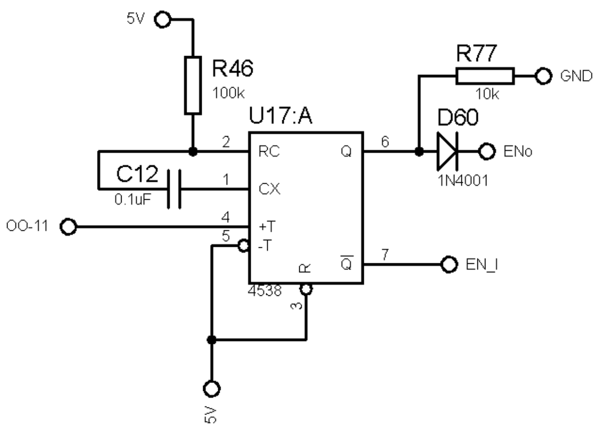


Figure 4.15 Computer system monitor charge pump

4538 IC function is monitor computer healthy, the CAM program in the computer send pulses at constant frequency (12.5 KHz), if CAM program stopped or malfunctioned for any reason the signal will stop and the IC will stop all inputs and outputs in breakout board to prevent accidentally operation which can cause serious injuries.

f. Jumper with pull up resistors to configure the stepper motors step size (full step or half step).

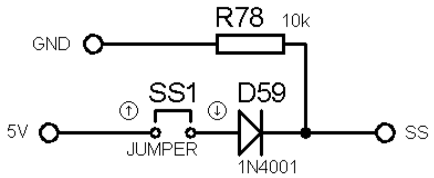


Figure 4.16 Full step/half step jumper

SS1 jumper select between half step and full step for stepper motors

g. Reversed current protection diodes for output signals.

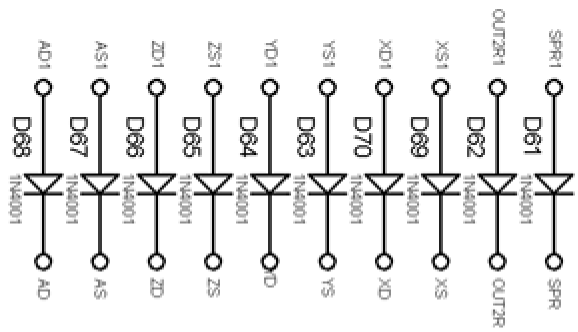


Figure 4.17 Output protection diodes

Accidentally Revers polarity in output signals can harm the breakout board ICs, Diodes function is protection if any inverse of polarity happened.

h. 5-volt Voltage Regulator.

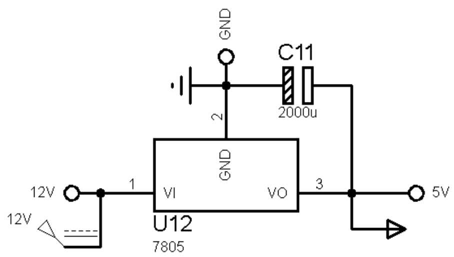


Figure 4.18 Breakout board voltage regulator

7805 IC used to regulate the breakout board DC current supply.

i. **Indicators light emitted diodes used to indicate signals status (from D71 to D84).**

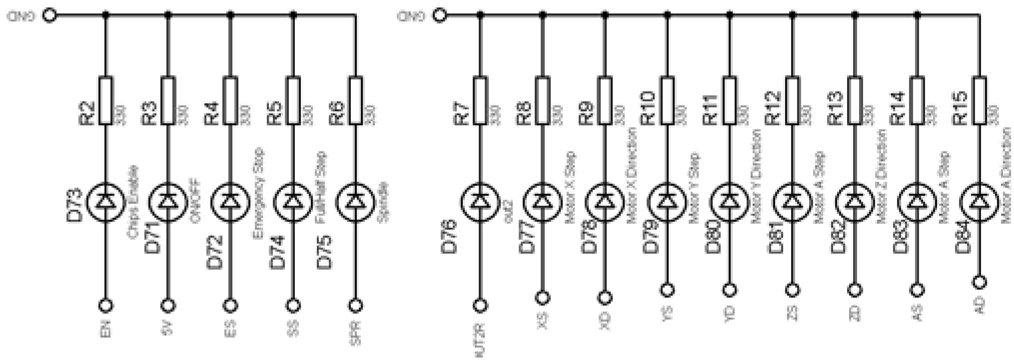


Figure 4.19 Output signals LEDs

The function of output signals LEDs is to assure the breakout board is sent the signal.

Refer to appendix 1 for full circuit diagram.

4.10 Motors Drivers Design

Motor driver provide the stepper coils with power in the required sequence to run the motor in the required direction and speed.

Motor driver consist of:

a. **5-volt Voltage regulator.**

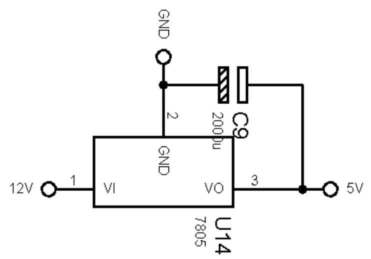


Figure 4.20 Motor driver Voltage regulator

7805 IC used to regulate Motor driver DC current supply.

b. NOT gate integral circuits(U5 to U11)

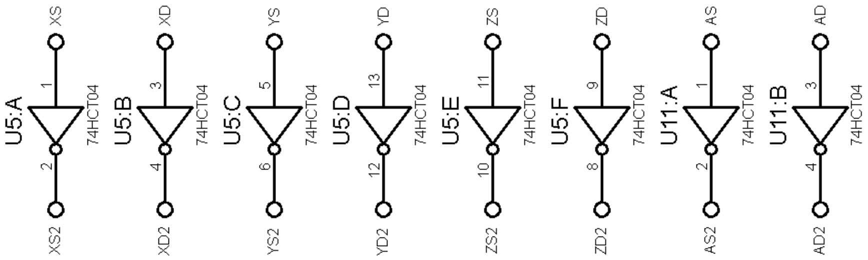


Figure 4.21 74HCT04 signal inverter

L297 IC step and direction pins are active-low, so the 74HC241 signal buffer output signal must be inverted,7404 Not gate used for this purpose.

c. Relays

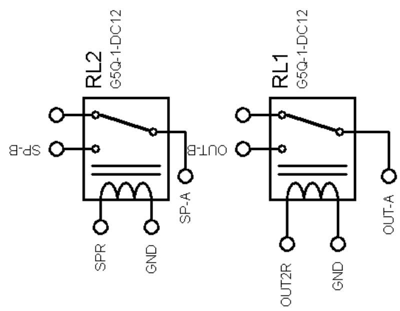


Figure 4.22 5-volt relays

5-volt relays used to operate spindle and general purpose contactor.

d. Sequence generator integral circuits(U1 to U4)

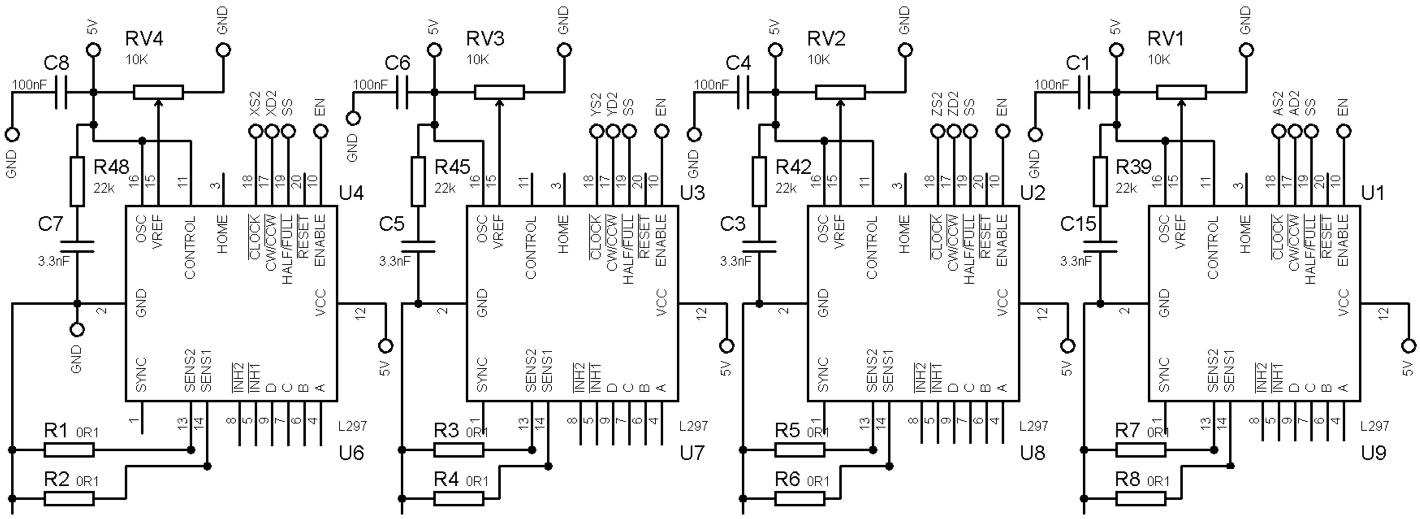


Figure 4.23 L297 Stepper motor Sequence generator

Stepper motors winds operating sequence generated by L297 IC, computer send tow signals to control the operation of L297, step signal generate the stepper motor winds energizing sequence and direction signal determine the motor rotation direction.

Pin 13 and 14 in L297 are sense pins, it sense the current in the outputs pins(2,3,13,14) in L298 IC if the current in output pins exceeded the critical value determined by pin 15.

e. L298 output signal buffer integrated circuits (ICs) (U6 to U9)

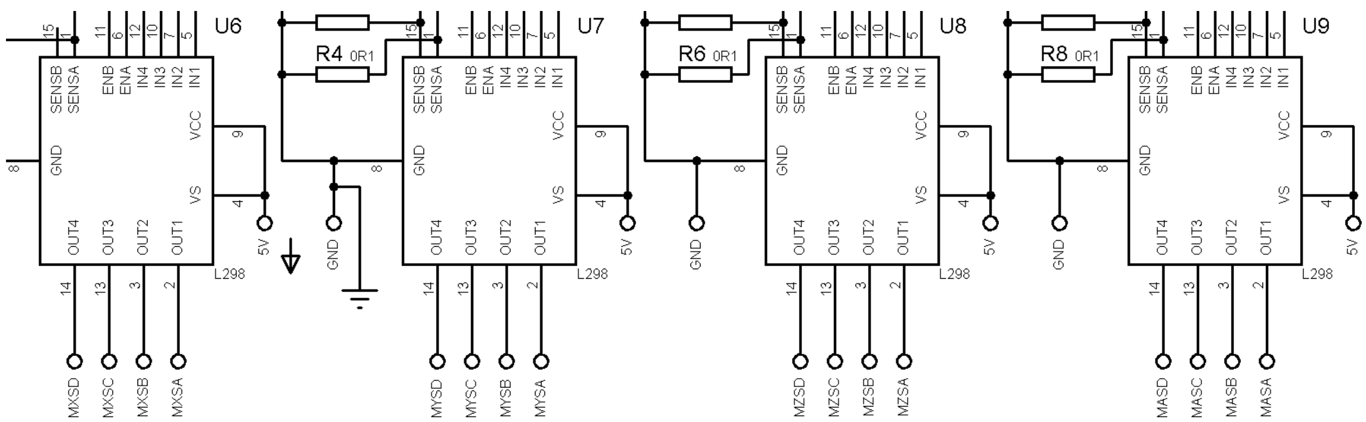


Figure 4.24 L298 output signal buffer

L298 IC buffer the L297 IC signal to ensure motor driver H-bridge gates triggered.

f. Power MOSFETs (Q1to Q32)

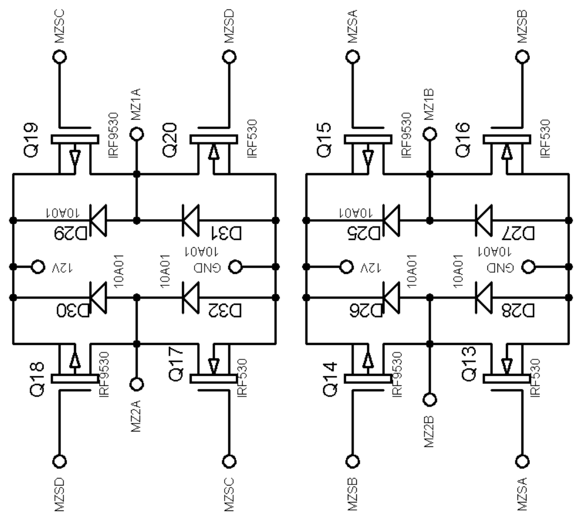


Figure 4.25 Bipolar stepper Motor H-bridge

H-bridge required to operate the bipolar stepper motor in two directions, IRF9530 P-channel and IRF530 N-channel MOSFETs and 10A01 diodes used to build the 10A current H-bridge.

Refer to appendix B for full circuit diagram.

4.11 Spindle

Spindle type, size and power selection is done by comparison with cnc router in the market.[11]

Figure 4.26 Spindle

Specifications:

- Brand Colombo
- Model RV90
- Power 4.5 KW
- Speed 18000 RPM
- Volt 220V
- Poles 2
- Cooling method: Fan(Shaft driven)
- Weight: 14.4 Kg

4.12 Limit switches positioning and interfacing

Figure 4.27 Siemens 3SE52 limit switch

Specifications:

- Rated current 3A at 24 DC Volt
- Mechanical endurance 15×10^{6} operating cycle
- Electrical endurance 10×10^{6} operating cycle
- Switching accuracy 0.05 mm

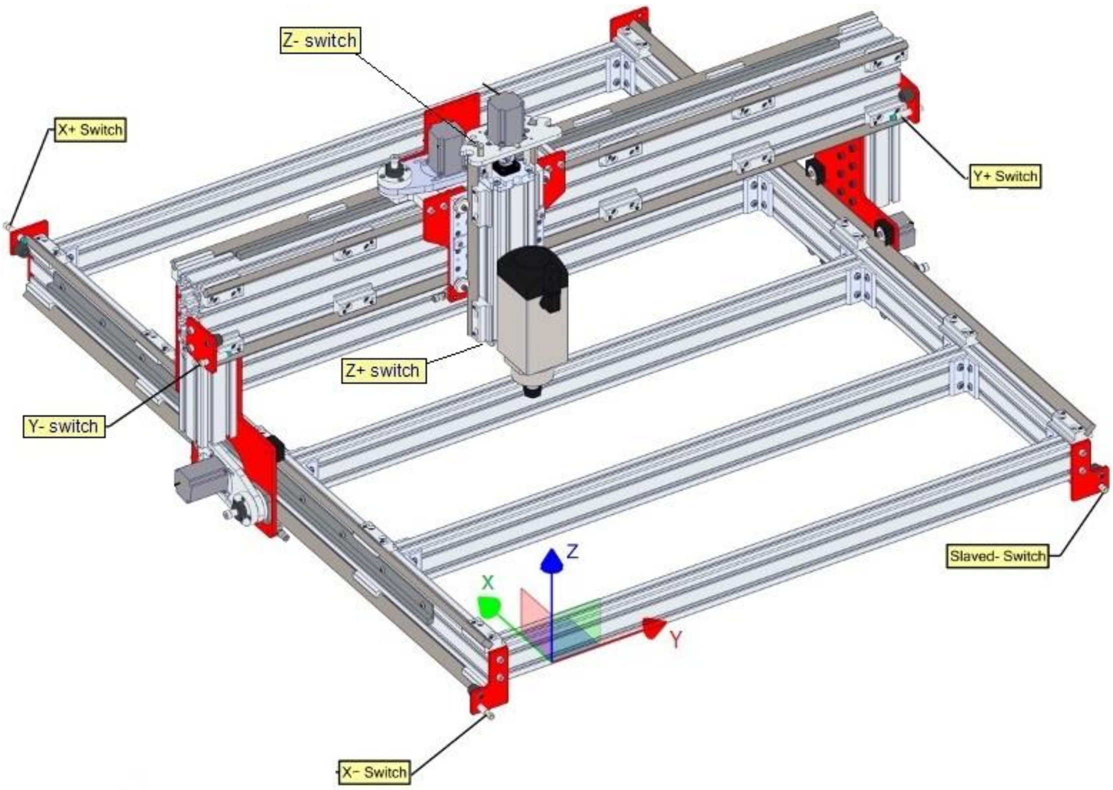


Figure 4.28 Limit switches positions

Limit switches positioned in every axes edges.

4.13 Ports Pin out

Communication between computer and controller breakout board will be established throw two DB-25 parallel ports due to Mach3 limitations. the breakout board need 15 inputs and 11 outputs. (SDP/SI)

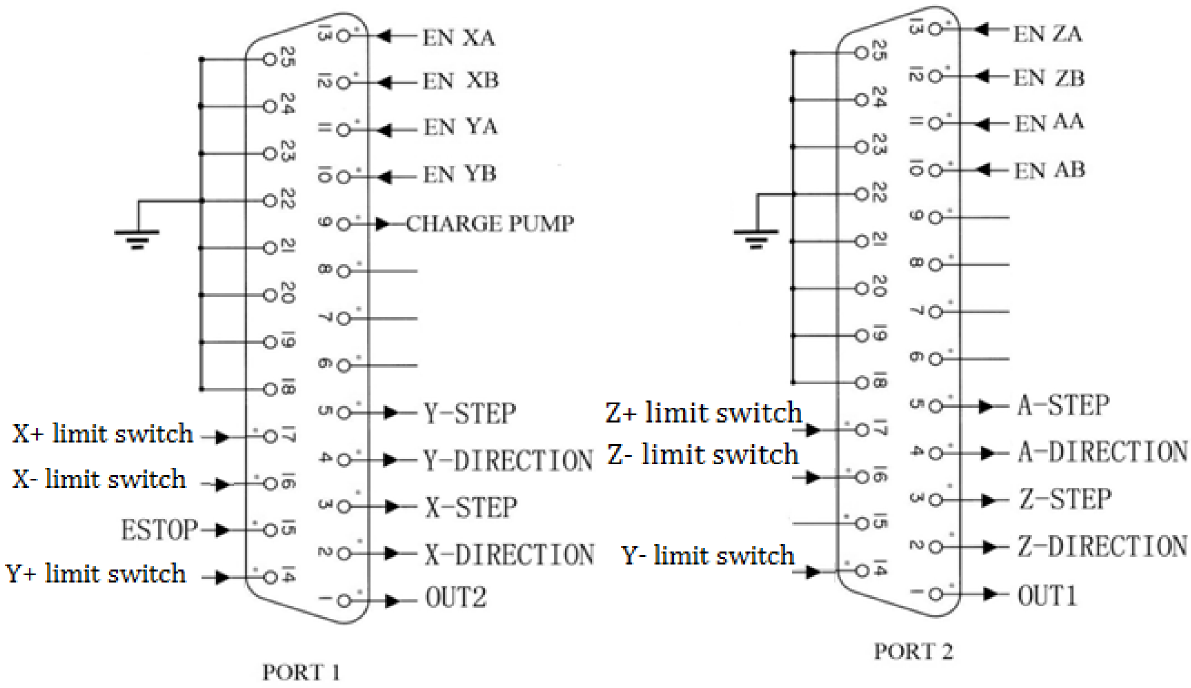


Figure 4.29 Breakout board ports pins

Input signals are:

i. EN XA pin A of X-axis encoder.
ii. EN XB pin B of X-axis encoder.
iii. EN YA pin A of Y-axis encoder.
iv. EN YB pin B of Y-axis encoder.l
v. EN ZA pin A of Z-axis encoder.
vi. EN ZB pin B of Z-axis encoder
vii. EN AA pin A of rotary A-axis encoder.
viii. EN AB pin B of rotary A-axis encoder.
ix. ESTOP emergency stop.
x. X+ limit switch
xi. X- limit switch
xii. Y+ limit switch
xiii. Y- limit switch
xiv. Z+ limit switch
xv. Z- limit switch

Output signals are:

i. X-STEP step of X-axis Motor.
ii. X-DIRECTION direction of X-axis Motor.

iii. Y-STEP step of Y-axis Motor.
iv. Y-DIRECTION direction of Y-axis Motor.
v. Z-STEP step of Z-axis Motor.
vi. Z-DIRECTION direction of Z-axis Motor.
vii. A-STEP step of rotary A-axis Motor.
viii. A-DIRECTION direction of A-axis Motor.
ix. CHARGE PUMP clock of safety charge pump.
x. OUT 1 spindle control signal.
xi. OUT 2 auxiliary output signal.

Chapter Five
Conclusion and Recommendations

5.1 Conclusion

CNC machine designed with workspace of 1220×2440 mm in horizontal plane and vertical axis of 300 mm, acceleration is 0.25m and speed is 15 m/m in in all axes. Resolution is 0.00466mm at X-axis, 0.00261mm at Y-axis and 0.00052mm at Z-axis. The control loop selected is the close control loop, stepper motors as actuators and computer as controller and incremental encoders as feedback sensors and limit switches for protection and homing.

The design of CNC included the primary structural properties as bed, gantry and spindles holder dimensions and thickness and weights to estimate the maximum elastic deformations and suitable size of motors to achieve the required acceleration and speed.

Calculations and selection procedure is applied to select linear guide rails, ball screw, transmission system, encoder and spindle. Motors size calculated according to moving parts, friction force and required speed and acceleration. Resolution calculated according stepper motor angle and transmission ratio and screws backlash.

The circuit diagram of motors breakout board or interfacing board is designed to interface between computer and motors power board, spindle inverter and protection limit switches and buttons, the power board designed to generate the suitable axes stepper motor poles magnetizing sequence according to required distance and direction with selectable step size, the two boards designed to run four axes. Protues V8 software is used to design and simulate the circuits diagrams.

5.2 Recommendations

1. More detailed structure design to increase resolution and decrease the cost of structure, replace full step motor driver by micro step motor driver to increase resolution, replace serial communication port with universal serial bus (USB) port because most modern personal computer do not include the old serial communication port, Replace the incremental feedback encoders with absolute encoder to minimize the need to frequently homing.

2. Put additional gantry in the CNC table and divide the carving job between the two gantries to decrease job time and increase production, modify G-code interpreter software to give it the ability to operate the two gantries simultaneously and synchronously and distribute the job carving paths between gantries by the most time efficient way.

3. Redesign the table and gantry to be a multipurpose, wood router, water jet cutting or plasma cutting machine.

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