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Cnc Engraving Machine Based On Open Source Electronics

Akhil A I[1], Prof. Ajith R R[2]
[1]M.Tech Student-Manufacturing and Automation, [2]Assistant Professor,
Department of Mechanical Engineering, College of Engineering, Trivandrum, Kerala, India
Corresponding Auther: Akhil A I

ABSTRACT: Open control architecture is a revolution in open source electronics which enables open architecture controller for CNC systems. This project emphasizes on proposing a design for CNC engraving machine based on open source electronics for engraving the side walls of the tyre mold. The designed engraving machine consists of 3 axis Z axis, Y axis and A axis or the rotary axis. An open source controller software known as GRBL which receives the G-codes from the CAM software is used to control the microprocessor which in turn control the machine drives. The open architectural controllers provide reliability, stability and modularity for the system. The application of open source electronic systems can provide similar accuracy and precision at an affordable budget.
Keywords: Non-traditional machining, open source CNC, CNC engraving.

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I. INTRODUCTION

The Computer-numerical control (CNC) machining is used primarily by manufacturers to manufacture machined parts, products, items, etc. A CNC machine utilizes Computer Numerical Control to control machine tools like lathes, routers, grinders or mills. The Computer Numerical Control is different from the typical PC type software used to control a machine. It is specially customized and programmed with G-Code, a specific CNC machine code language that allows precise control of the features like speed, location, co-ordination and feed rate. Specialized software drives the computerized machining process. The G-code loaded software sits within a computer that looks like a sophisticated desktop. A programmer at the computer console can control machine work that would be equivalent to multiple operators on lathes, grinders, routers, mills and shapers. The automated machining method can achieve actions that human operators and conventional machines typically don't do efficiently. A variety of CNC machines offer the advantage of having multiple axes, that can adjust to difficult angles and help manage hard to cut materials. Basic machines have cutting implementation along X and Y axes that can work independently and simultaneously. Advanced machines have more than five axes that perform similarly and have the capacity to turn and flip the part. CNC machines can automate the jobs that require several cuts. A router or spindle turns to implement the cutting operation, resembling a drill bit. A true drill bit cuts only at the tip, while nearly all of a router bit cuts the material. The programming in CNC machines incorporates all the co-ordinates and high-speed movements required to manufacture the object and it enables detailed customization. CNC machining is gaining popularity as a way to fabricate metal parts as well as plastic parts, as it allows the manufacturer to produce complex shapes that would be nearly impossible to create manually. Many manufacturing industries consider CNC machining as an advantage for production solutions involving metal and plastic and complex machining processes.

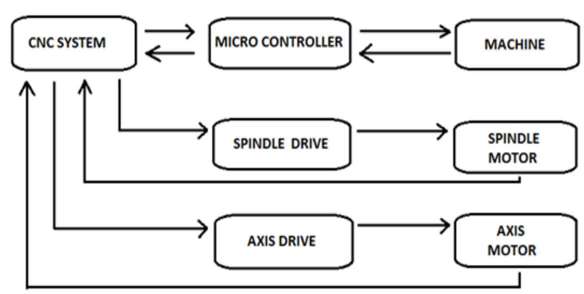


Fig.1 Schematic representation of CNC system

II. LITERATURE REVIEW

Jorge E. Correa et al. (Jorge E. Correa, 2017) presents the general ideas, like implementation and latest advancements of the open architecture controller for CNC systems based on open source electronics. The multiprocessor and distributed architecture of this controller empowers the platforms like Arduino, TI Launchpad, etc. to realize the CNC systems with increased computational resources, closed-loop position controls of the tool, smoother motion and higher feed rates. His work also demonstrates the first steps in the development of virtual machine as a new software component of the architecture. [1]

Correa J et al. (Correa J, 2016) discuss a software architecture which is focused on a component-based approach where in each component has an independent finite state machine (FSM) model. The hardware architecture discussed is a multiprocessor distributed controller that has different levels of processing and is adaptable for different hardware specifications. A discussion on the basic control algorithms, with examples of implementation to the open source platform Arduino, is mentioned as part of methodology. Other results include the preliminary test of the control system for a two-axis CNC and the mathematical model of control loop in Simulink. The architecture according to this paper has the potential of transforming the CNC in open source electronics from a device oriented systems to a systems where in the users can design their controls for special purpose machines. [2]

Pritschow Gunter et al. (Pritschow Gunter, 2016) provide an insight about the past, present and future of the Open Controller Architecture. After considering the different criteria, categories and characteristics of open controllers in general, the CNC products in the market are evaluated and an overview is mentioned. Subsequently, efforts to harmonize the different results are mentioned to establish a common world-wide standard in the future. Due to the "mix-and-match'' nature of open controllers concentrated attention must be paid to testing mechanisms in the form of conformance and interoperability tests. [3]

Yusri Yusofa et al. (Yusri Yusofa, 2015) emphasizes on the function of an interpreter to extract data from CAM system generated codes and convert it to the controller motion commands. He exclaimed that with the development of Numerical Control technology, existing CNC systems are limited with an interpreter lacking in expansibility, modularity and openness. To overcome these problems open architecture control was introduced. A conceptual module of a new software system is mentioned which is able to interpret the ISO 14649 and 6983 code and translate it as it is required by the CNC machine. It is capable of interpreting position, feed rate, tool, spindle etc data and translates it into CNC machine language or output in the form of text or XML files as per the user defined file structure. [4]

Georgi M. Martinova et al. (Georgi M. Martinova, 2014) emphasis on the procedure in synthesizing a specialized CNC systems illustrated by an example of a five-axis water jet cutting machine and selective laser sintering machine. The development of an underlying computing platform that enables the building of a specialized CNC system for non-traditional processes has been mentioned. A limited yet extensible set of software and hardware components used to implement the new processing technologies was defined and a solution matrix for the subsequent synthesis of the specialized CNC system has been developed. [5]

S. Cuenca et al. (S. Cuenca, 2011) emphasize on the importance of Tool path generation by the controller of a STEP-NC compliant CNC machine tool. These algorithms demand a higher computational performance and make the implementation on many existing systems very slow or even impractical. [6]

- This paper provides idea related to CAM.

Pengfei Li n et al. (Pengfei Li n, 2010) discuss about a open architecture CNC system based on CAD graph-driven technology and it is designed together with the key hardware PC+PMAC controller. This intelligent CNC system software includes several function modules developed under Visual C++6.0 environment. The Graphic feature identification and geometric parameter extraction from CAD-part-drawing saved as DXF format are performed to control the relative motion between the cutting tool and the part. The ant-colony algorithm is applied to auto-optimize the cutting tool paths in machining process. [7]

- This paper gives an idea of the open architecture control system, different functioning modules and interfacing.

Yu D et al. (Yu D,2009) says that in a conventional CNC system, the communications between the motion controller and the analogue servo driver is unidirectional, i.e., from the controller to the driver. A Fieldbus is used to increase the interoperability level between the motion controller and the driver. The driver performs the functions that have been traditionally executed by the motion controller. In this research, the traditional CNC system has been redesigned based on the component technology. A component models have been developed for the motion controller and the driver based on the analysis of the architecture of a traditional CNC and the features of a Fieldbus. This Fieldbus based CNC system provides the desired interoperability between the motion controller and the driver. To showcase the component model-based system a comparative experiment based on a four-axis CNC system was performed. [8]

X.W. Xu a et al. (X.W. Xu a, 2006) discuss about a new standard known as STEP-NC developed as the data model for a new breed of CNC machine tools. Specifically aimed at the intelligent CNC manufacturing workstation the data model represents a common standard, making the goal of a standardized CNC controller and the NC code generation facility a reality. It is believed that CNC machines implementing STEP-NC will be the basis for a more open and adaptable architecture. A futuristic view of STEP-NC to support distributed interoperable intelligent manufacturing through global networking with autonomous manufacturing workstations enabling STEP compliant data interpretation, intelligent part program generation, diagnostics and maintenance, monitoring and job production scheduling is discussed. [9]

Altinas Y et al. (Altinas Y, 1994) describes a hierarchical open architecture multi-processor CNC design for machine tools. The computer modules which look after the user interface, machining process control and monitoring tasks is accommodated in the system's primary bus. The secondary bus consists of a high performance CNC module which is used for the communication with dedicated micro-controller based drive control modules. There is an open flow of position, feed and machining commands and states between CNC master, machining process control and monitoring modules in the system. To illustrate the openness of the designed system for intelligent machining operations, a Sample test results for parallel implementation of NC tool path control, adaptive cutting force control and tool breakage detection are mentioned. [10]

III. PROPOSED DESIGN

The special application CNC engraving machine consist of 3 axis,

- Z axis
- Y axis
- A axis or the rotary axis

The Z axis is responsible for the tool feed motion i.e. the depth of cut, jog height etc. The Y axis is responsible for the feed in linear direction and the A axis in the rotary direction. The cutting action takes place in the Y, Z and A axis directions. An open source controller software known as GRBL which receives the G-codes from the CAM software is used to control the microprocessor which in turn control the machine drives. The machine occupies a work volume of 1000mm x 1100mm x 935mm.

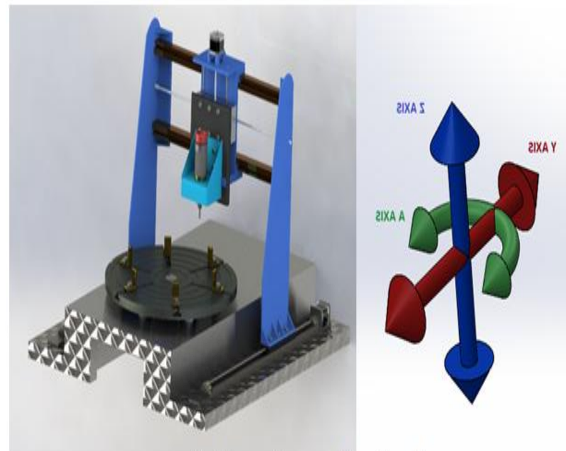
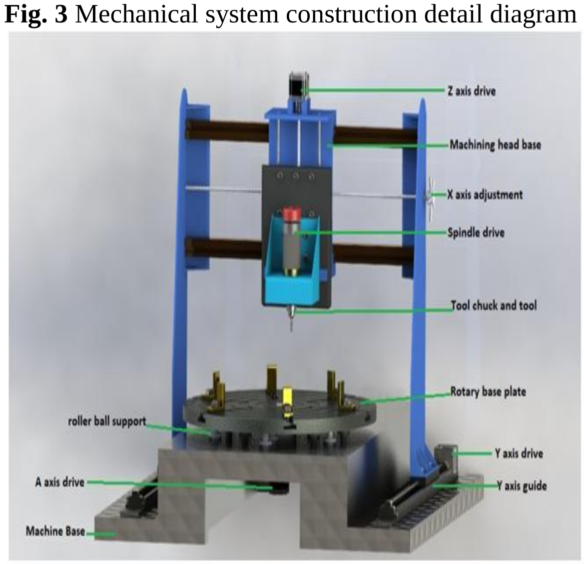


Fig.2 Proposed system axis configuration

3.1MECHANICAL SYSTEM

Fig. 3 Mechanical system construction detail diagram



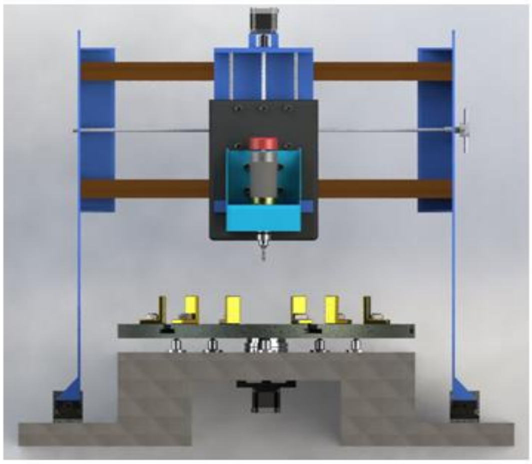
The mechanical system is responsible for performing the machining operation. The basic components of the mechanical system include

- Rotary base plate
- Z axis drive
- Y axis drive
- Z axis guide
- Y axis guide
- X axis guide
- X axis adjustment
- Spindle motor

- Tool holder
- Roller support

A axis drive or rotary axis drive

Fig. 4 Mechanical system elevation



Stepper Motor Calculations

Fig. 5 sure step motor specification [11]

SureStep Series Specifications – Connectorized Bipolar Stepping Motors		High Torque Motors						Higher Torque Motors			
Bipolar Stepping Motors		STP-MTR-17040(D)	STP-MTR-17048(D)	STP-MTR-17060(D)	STP-MTR-23055(D)	STP-MTR-23079(D)	STP-MTR-34066(D)	STP-MTRH-23079(D)	STP-MTRH-34066(D)	STP-MTRH-34097(D)	STP-MTRH-34127(D)
NEMA Frame Size		17	17	17	23	23	34	23	34	34	34
* Maximum Holding Torque	(lb·in)	3.81	5.19	7.19	10.37	17.25	27.12	17.87	27.12	50.00	80.50
	(oz·in)	61	83	115	166	276	434	286	434	800	1288
	(N·m)	0.43	0.59	0.81	1.17	1.95	3.06	2.02	3.06	5.65	9.12
Rotor Inertia	(oz·in²)	0.28	0.37	0.56	1.46	2.60	7.66	2.60	7.66	14.80	21.90
	(kg·cm²)	0.05	0.07	0.10	0.27	0.48	1.40	0.48	1.40	2.71	4.01
Rated Current (A/phase)		1.7	2.0	2.0	2.8	2.8	2.8	5.6	6.3	6.3	6.3
Resistance (Ω/phase)		1.6	1.4	2.0	0.8	1.1	1.1	0.4	0.3	0.3	0.5
Inductance (mH/phase)		3.0	2.7	3.3	2.4	3.8	6.6	1.2	1.5	2.1	4.1
Insulation Class		130°C [266°F] Class B; 300V rms									
Basic Step Angle		1.8°									
Shaft Runout (in)		0.002 in [0.051 mm]									
Max Shaft Radial Play @ 1lb load		0.001 in [0.025 mm]									
Perpendicularity		0.003 in [0.076 mm]									
Concentricity		0.002 in [0.051 mm]									
* Maximum Radial Load (lb [kg])		6.0 [2.7]			15.0 [6.8]		39.0 [17.7]	15.0 [6.8]	39.0 [17.7]		
* Maximum Thrust Load (lb [kg])		6.0 [2.7]			13.0 [5.9]		25.0 [11.3]	13.0 [5.9]	25.0 [11.3]		
Storage Temperature Range		-20°C to 100°C [-4°F to 212°F]									
Operating Temperature Range		-20°C to 50°C [-4°F to 122°F] (motor case temperature should be kept below 100°C [212 °F])									
Operating Humidity Range		55% to 85% non-condensing									
Product Material		steel motor case; stainless steel shaft(s)									
Environmental Rating		IP40									
Weight (lb [kg])		0.6 [0.3]	0.7 [0.3]	0.9 [0.4]	1.5 [0.7]	2.2 [1.0]	3.9 [1.7]	2.4 [1.1]	3.9 [1.7]	5.9 [2.7]	8.4 [3.8]
Agency Approvals		CE (complies with EN55014-1 (1993) and EN60034-1.5.11)									
Design Tips		Allow sufficient time to accelerate the load and size the step motor with a 100% torque safety factor. DO NOT disassemble step motors because motor performance will be reduced and the warranty will be voided. DO NOT connect or disconnect the step motor during operation. Mount the motor to a surface with good thermal conductivity, such as steel or aluminum, to allow heat dissipation. Use a flexible coupling with "clamp-on" connections to both the motor shaft and the load shaft to prevent radial and thrust loading on bearings from minor misalignment.									
Accessory Extension Cable		STP-EXT-020						STP-EXT**H**-020			

* For dual-shaft motors (STP-MTR-xxxxxD):
The sum of the front and rear Torque Loads, Radial Loads, and Thrust Loads must not exceed the applicable Torque, Radial, and Thrust load ratings of the motor.

Motor selected : STP-MTR-17060(D)
Frame size : NEMA17
Maximum holding torque : 115 oz-in = 0.81Nm
= 8.259 kgcm
Rotor inertia : 0.56 oz-in^2
Maximum radial load : 2.7kg
Maximum thrust load : 2.7kg

No. of pulses per second

Pitch of the lead screw = 1mm

⇨ 1 rev = 1mm

Step angle = 1.8® / pulse

⇨ 200 steps per revolution

Required speed = 15mm in 1.5sec

Total No. of pulses

$$=15mm\ x\ \frac{1rev}{1sec}\ x\ \frac{2oopulses}{1\ rev} = 3000\ pulses$$

No. of pulses per second $= \frac{3000}{1.5} = 2000\ pulses$/sec

Position Accuracy

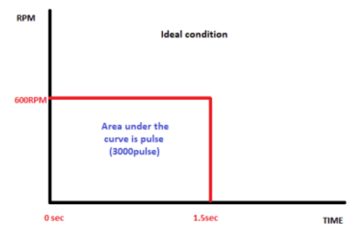
Resolution $= \frac{1mm}{1\ rev}\ x\ \frac{1\ rev}{200\ pulse} = 0.005\ mm/pulse$

Motor speed

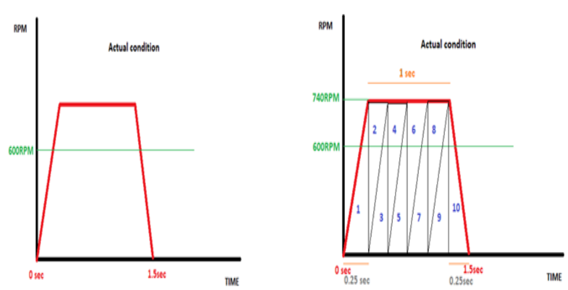
Total no. of revolutions $= 15\text{mm x } \frac{1\text{ rev}}{1\text{ mm}} = 15\text{rev}$

No. of revolution per second $= \frac{15\ mm}{1.5\ sec}$ = 10 rev/sec

=600 RPM



But in actual condition the motor will accelerate when started and then decelerate while approaching the end.



The total no. of pulses = 3000

Assuming the accelerating time and decelerating time =0.25sec

Consider dividing the entire curve into 10 triangles

⇨ 10 triangle = 3000pulses

⇨ 1 triangle = 300pulse

8 triangles are covered in 1sec

⇨ 8 triangle = 2400pulse

⇨ 2400pulses = 1 sec

1 rev = 200pulses

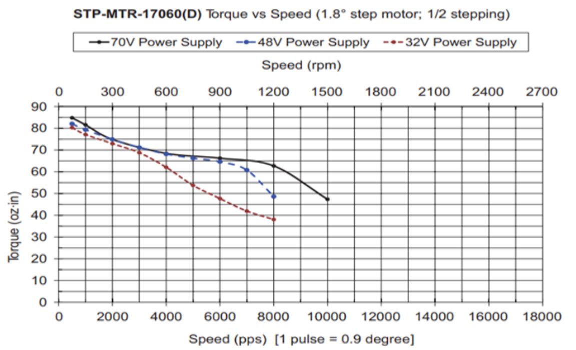
⇨ 2400pulses $= \frac{2400}{200} = 12\ rev$

⇨ 12 rev/sec

⇨ <u>740RPM</u>

Therefore the maximum rpm of the motor is set as 740RPM

Fig. 6 sure step motor characteristic curve [11]



Torque

$Torque_{total} = T_{running} + T_{acceleration}$

$T_{running} = T_{friction} + T_{gravity} + T_{external}$

$T_{acceleration} = J_{total}\ x\ (\frac{\Delta speed}{\Delta time})$

$J_{total} = J_{motor} + J_{gearbox} + J_{coupler} + J_{leadscrew} + J_{carriage}$

Assumption

⇨ Torque is calculated in no load condition.

⇨ Running torque is zero since; it is dynamic and depends on the machining parameters.

⇨ Since we don't have a gearbox. Moment of inertia due to gearbox is assumed to be zero.

For Y axis

Payload inertia factor = 0.001 in^2

J_{motor} = 0.56 oz-in^2 (given in motor specification) = 0.00015 oz-in-sec^2

$J_{coupling} + J_{leadscrew}$ = 0.020 $lb_m\, in^2$(given in leadscrew specification) = 0.00080 oz-in-sec^2

$J_{carriage}$ = (weight(lb) /acceleration due to gravity(in/sec^2)) x payload factor

= ($\frac{75 lb}{386.4\ in/sec^2}$ x 0.001in^2)

= 0.0001941 lb-in-sec^2= .0031 oz-in-sec^2

J_{total} = 0.00015 + 0.0008 + 0.0031

= 0.00405 oz-in-sec^2

$T_{acceleration} = J_{total}\ x\ (\frac{\Delta speed}{\Delta time})$

= 0.00405 oz-in-sec^2 x ($\frac{12\ rev}{0.25 sec}$)

= 0.1944 oz-in-rev

= 0.1944 x 2π oz-in

= 1.22 oz-in

For Z axis

Payload inertia factor = 0.001 in^2

J_{motor} = 0.56 oz-in^2 (given in motor specification) = 0.00015 oz-in-sec^2

$J_{coupling} + J_{leadscrew}$ = 0.020 $lb_m\, in^2$(given in leadscrew specification) = 0.00080 oz-in-sec^2

$J_{carriage}$ = (weight(lb) /acceleration due to gravity(in/sec^2)) x payload factor

= ($\frac{33 lb}{386.4\ in/sec^2}$ x 0.001in^2) = 0.0000854 lb-in-sec^2

= 0.00137 oz-in-sec^2

J_{total} = 0.00015 + 0.0008 + 0.00137

= 0.00232 oz-in-sec^2

$T_{acceleration} = J_{total}\ x\ (\frac{\Delta speed}{\Delta time})$

= 0.004232 oz-in-sec^2 x ($\frac{12\ rev}{0.25 sec}$)

= 0.11136 oz-in-rev

= 0.11136 x 2π oz-in

= 0.6997 oz-in

For A axis or Rotary axis

Assumptions

⇨ No vertical load acts on the motor. The entire load is balanced by the roller support.

⇨ Frictional force is assumed to be zero.

⇨ The calculation is done on no load condition.

Payload inertia factor = 0.001 in^2

J_{motor} = 0.56 oz-in^2 (given in motor specification) = 0.00015 oz-in-sec^2

$J_{coupling} + J_{leadscrew}$ = 0

$J_{carriage}$ = 0

J_{total} = 0.00015 = 0.00015 oz-in-sec^2

$T_{acceleration} = J_{total}\ x\ (\frac{\Delta speed}{\Delta time})$

= 0.00015 oz-in-sec^2 x ($\frac{12\ rev}{0.25 sec}$) = 0.0072 oz-in-rev = 0.0075 x 2π oz-in

= 0.0452 oz-in

The torque in the no load condition of all the above motor is negligible(1%) compared to the maximum holding torque(115oz-in) capacity of the motor. This gives the motor adequate amount of torque for machining process. The machining parameters should be selected in such a manner that the maximum torque required for machining is less than 75% of the maximum torque for safety purpose.

Spindle Motor Calculation

Assumptions

⇨ The maximum cutting tool diameter is 6mm.

⇨ Maximum spindle speed during machining is assumed 1000RPM.

⇨ The no. of flutes is fixed as 4.

⇨ Maximum depth of cut is assumed as 5mm

⇨ Maximum width of cut is the tool diameter

⇨ Machining is done in ideal condition.

Cutting speed (V_C)

$V_C = \frac{\pi.D.N}{1000}$ m/min

Where,

- V_C= cutting speed (m/min)
- N = spindle speed (RPM)
- D = cutter diameter (mm)

$V_C = \frac{3.14 \text{ x } 6mm \text{ x } 1000 rpm}{1000}$ m/min

= 18.84m/min

Table feed (f)

f = z x n x N mm/min

Where,

- z = feed per tooth(assumed as 0.1mm/tooth)
- n = no. of flutes
- N = RPM

f = 0.1 x 4 x 1000

= 400 mm/min

Cutting power (P)

Cutting power required = $\frac{\text{w x d x f x k}}{60 \text{ x } 10^6 \text{ x } \mu}$ kW

Where,

- w = width of cut (mm)
- d = depth of cut (mm)
- f = table feed (mm/min)
- k = specific cutting force (N /mm 2) = 1980 N/mm2 (medium steel from the table)
- μ = machine coefficient assumed to be 1

P = $\frac{\text{6mm x 5mm x 400 x 1980}}{60 \text{ x } 10^6 \text{ x 1}}$

= 0.396Kw

= 400W

Therefore the motor power is chosen as 400W.

Fig. 7 specific cutting force for different materials chart [12]

Work Material	Tensile Strength (N/mm²) and Hardness	Specific Cutting Force Kc (N/mm²)				
		0.1mm/tooth	0.2mm/tooth	0.3mm/tooth	0.4mm/tooth	0.6mm/tooth
Mild Steel	**520**	2200	1950	1820	1700	1580
Medium Steel	**620**	1980	1800	1730	1600	1570
Hard Steel	**720**	2520	2200	2040	1850	1740
Tool Steel	**670**	1980	1800	1730	1700	1600
Tool Steel	**770**	2030	1800	1750	1700	1580
Chrome Manganese Steel	**770**	2300	2000	1880	1750	1660
Chrome Manganese Steel	**630**	2750	2300	2060	1800	1780
Chrome Molybdenum Steel	**730**	2540	2250	2140	2000	1800
Chrome Molybdenum Steel	**600**	2180	2000	1860	1800	1670
Nickel Chrome Molybdenum Steel	**940**	2000	1800	1680	1600	1500
Nickel Chrome Molybdenum Steel	**352HB**	2100	1900	1760	1700	1530
Cast Iron	**520**	2800	2500	2320	2200	2040
Hard Cast Iron	**46HRC**	3000	2700	2500	2400	2200
Meehanite Cast Iron	**360**	2180	2000	1750	1600	1470
Grey Cast Iron	**200HB**	1750	1400	1240	1050	970
Brass	**500**	1150	950	800	700	630
Light Alloy (Al-Mg)	**160**	580	480	400	350	320
Light Alloy (Al-Si)	**200**	700	600	490	450	390

3.2 MODAL ANALYSIS

The maximum speed of the spindle motor is 3000rpm at 12V.

N = 60 F

Where,

N= RPM

F= Frequency (Hz)

Therefore the frequency of the motor is 50Hz

The following assumptions were made for the analysis

- The vertical load at the center is assumed to be 200N. which is corresponding to the weight of the head assembly.
- All the frame material is assumed to be carbon steel.
- The force along the Y axis is assumed to be 1000N. The cutting force according to an online cutting force calulator[13] was found to be around 275.6N and torque 0.83Nm with the following cutting parameters assumption:

  - Brinell Hardness : 200 HB (for stainless steel annealed)
  - Effective cutting diameter : 6 mm
  - Number of inserts/cutter : 4
  - Cutting speed : 18.84 m/min
  - Axial Depth of cut : 5 mm
  - Radial width of cut : 6 mm
  - Required feed per tooth : 0.1 mm
  - Machinability factor : 1
  - Tool wear factor : 0.4
  - Machine efficiency factor : 0.8

Applying all the above assumptions, a modal frequency analysis of the structure is done in solidworks simulation and the natural frequency of the structure is found to be greater than the motor frequency. This implies there is structural stablity for the system in above condtions.The natural frequency of the system can be improved by either improving the thickness or by providing suitable reinforcements as required.

Two differents modes of the analysis is shown in figure 5 and 6.

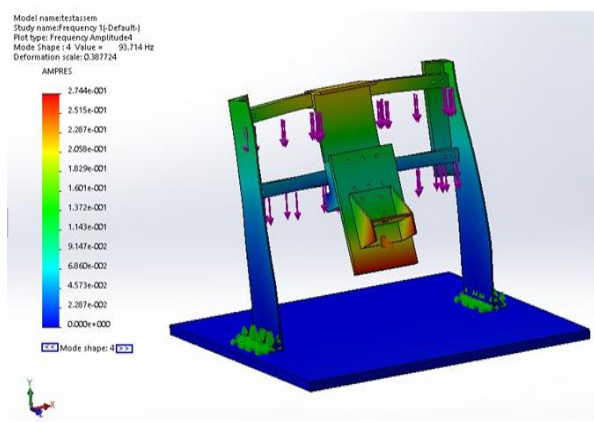


Fig. 8 Solidworks frequency simulation mode 4

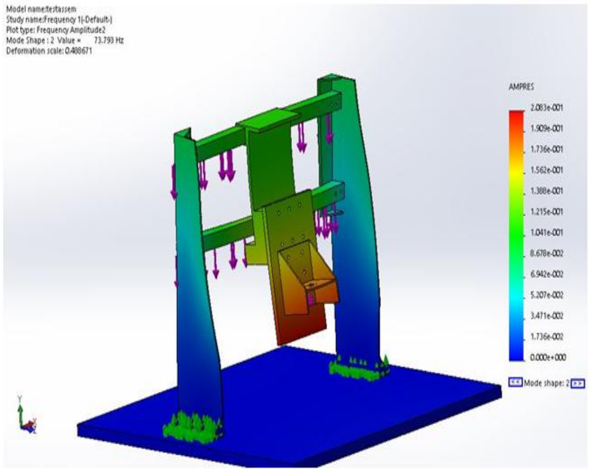


Fig. 9 Solidworks frequency simulation mode 2

3.3 Electrical Circuit And Control System

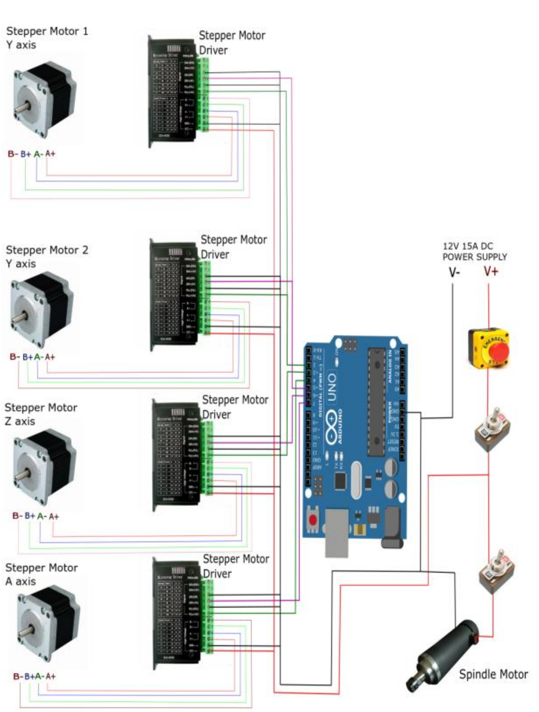


Fig.10 Electrical circuit diagram

The electrical circuit consists of,

- 3 stepper motor.
- 3 microstepping drivers.
- Arduino UNO board.
- Spindle motor.
- An emergency stop switch.
- A main on/off switch.
- A spindle on/off switch.

The CAD model is feed into CAM software like Autodesk fusion 360, NX CAM, etc where the CAM programming is done. The g-code file i.e., the (.nc) file is obtained as output from the CAM software with GRBL as the controller. The GRBL software accepts the Gcode file and controls the drivers via the Arduino Uno board which is loaded with the GRBL library.

The Arduino board is connected to the computer via USB cable. The power for the Arduino board and the I/O communication is done through this port. The Arduino then sends signals to the micro stepping driver that controls the motion of the stepper motor in accordance with the NC program.

A DC power supply of 12V 15A is used to power the entire system. An emergency on off switch is used to cut the power supply to the entire in an event of emergency. A main switch is used to turn on the entire system. A separate switch is provided to turn on/off the spindle. The spindle motor is made to rotate a single speed that is 3000rpm at 12V.

3.4 COST ESTIMATE

- Stepper motor = 1,020 x 3 = 3060
- Stepper motor drive = 700 x 3 = 2100
- Arduino UNO board = 473
- Lead screws and guide ways = 8000
- Machine structure = 12000
- Machine structure base = 5000
- Power supply = 1200
- Roller support = 600 x 10 = 6000
- Spindle motor = 14000
- Misc = 5000

Total = Rs 60000 (approx)

IV. CONCLUSION

The Special Application CNC engraving machine based on open source electronics is designed. The open source based CNC machine has 3 axis motions that is controlled by the GRBL controller which communicates with the Arduino board which in turn drives the stepper motor drivers which run the stepper motor. The motor load calculations were done on no load condition and suitable allowance for machining is provided. The cost estimate of the system is done and is found to very cost effective compared to the closed source systems.

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