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Design & Implementation of an IoT Based 3-Axis CNC VMC

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Abstract— Computer numerical control is a very broad term that encompasses a variety of types of machines— all with different sizes, shapes, and functions. But the easiest way to think about CNC is to simply understand that it's all about using a computer as a means to control a machine that carves useful objects from solid blocks of material. Our Project mainly deals with implementation of a desktop-sized 3-Axis CNC machine and necessarily adding the functionality of controlling the machine from anywhere with an Internet Connection. One of the primary target of this project revolves around low-cost Printed Circuit Board (PCB) manufacturing and essentially making it available for and end user who can create their own custom PCBs without prior complicated knowledge of CNC milling and investing on costly machines. The main motive behind wireless machine control from the internet is to create an ecosystem of these kind of connected devices which could act as a step ahead towards the goal of providing industry-grade solutions for total sales-cycle automation in the PCB manufacturing industry all the way starting from order procurement to supply chain, manufacturing and delivery cycle automation. Distribution of these kind of devices to the engineering institutions could also be a venture to be worked upon as there is a need for making custom PCBs there. Apart from PCB manufacturing, robust solutions for customized wood and plastic surface engravings can also be provided through this project. The Prototype Model is IoT based thus providing it a scalable architecture to use it from practically anywhere with an internet connection. This is a 350mm x 350mm CNC with a 250mm x 240mm work area, running on open source motion control software(GRBL). Even our Hardware is also mostly open source and thus comes the major cost cutting. This machine is made wholly from locally purchased items and can machine on wood, plastics, hard rubber, hard resin etc. The primary target is low-cost PCB manufacturing.

Index Terms— CNC, Industrial Automation, PCB Manufacturing, IoT, Machining, Manufacturing, Control Software

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1 INTRODUCTION

The Gross Value Added (GVA) from the Indian manufacturing sector is estimated at 19,560 Crore INR in FY18. The sector's contribution to the country's GDP stood at 16.51 per cent in 2017, which is set to increase in the next upcoming quarters to around 20 percent because of the active wave of manufacturing revitalization efforts taken by the Indian Government, like Make in India etc. So, CNC machines like ours is really a snug fit for the Indian manufacturing sector, enabling low-cost engraving, face milling possible and more reachable to the consumer and B2B sector as well. There is a huge need for in-house professional manufacturing equipment to get end-to-end benefits from the manufacturing sector boom that can be made possible in the upcoming years.

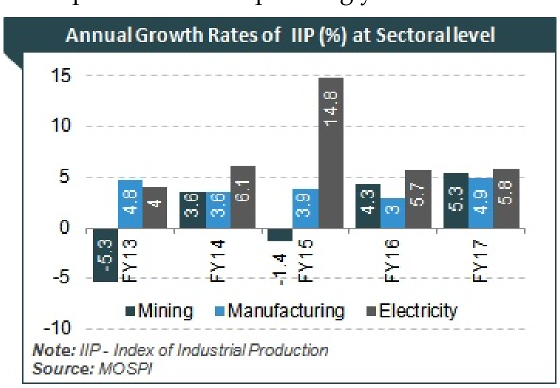


Figure 1 Recent Indian Manufacturing Sector Scenario

This paper is a step forward to the goal of making connected industrial systems for the Industry 4.0 revolution that is being seen worldwide. We want to achieve high precision double sided PCB manufacturing with our prototype machine while the prospect of Our fundamental objective lies in making low-cost manufacturing possible. This objective is followed by our long-term professional-grade wood craving is also there. We're Planning to add Laser Machining support as part of our future project. As the system can be presently controlled from a local Intranet wirelessly as of now, we want to scale it further to make a distributed model web application to make and connect an ecosystem of multiple number of these-kind-of-devices. The possibilities are unlimited with this machine.

2 PROPOSED MODEL

2.1 Brief

The prototype model has its base frame made out of 2020 T-slotted Aluminum Extrusions and L-Joints. The machine gives roughly about 80-85 Watts power with its 2000 rpm DC controlled spindle. It has lead screw and threaded rod movement scheme with guiding smooth rods having radial groove snap fit ball bearings for smooth operations along all the 3 axes. The minimum lead pitch is 0.8mm/revolution with a 2000 steps/revolution we have a resolution of 1600 for all the axes. Our rough machine size is about 430x430x330mm and work area is about 270x170x65mm with 0.04mm positional accuracy. Our Z axis gantry is 3d printed from scratch with dual guiding rods. The Z axis travel 4.8 cm with spindle bit mounted. We're using 45° V-bit cutting tool for PCB engraving purposes, it also supports 0.2mm to 1.8mm end mill bits. We're using NEMA 23 Stepper motors with 3A max current for each axis main drive. The motors are driven by 2.5A A4988 drivers with 1/16th maximum micro-stepping resolution providing us the ultimate machining precision at a very economic cost. For the IoT (Internet of Things) part, we have made it possible to control the CNC router from a headless display like a mobile / tablet screen (acting as our HMI here) from anywhere with an Internet connection. We're using a Raspberry Pi and a Router(security) arrangement connected to the internet and running a webserver to provide an interface for controlling our CNC wirelessly. We're also planning to get hold of valuable machine part insights like real time motor torque, current drawn, vibration, noise etc. and draw real time insights in a web platform for better collaboration. Which is perhaps called in the manufacturing sector as the Industrial IoT (INDUSTRY 4.0) or IIOT.

2.2 Main Components

- X, Y and Z axis mountings and gantry assembly.
- Electronic Components.
- Motors.
- Power Supply.
- IoT and networking equipment.
- CAD/CAM Design Software.
- Machine Control Software.

2.3 Functional Block-Diagram:

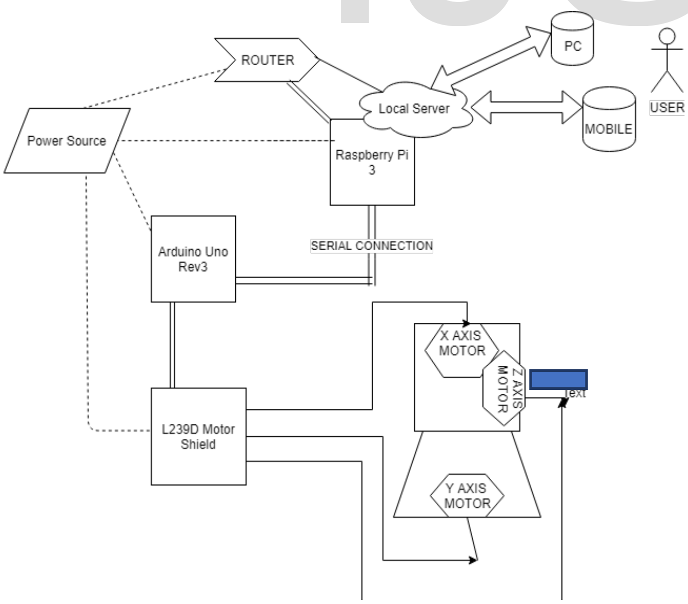


Figure 2 A Rough Functional Block Diagram of our 3Axis IoT CNC VMC

In the bock diagram described above, there is a synchronous link between the device running the webserver and the device to be controlled. Moreover, closed loop control has been incorporated in the control device for accurate and precise outputs. The Controlling computer can be a desktop sized PC or a palm sized mobile computing platform. The total power needed by the system can be provided easily with Li-Ion battery banks which essentially makes the system wholly portable.

2.4 Circuit Schematic:

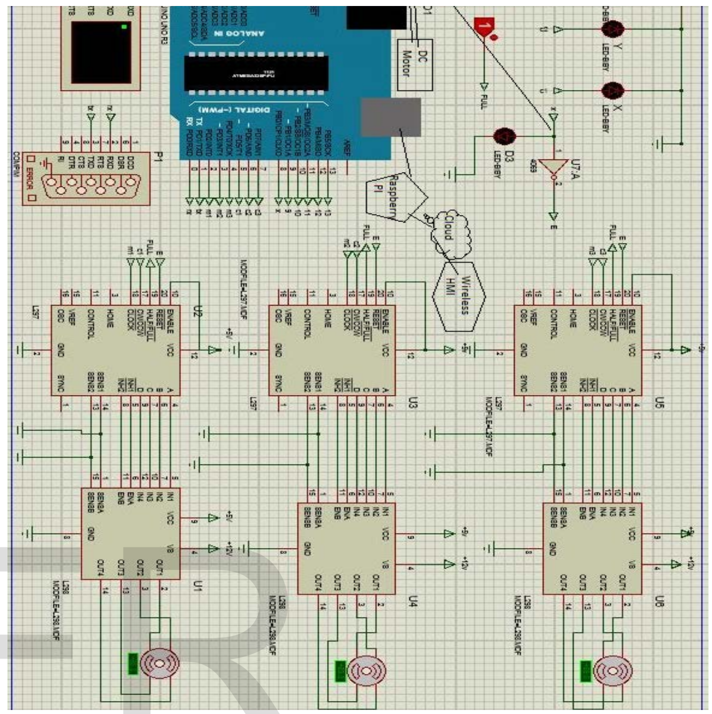


Figure 3: PROTEUS Simulation of 3-Axis CNC with Arduino as MCU.

3. METHODOLOGY

3.1 Hardware

The major hardware components used in the prototype model are:

- NEMA 23 Stepper Motors
- 555 air-cooled 2000rpm 12-24V spindle motor
- 2020 Aluminum extrusions
- Threaded rod
- Lead Screw
- Guiding Smooth Rods
- Ball Bearings
- L-joints
- Motor Shaft Couplers
- M5, M8, M3, M4 type machine head screws and bolts
- M3 T-Nuts
- Size 2 and Size 4 Hex Screws
- Arduino Nano (open-source board design)
- A4988 Stepper Driver
- Arduino Nano compatible (3stepper+1dc) shield (open-source board design)
- Z-axis gantry mount and X, Y axis risers.
- Control Station Computer (Raspberry Pi / PC)

- HMI station (Smartphone / tablet)
- Network Router
- 12V/5A Switched Power supply (for machine only), 12V/2A for Raspberry Pi and 5V/800mA for Router.
- Control Board Cooling Fan

3.2 Stepper Motors

NEMA 23 standard bipolar stepper motors have been used in the project for all the 3 axes. They provide 1.8° step-angle (200 steps/revolution) with each phase drawing 2.8A at 2.5Volts, which is about 12Volts.It has 10N axial force and 28N radial force at highest holding torque of 126 N-cm. These motors are 24 Volts tolerant having 4 wire switching leads and 1/8th micro-stepping support.

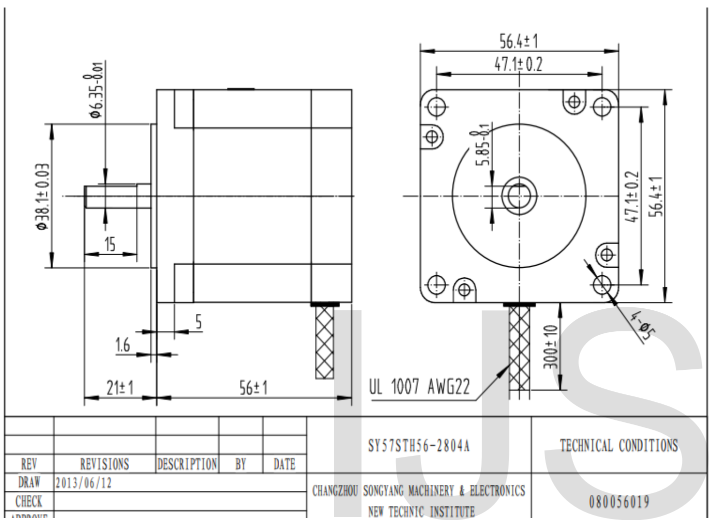


Figure 4 NEMA 23 Specs & drawing

3.3 Spindle Motor

For Spindle motor of the Z-axis, a 555-DC motor is used. It is a 12V/1200mA low speed high torque motor with maximum load condition speed is 2000rpm and no-load speed being 6000rpm. The Speed control is done by an IRF 540 Power MOSFET and 555 timer IC for PWM switching inbuilt within the motor shield.

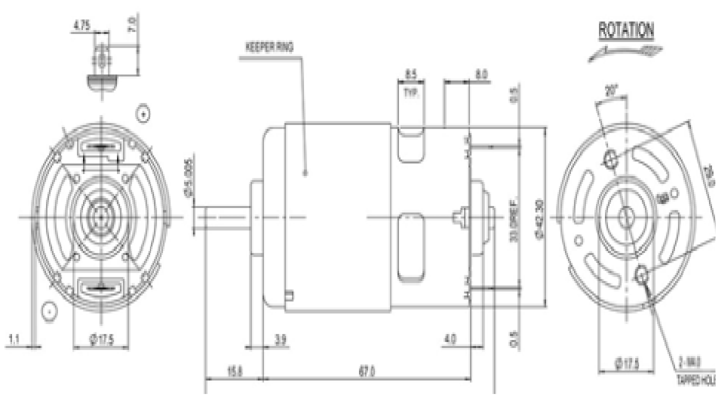


Figure 5: 555 DC motor Specs & Drawing

3.4 A4988 Stepper Driver

This is a DMOS Micro-stepping Driver with Translator and Overcurrent Protection. This stepper motor driver controls one bipolar stepper motor at up to 2 A output current having 1/16tm maximum micro-step resolution. The board is 3.3v -5v logic tolerant.

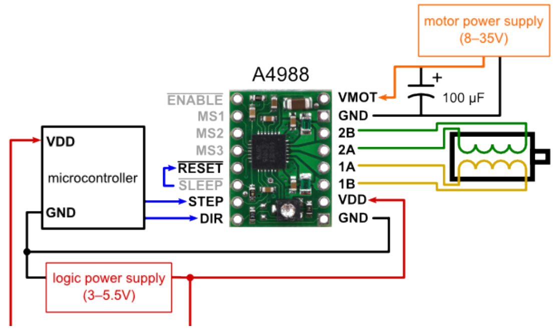


Figure 6: A4988 pinout

3.5 The main mechanical building block—2020 aluminum extrusions

These are aluminum T-slotted profiles with considerable tensile strength which forms the main building blocks of the CNC machine along with L-Joints. The main feature of these profiles is their rigidity.

Standard Extrusion Size(mm)	20	Extrusion Size	20x20
Extrusion Series	5 Series	Extrusion Type	Square
Number of Extrusion Slots	1 Slot-1 Slot	Extrusion Type	HFS
Surface Finish	Clear Coating	Number of Grooved Surfaces	Four Side Slots
Surface Milled	None	Material	A6N01SS-T5 Aluminum Alloy
Extrusion Size - Width (A)(mm) (mm)	20	Extrusion Size - Thickness (T) (mm)(mm)	20

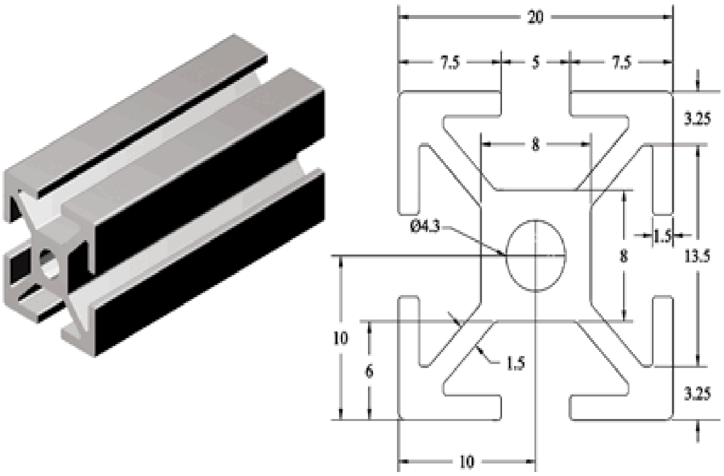


Figure 7: 2020 T-slot profile Drawing (sideview)

3.6. Machine Design/Original Drafts (Top view and Isometric Projection)

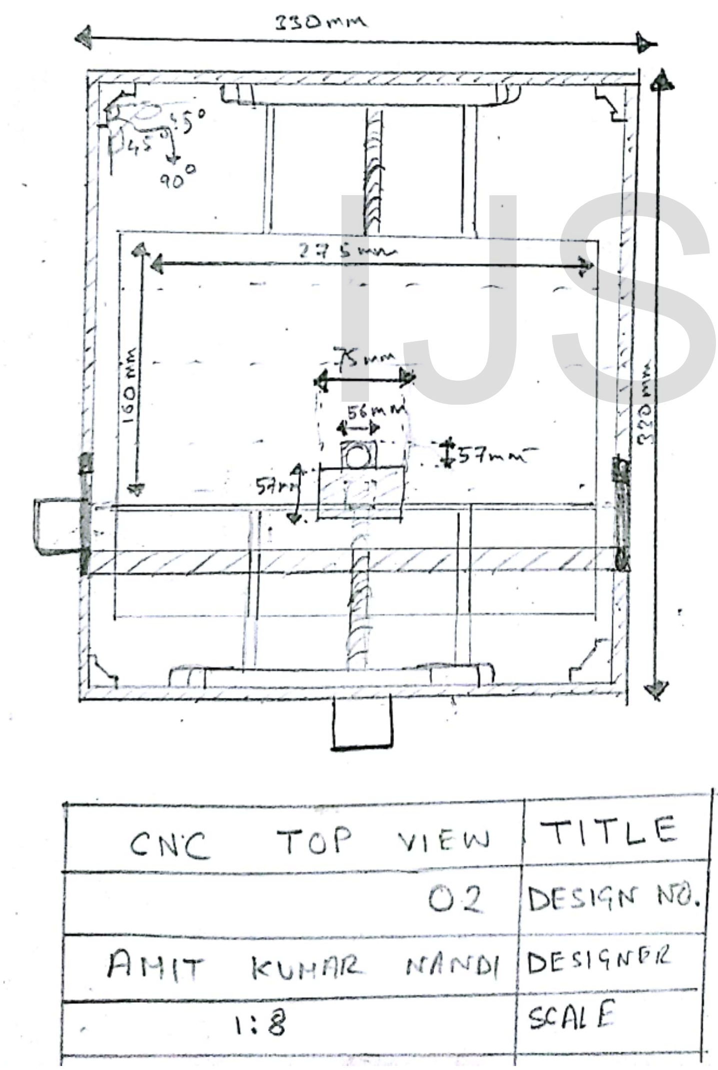


Figure 8 TopView of IoT Based CNC VMC

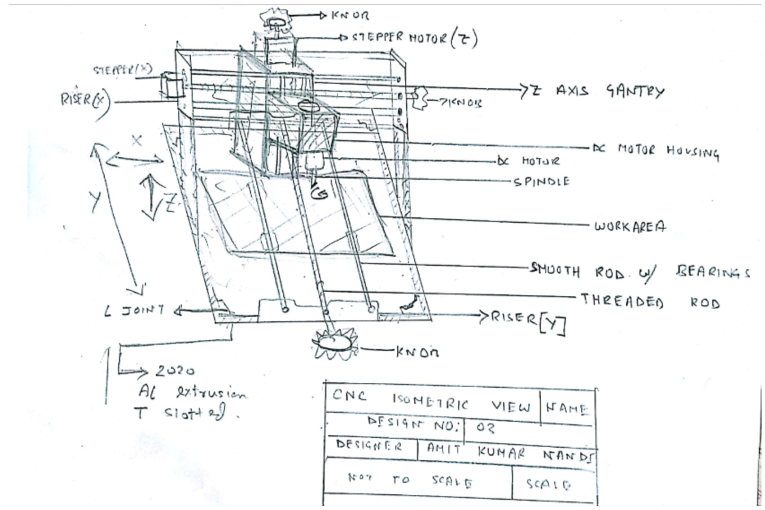


Figure 9 isometric Projection of 3-axis CNC VMC

3.7 Control and Design Software

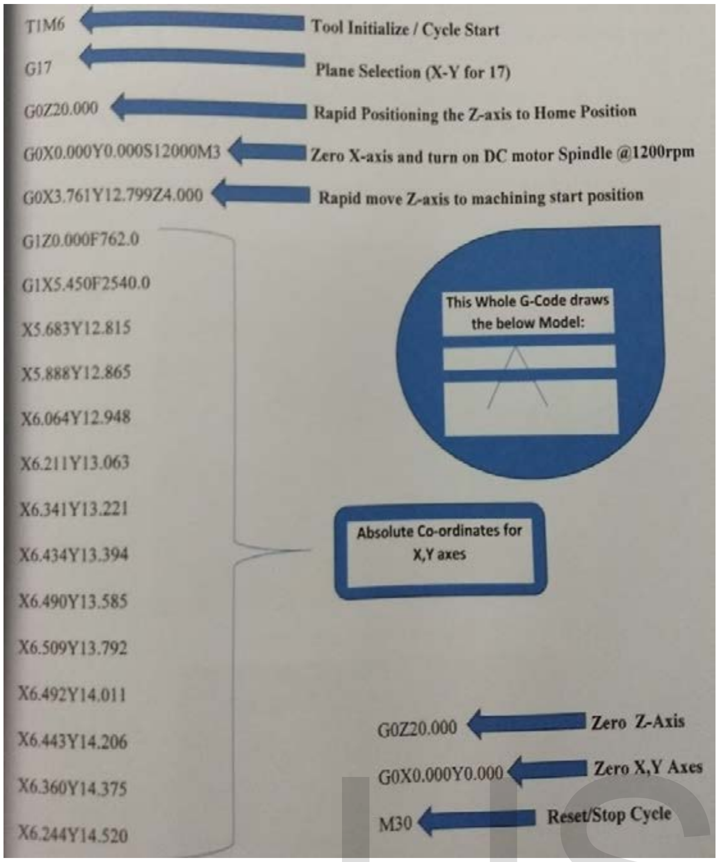
For all the design, modeling, G-Code generation and machining simulation needs, AutoDesk Fusion 360 software's 3-year Free Student License is being used. Though there are lot of other proprietary and open source applications available in the market for G-Code/Toolpath generation, we found AutoDesk's solutions to be best fitted for our project.

For machine Control software, the GRBL(v0.9)* Open-Source Firmware for the Atmel ATmega microcontrollers is chosen. It is a community-based, free and open source, embedded, high-performance G-Code-parser and CNC milling contour controller written in hardware-optimized C that runs on any ATMega Based MCUs (Arduino in our project). The firmware/driver runs on the Microcontroller while the software to control that firmware runs on any x86 or GNU based computing platform.

*Grbl is free software, released under the GNU LGPLv3 license.

**GitHub Repository link: *https://github.com/grbl/grbl.*

The Prototype machine can only interpret G-Codes, so any model which needs to be milled must be converted to its equivalent G-Codes by a process called toolpath generation. Softwares like ArtCAM, PyCAM (open-source) are used to generate G-Code from CAD model files. An Example Model and its equivalent G-Codes with their relevant meanings are given below:



Photograph 1 Example Model with corresponding G-Codes and their working

4 RESULTS AND DISCUSSION

The outcome of the project is pretty impressive as the machine can draw curved points as small as 0.6mm diameter. With a 12V/5A total power consumption, this machine can bear tool axis torque of up to 24 N-cm. 0.5mm PCB channel widths is cleanly milled with this machine.

Though the Z-axis needs a bit of more stability in terms of mechanical fittings. We are using closed loop stepper control, so machine homing/zeroing is steady, although the positional control accuracy needs to be increased.

At 2000rpm, 60% feed rate and 34% plunge rate, a 30mm x 30mm work-area, 28-lead channel engrave-milling required around 4 minutes time, which is more than expected from the 85watts effective power the machine.

Vector images can also be engraved in hard TPU plastics with 2.5D raster milling techniques.

4.1 NOISE AND VIBRATION ANALYSIS OF THE MACHINE:

The Bosch iNVH Andoid App is used to measure and analyze vibration and noise level of the machine in steady state running condition. The outputs are satisfactory for a machine of this size and vibrations can be minimized to a greater extent by using gantry mufflers and high-quality stepper motor coupling bearings. Further noise reduction can be done by using pulley sliders in place of ball screws.

The below two graphs describes the change in terms of vibration v/s time of the machine at 1second interval.

Figure 10: Vibration output analysis from all the 3 axes

The graph below describes the overall normalized noise level from the machine at 10cm radius.

Figure 11 Normalized Noise Levels

As it can be observed from the above noise data the levels do not reach above 72dB even during the most challenging machining operations. The noise testing has been done on mobile device microphone having 10KHz unidirectional resolution which can prove to be a major bottleneck while measuring the noise output. Use of condenser microphone with relatively higher omnidirectional resolution can solve this problem.

The vibrational outputs are measured on a Bosch BM421 gyro accelerometer sensor having 12-bit digital output resolution and accuracy of measurement in terms of ±2g.

The graph below describes the change in terms of instantaneous noise level [dB(A)] v/s time(seconds) of the machine at 1s interval.

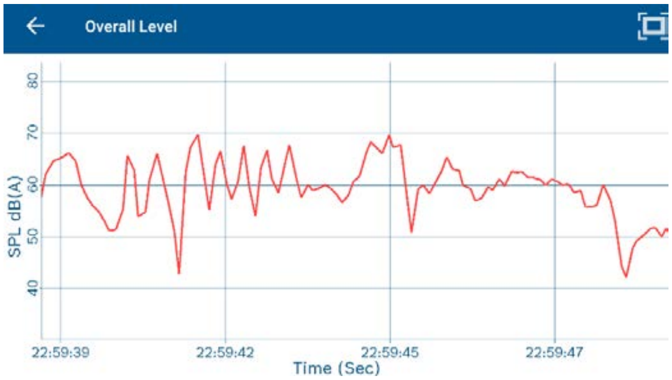
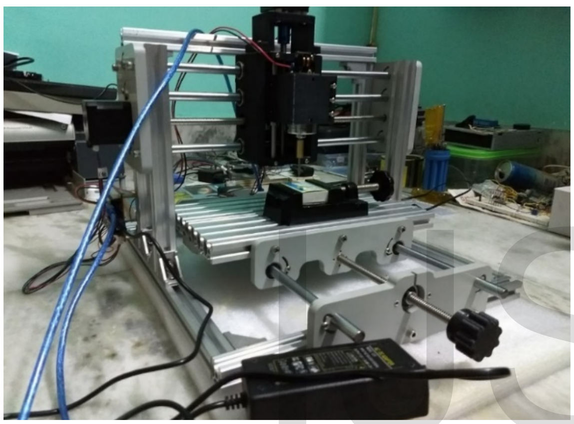


Figure 12: Noise Output Analysis



Photograph 2: Final CNC Machine..

Photograph 3 :PCB with 0.8mm channes widths of an ATmega 328p SMD chip.

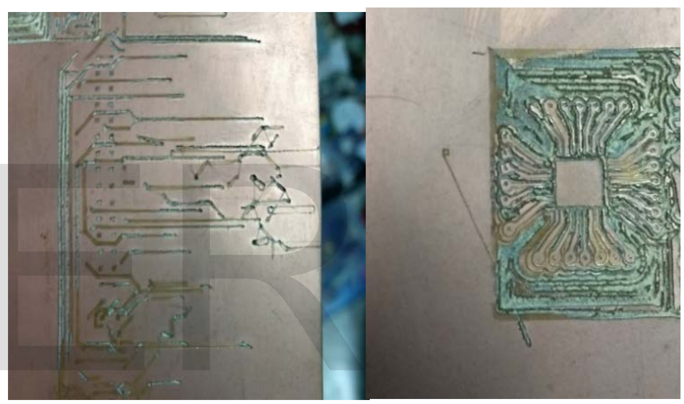
High precision circular raster milling can also be achieved with our machine in order to engrave high resolution images. Point to point milling of considerable accuracy can be obtained from the machine.

Due to software limitations spindle control can be handled up to 2000rpm only. An added step of precision can be added to the machine by introducing positive and negative limit switches for all the three axes.

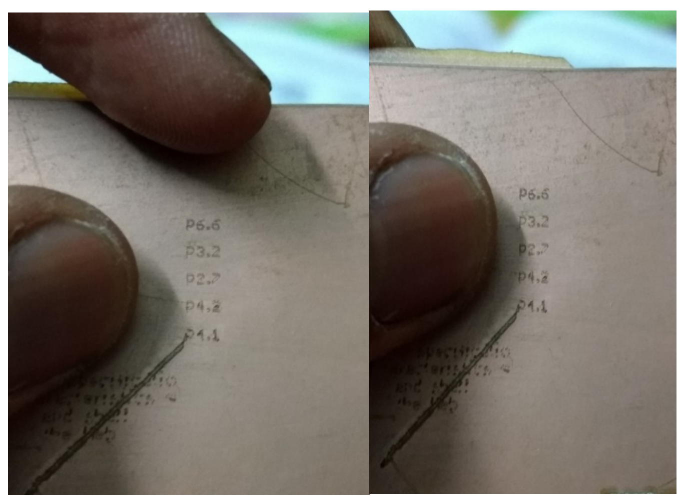
Essentially, addition of an integrated application layer to our product will help it to achieve supply chain to delivery cycle automation especially in the PCB manufacturing industry. Which will eventually cut down sales overheads and maximize production. This project is published in the open-source makers' community called 'Hackster' under GNU LGPL open source license having 50+ community respects in under a month.

URL: *https://www.hackster.io/amitnandileo/diy-3-axis-cnc-vmc-4817ba*

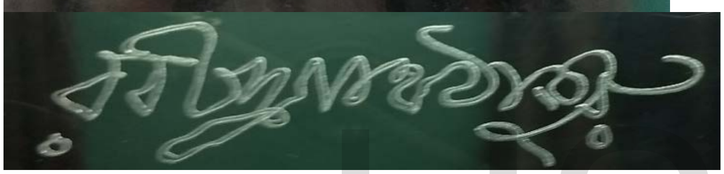
Below are some photographs taken on copper clad boards and TPU plastics demonstrating finished end milling processes:



Photograph 4: End milling of PCBs on dual-sided copper clad board done on our 3 axis CNC.



Photograph 5: Precision Micro Lettering witch each letter having dimensions of the order of 1/8th of an inch i.e. 3.1mm roughly. [thumb and index finger for scaling]



Photograph 5: Circular Rastering of a 400x400px. resolution image (top)

Photograph 6: Point to Point milling of 3rd Reich Emblem (middle) and an engraved signature of great poet Rabindranath Tagore. (bottom)

4.2 Global Competition:

hat we have figured out after a brief market study about our product is that, there are currently a lot of companies who are pushing this idea of low-cost machining into reality. Some of the renowned companies making products somewhat similar in functionality to ours are as follows:

Carbide 3D LLC – The 'Shapeoko' Milling Machine, specially designed to mill PCBs

X-Carve – Open Source Hardware project

PocketNC – An US based 2012 crowdfunded startup providing professional 5-Axis CNC machines that fits in a desktop table and can mill on 4140 Aluminum

Isel AG – A German company providing end to end desktop sized CNC machines and OEM user replaceable part manufacturing for their machines.

5 ADVANTAGES

Some of the major advantages of our CNC machine are as follows:

- Low-Cost 3-axis CNC Automation.
- Low-Maintenance Design.
- PCB manufacturing using precision milling technique at incredibly low cost.
- Z-axis tool can be fitted with a spindle motor or a Laser diode module (for laser engraving).
- The whole system is 12V operable and 24 volts tolerant for industry standard DC supply scenarios.
- High torque steppers and spindle perfect for low to medium speed milling operations.
- Hard Rubber, Soft Metal, Wood, PVC, PET and other plastics can be milled and engraved upon.
- Y-Axis workpiece supports 2.8kg maximum load without noticeable vibrations
- guiding rods for smooth and strong X to Z axis gantry coupling.

6 LIMITATIONS

With 85Watts maximum power output from all the 3 axes, this CNC machine cannot mill on alloy steel or hard metals. The Depth of Cut (DOC) is also limited to 3mm maximum for 2000rpm spindle motor. Greater DOC (>1cm) can be achieved with higher speed spindle motor(12000rpm) which we aren't able to use in order to keep the design and prototyping costs low. The steppers have 200steps/revs resolution which gives 0.8mm minimum pitch and 0.06mm positional accuracy. With high quality, imported (2000steps/revs) motors, we can achieve even greater positional accuracy in the terms of 0.01mm.

7 CONCLUSIONS

Our project prototype described in this paper is a very generic approach to low-cost, affordable and connected machining centers. With the advent of the recent automation trend-INDUSTRY 4.0, we need more and more of these kind of machining products for specific industrial needs which will provide a connected ecosystem for the machining needs and serve as a platform for generation of huge manufacturing insights through IoT based data aggregation in the Cloud.

ACKNOWLEDGEMENT

The completion of any project brings with it a sense of satisfaction, but it is never complete without thanking those people who made it possible and whose constant support has crowned our efforts with success.

I would like to thank Prof (Dr.) Anil Kumar Bag of Heritage Institute of Technology, Kolkata for letting us form a group and carry out the project and also for allowing us to use the college infrastructure to complete the project and test it. We hereby thank our respected Head of the Dept. of Applied Electronics & Instrumentation Dept., Prof (Dr.) Madhurima Chattopadhyay for providing constant inspiration.

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us with the required facilities and supports towards the completion of the project.

*All the photographs given in this project has been taken on authors' personal mobile phone camera.

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