Design Development of Computer Numeric Controlled Milling-Cum-3 D Printing Hybrid Model

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Abstract. This work proposes design development of a new Computer Numeric Control (CNC) milling-cum-3D printing hybrid model. The successful prototyping of the machine with CNC Milling and 3D Printing ability may be accessed as a workstation and is viable for limited production. Initially the layout of the machine is designed on Google SketchUp providing a model for reference with correct dimensions and proportional imagery. After the construction and assembly of the mechanical components, motors are mounted and transmission system is calibrated. When the motor dryrun calibration is completed, electronics connections are formulated. Obtaining the correct microstep settings in coordination with software pulsing is accomplished after using combination of several iterations. Computer controlled calibration to define the actual dimensions of the work area is done considering the endstop placement and actual physical bounds. Open source software like Autodesk 123D design, Repetier host, ReconstructMe, Slicer and CamBam are also used to ensure that the work holds minimal prototyping cost. The performance evaluation hybrid model so developed is presented to ensure that the prototype is effectively functioning.

Keywords: 3D printing, additive manufacturing, CNC milling, hybrid model, open source software, optimization, prototyping

1 Introduction

CNC refers to Computer Numerical Control [1]. It is an automation process in which a part of the machine is controlled with no (or indirect) human interaction. It executes

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directions provided by computer generated programming codes based on algorithms that consist of numerically calculated formulations [2-3].

A CNC machine may be used for additive or subtractive manufacturing [4]. For subtractive manufacturing [4] applications, a CNC machine is equipped with a milling head or a laser apparatus and for additive manufacturing [5], an extruder head is used. The former is called a milling machine whereas the later refers to 3-D printing. Milling machines are used in metal removing and fabricating industries, firearms, electrical discharge machining applications, pharmaceutical industries, biomedical applications, food and beverage industries etc. [3-6]. 3D printing is basically used to develop parts by layer through additive manufacturing which is being largely used towards mass customization, prototyping, and open source designing in cultivation, radar and aviation, healthcare, locomotive, aerospace and automotive industries [7-10].

In past, many researchers have proposed different types of additive [4,5] as well as subtractive manufacturing [6-9] technologies separately, but the amalgamation of 3D-printing and CNC milling arrangement in a single machine, what is called here as hybrid model' is scarcely found in the literature. In 2015, Quan et al. [8] discussed over the opportunities and applicable challenges towards 3D printing for studying the large fidelity between additively manufactured models and reinforced composite structures. In 2017, Lynn et al. proposed Voxel based models [11] for customizing the digital based subtractive manufacturing [12]. In 2017, a comparison between application of subtractive and additive manufacturing technique with reference to biomedical implementation was presented in [13]. Paper [14] reported the research gaps in developing hybrid workstations capable of doing milling and 3 D printing on a single machine. In 2019, Marcel and Wings [15] presented the architecture of a hybrid CNC machine using fused layer modeling (FLM) technique, but the same paper was limited to the theoretical aspect only.

Traditional manufacturing techniques for several daily as well as scientific applications are either expensive or time consuming. In most of the prior arts available in the literature [2-15], the practical implementation and prototyping of a single machine (what is called here as 'hybrid model') capable of doing both milling and 3D printing is missing to the best of our knowledge. As a result, the thought of an integration of CNC milling machine with 3D Printing [3] technology sounds to be a perfect advancement in technology. In a Hybrid model, a CNC milling (subtractive manufacturing) and a 3D printing (additive manufacturing) apparatus is used in conjunction on the same CNC machine. Consequently, an identical precision profile is achieved for both techniques of manufacturing. This also enables the possibility for implementation of composite structures by using both methods of manufacturing simultaneously.

In this research, the design development of an innovative CNC milling and 3D printing hybrid model is proposed. The machine so developed is capable of doing additive and subtractive manufacturing at a time and separately as well. Hence, the cost of installation, maintenance, training etc also minimised. The real time implementation process includes uses of free software (open sources) like Arduino IDE [16], Repetier Host Software [17], CamBam [18], Slicer [19-20], SketchUp [22], Autodesk 123D [24] and ReconstructMe [26]. This has significantly reduces the cost in prototype stage as well. This paper has manifold contributions. Firstly, a novel hybrid model integrating 3D printing and CNC milling facility is proposed and developed with production capability; secondly, this model is realized by use of open source software which is going to save additional burden and costing in its manufacturing; thirdly, the proposed model will make the prototyping easier and an inexpensive deal; and fourthly, the suggested future scope in this paper generates an opportunity for researchers to deep dive and explore the optimization of CNC milling and additive manufacturing parameters by the novel application of evolutionary algorithms like Symbiotic Organism Search (SOS)[27], Teaching learning based optimization(TLBO)[28] and many others.

The paper is organised as per following details. Section 2 discusses the design development of the machine. Section 3 elaborates machine electronics software interaction followed by Section 4 which gives the results and performance evaluation. Section 5 deals with the applications and future scope. Lastly some conclusions have been drawn in section 6.

2 Design and Development of Machine

The design and development aspect proposed in the paper covers all areas such as design, mechanics, electronics and software used. The concept lies in making of printed 3D models through computer-aided design (CAD) [1-2, 25] software with the help of a 3D scanner. Such models results in minimal errors with options for corrections before final printing. 3D scanning refers collecting data in digital forms on the real object's appearance and creating its digital model. As soon as it is done, STL file [21] is processed by well known software "slicer" [19-20] that transforms the model to a series containing slices of thin layers. It may be mentioned here that an STF file does not represent any texture, colour, or other common attributes but only 3D appearance. It follows producing G-code [2] files that have instructions tailored to some particular 3D printer type (say FDM printer). Such G-code files may be printed with the help of 3D printing client software (that loads G-code, and applies the same to command the complete 3D printing process). The machine philosophy used in this project is a Cartesian style open design with 3 independent axes allowing 3 degrees of freedom. The work volume is 500mm x 700mm x 200mm in width, length and height respectively. The machine is built from high quality materials like 6061 aluminium plate and stainless steel. The choice of two different materials for two different axes is done to reduce vibration by resonance which is produced due to moving parts and the high frequency spindle motor. The frame and the components setup is designed in Google SketchUp [23]. Since this CAD software is precise in measurement implementation to the 3D graphic, it is very convenient to assemble the fabricated components referring to this. The electronics system consists of open source components like Arduino Mega 2560 [16] and ramps 1.4 boards. The Electronic components interact with the computer system over a USB connection. The design of the system consists of the Arduino powered ramps 1.4 board which is an open source design for a CNC and a 3D Printing Setup. Figure 1 displays the block diagram of proposed electronic systems which is involved in our work. The motion system consists of 4 micro-stepping drivers for 4 stepper motors. The micro-stepping drivers are separately powered by a 24 V power supply. The CNC machining circuit consists of a 400W DC spindle motor controlled through a pulse-width modulation (PWM) speed controlling Circuit [16]. The Spindle motor is also separately powered through a different power supply unit. The 3D printing circuit consists of an extruder stepper motor which is controlled by the micro-stepping driver plugged directly onto the

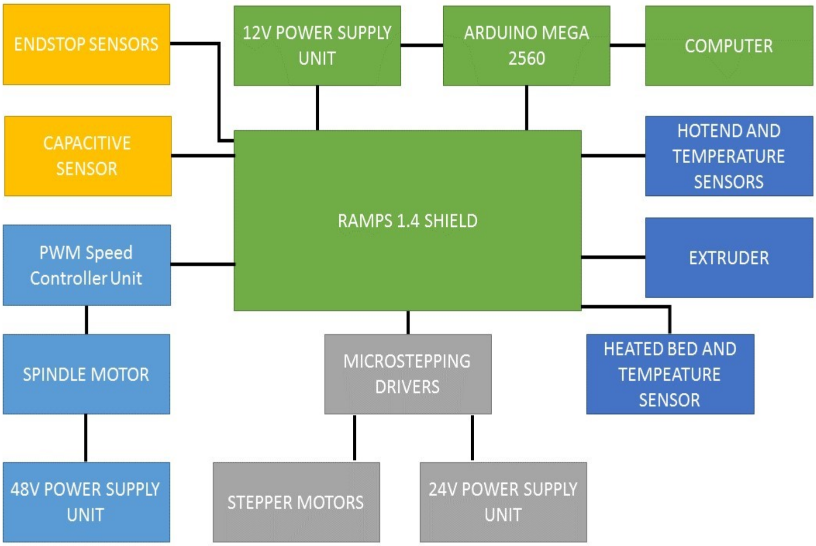


Fig. 1. Block diagram of the Electronic Systems for the proposed CNC Milling-cum-3D printing hybrid model.

amps 1.4 board. The hot-end and temperature sensors are plugged directly into the ramps 1.4 shield which directly supplies it with power. The heated bed is also controlled directly by the ramps 1.4 board which has a dedicated MOSFET unit for controlling the temperature. The machine runs on serial interface with the computer and also contains an independent environment to engrave and print using G-code files on an SD card. Major softwares used are arduino IDE, repetier host software, CamBam, Autodesk123, and ReconstructMe. For details of specific software, readers may refer to specific cited papers/links with corresponding references.

3 Machine-Electronics Software Interaction

The work-course of the system starts with a 3D design or a 3D model which is obtained by Autodesk 123D design [24-25]. The 3D model is then converted into a sequence of G-codes. The machine consists of X, Y and Z axes which are controlled by G-codes fed into the Arduino microcontroller which runs on the Repetier Firmware configured for this machine. The G-Codes are either stored on an SD card or sent through the Repetier host software.

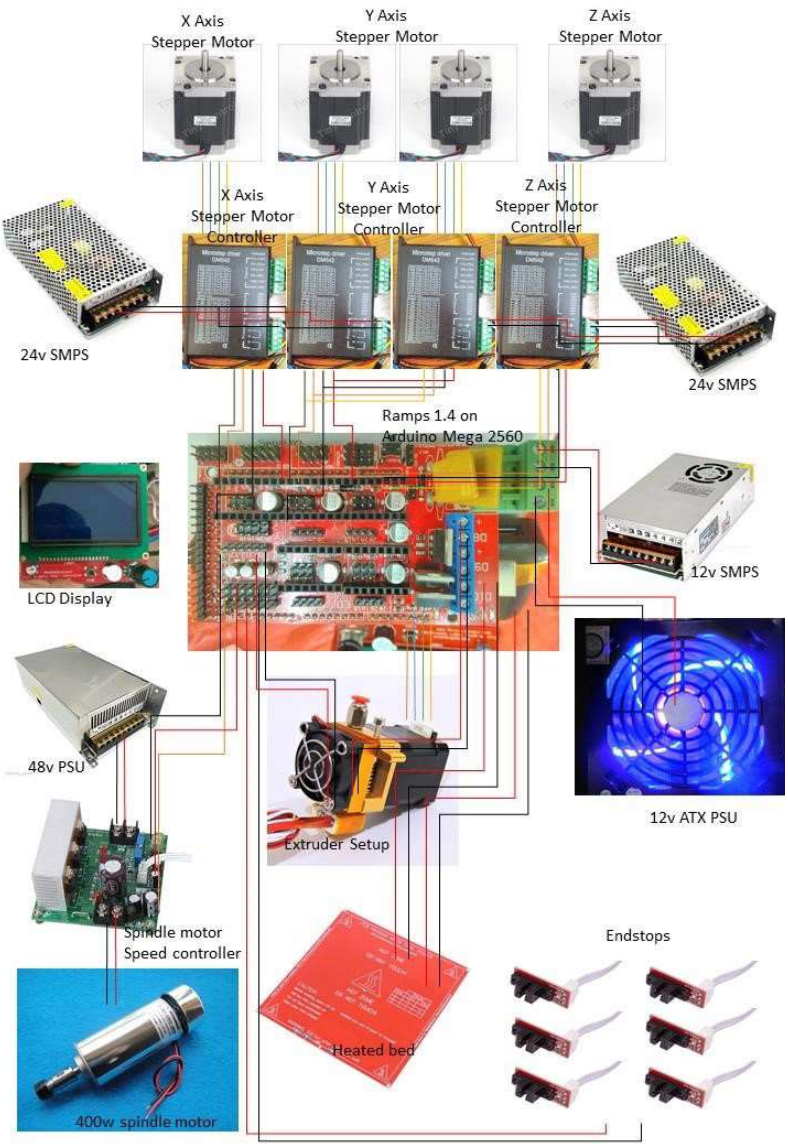


Fig. 2. Indicative representation of the circuit diagram of the CNC milling-cum-3D printing hybrid model

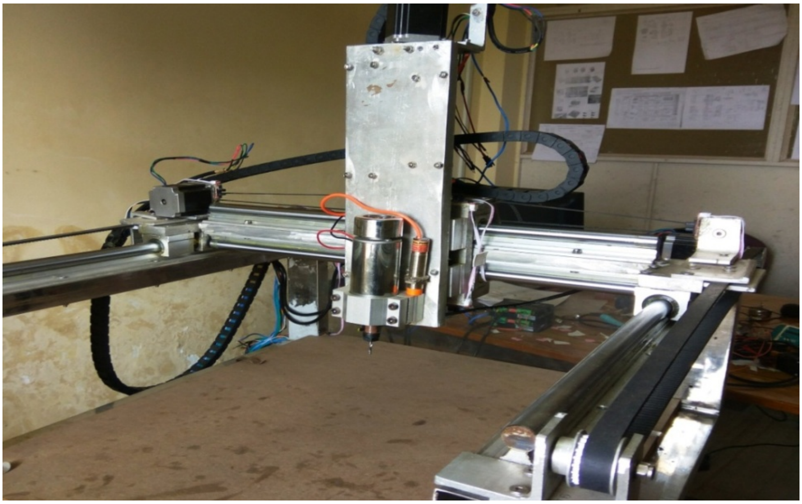
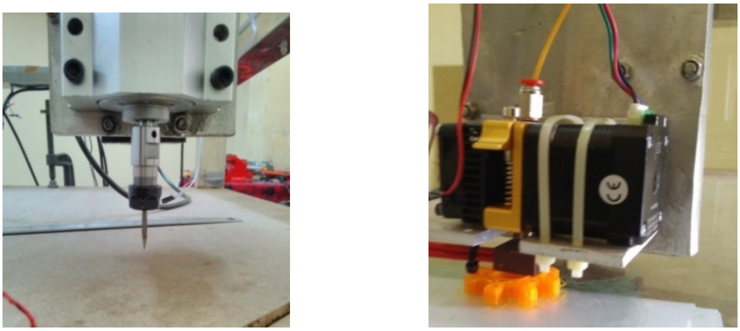


Fig. 3. Working model of the proposed CNC Milling-cum-3D printing work-station



(a) CNC milling (b) 3D printing

Fig.4. Hybrid prototype demonstration

The Repetier firmware [17] is the governing operating system of the machine. It controls and executes G-code commands and the machine motions.

The circuit of the proposed work consists of several standalone components connected to the main controller board through wires of different gauges and kinds. The heart of the circuit lies at the Arduino mega 2560 [16] controller board running Repetier firmware. The Arduino hoard has a ramps 1.4 shield over it. All the wiring connections are done directly on the ramps 1.4 shield. The indicative representation of the circuit diagram of proposed system is displayed figure 2. Figure 3 gives the original prototype of the integrated CNC milling-cum-3D printing hybrid model developed. The demonstration of the hybrid model of the CNC milling and

3D printing of the developed prototype has been illustrated in figure 4 (a) and figure 4(b).

4 Results and Performance Evaluations

For performance evaluation, different tests including traversal jogging test [15], CNC milling test [15] and 3D printing tests [15] are performed. The traversal test consists of three parts- microstep calibration, velocity calibration and the endstop homing calibration. During microstep calibration, the axes were moved in each of the dimensions separately. The actual distance and the expected distance were compared for 0.1mm, 1mm, 5mm and 13mm in the X and Y axis and for 0.05mm, 0.1mm, 0.3mm, 1mm and 10mm in the Z axis. The configuration that was found to give the smoothest results is shown in Table 1. Velocity calibration consisted of tests for calibrating the speed and acceleration in each of the axis for zero-vibration motion. Each axis was again tested for several feed rates for both CNC milling and 3D printing applications on different materials. Table 2 given below may be referred to see the optimum feed rate for CNC milling that was practically found on acrylic. It can be noted from the same table that feed rates for acceleration were set for default values; however, the actual feed rates are governed by the G-code for a particular milling or printing job. The CNC milling spindle is tested at different value in terms of rotation per minute (RPM) for different materials. The different milling heads are also tested on different materials. The results were noted and displayed as in Table 3. The Repetier firmware is then configured accordingly for the PWM control. The accuracy in depth is found to be upto 0.01mm. The error in the x and y axes are not more than 0.05% which is negligible. The 3D printing apparatus was tested thoroughly by using two different materials namely Polylactic acid material (PLA) and Acrylonitrile butadiene styrene material (ABS). Table 4 shows the actual settings that were found to be apt for 3D printing application. The setting up of temperatures as per Table 4 results in some minor errors in different print category which are displayed in Table 5. The maximum error that is found with ABS material is 0.05 (5%) and that with PLA material is 0.02 (2%) which is negligible in both cases.

Table 1. Configuration and results during microstrip calibration

Axis	Microsteps (Pulse/rev)	Software pulsing/mm

Z	3200	1600
Y	8000	64
Z	400	2560

Table 2. Optimum feed rate for CNC milling on acrylic

Axis	Machining(mm/sec)	Homing(mm/sec)
X	200	80
Y	200	80
Z	5	3

Table 3. Performance of the CNC milling spindle at different rpm and different materials including acrylic, medium density fireboard (MDF) and wood

Material	Speed Range (RPM)	Milling Head Type	Milling Head diameter
Acrylic	10000-12000	Steel	0.5mm Tapered
MDF	9000-11500	Steel	3mm Twisted
Wood	9000-10000	Steel	3mm Twisted
Aluminium	5000-6000	Steel, Carbide	3mm Flat

Table 4. Performance of 3D printer using PLA and ABS materials

Material	Printed Temperature (℃)	Extruder Temperature (℃)
ABS	95-105	220-240
PLA	0-55	200-210

5 Applications and Future Scope

5.1 Applications

The model proposed in this paper has production potential and may be applied for a wide application both in computer numeric control (CNC) milling and 3D printing areas. The CNC milling may be done for manufacturing of electronics parts, machine engraving applications, composite-machining, 5 axis machining, biomedical milling for prosthetic applications, machining aluminium and plastics, and drilling etc. Being hybrid architecture, the same machine may be implied for 3D printing for prototypes and functional production parts for robots, drones and other embedded systems, developing tough machine components and accessories for high tech products, creating new structures and forms to improve existing objects for automotive, biomedical and retail industries. The development of commercial products at large scale using the proposed project is beyond the scope of this paper.

Table 5. Results in error obtained on 3D printing using ABS and PLA material at specified temperatures

Material	Print Name	X warp (mm)	Y warp (mm)	Z warp (mm)
ABS	5x5x5mm calibration cube	0.04	0	0.05
PLA	5x5x5mm calibration cub	0.02	0.03	0.01

5.2 Future Scope

The work presented here has a scope for improvement without major design changes. Possibilities for improvement include installation of an automatic changing mechanism to rapidly switch between CNC milling and 3D printing apparatus, installation of laser engraving and cutting heads on the same hardware setup and improvement of electronics design for a more integrated solution of control electronics and power supply. Further improvement in the efficiency of the machine may also be achieved by applying various powerful evolutionary and meta-heuristic algorithms like SOS, TLBO, Crow search algorithm etc. These type of algorithms can be applied to improve both the subtractive and additive manufacturing parameters like cutting speed, cut-depth, material removal rate (MRR) and surface-roughness. Apart from this, by the use of other soft computing approaches, the process parameters and desired quality outcomes can be achieved. Different approaches towards the optimum utilization of different parameters of machining may further give better results in performance of the machine.

6 Conclusion

The research project has been successfully implemented and the end product is in compliance with the expected outcome. The complete prototype has been successfully implemented using open source software which makes it low cost and affordable. The CNC milled parts are extremely precise with only MDF showing certain signs of imperfections, mainly due to material properties. Control in X, Y and Z axis has also been found to be precise at satisfaction level with negligible error and maximum repeatability. The accuracy is found to be uniform throughout the build surface and build volume. The machine establishes the possibility of reducing the cost involved in the field of automation, robotics and mechatronics. The present research may prove very encouraging with regard to the purpose of training & research activities towards commercialization and start-up ecosystem.

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