# A LOW-COST BUILD-YOUR-OWN THREE AXIS CNC MILL PROTOTYPE

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**Abstract- Hands-on laboratory instruction is essential to improve student learning in engineering education. In the area of CAD/CAM/Manufacturing Technology lab courses, the high cost of commercial CNC machines like mills and lathes limits the quantity of machines accessible to the students. In this paper, a low-cost, build-your-own (BYO) three axis vertical computer numerical control (CNC) mill prototype is developed using off-the-shelf components, stepper motors with drivers, Arduino open source microcontroller, and open source motor control software. The machine can be easily customized for modification and replication and provides students better access and insight into the operation and use of CNC mills.**

**Index Terms- Arduino microcontroller, Build-your-own technology, CNC mill, open source hardware and software.**

## I. INTRODUCTION

Modern manufacturing industry has become highly flexible and specialized due to the use of computer numerical controlled machines and robotic systems. This has been necessitated by the emergence of planned obsolescence, popularity of high-tech gadgets with short lifetimes, and popularity of fast-changing fashion items like clothing. As a result, computer aided design (CAD), computer aided manufacturing (CAM), CNC technologies, and robots are at the heart of flexible manufacturing systems (FMS) and computer integrated manufacturing (CIM).

Laboratory education in CAD/CAM software and CNC machine programming and operation is central to the teaching of mechanical, manufacturing, and production engineering students at the undergraduate level. However, in many Indian engineering educational institutions the CAD/CAM and Manufacturing Technology Laboratories are equipped mainly with large commercial CNC machines which are prohibitively expensive and moreover are overdesigned considering the pedagogical needs of undergraduate students. They come with costly annual maintenance contracts and are time-consuming and expensive to repair in the case of breakdowns.

Many of these arguments hold good in the case of polytechnic colleges in India, which are heavily hands-on and are in need of affordable laboratory CNC machines. The situation is similar for specialized research laboratories in related fields like control systems, e.g., [1]. In view of the above factors, it is desirable to come up with in-house, build-your-own, or do-it-yourself (DIY) design, development, and testing of laboratory equipment and systems, e.g., [2], [3]. Therefore, low-cost, desktop and small-to-medium sized CNC machines such as mills, lathes, routers, and laser and plasma cutters can be built with an open structure so that the construction of the machine is clear and understandable to the students. The cost of the machines may be minimized by using inexpensive yet sufficiently powerful off-the-shelf stepper motors and servomotors with motor drivers. Legacy controllers can be replaced with PC-based control systems with low-cost data acquisition (DAQ) cards and sensors.

In recent years, developments in high strength magnetic materials have led to availability of compact, versatile, high power, high torque stepper motors and AC/DC servomotors with built-in optical encoder feedback at low-cost. Likewise, sensors such as optical encoders and Hall Effect sensors, tachometers, and load cells are also becoming smaller and cheaper. The increasing popularity of low-cost network technologies such as wireless Ethernet, Bluetooth, Xbee, and wireless sensor networks, have also resulted in an ability to interconnect the limited number of available CNC machines to the multiple desktop, or student-owned laptop, personal computers in the laboratory, improving student access and reducing wait times.

In this paper, a low-cost, desktop prototype 3-axis vertical CNC mill is developed for purposes of student experiments in CAD/CAM and CNC programming areas. Open source microcontroller platform Arduino is used for control of the motors, and open source software is used for executing the G code and M code for machining applications.

## II. REVIEW OF LOW-COST CNC MACHINE DEVELOPMENT

Given the limitations of commercial CNC machines for large scale deployment in educational environments, several authors have studied the development of such machines on a smaller, low-cost scale. For example, Pabolu and Srinivas [4] have designed and implemented a three axis CNC machine using an 8-bit microcontroller. The development is in .Net platform using C# programming language on a Windows XP computer, but the motors have limited power. Andrei and Nae [5], [6] have developed a simpler commercial size CNC router (worktable dimensions: 624x824 mm) running with Mach3 software on a desktop PC, but requiring a parallel port.

A low-cost, desktop design and evaluation of a CNC machine for modeling and educational purposes is proposed by Pahole, et al. [7]. The working dimensions are 180x140x250 mm. The static rigidity and positional accuracy of the machine are experimentally measured, and the commercial Mach3 machine control software is used with a parallel port-equipped personal computer. Sherring da Rocha, et al. [8] have presented a prototype CNC machine under development running on a PC with LabVIEW which has advantage of ease of visual programming tools. The PC is interfaced with low-cost embedded microcontrollers through the serial port.

The CNC machine designs above rely on the use of stepper motors of limited power in open loop mode. Xu, et al. [9] discuss results of research on an open CNC system using Windows PC with a four-axis motion controller. Wang, et al [10] have developed a CNC system using real-time Ethernet for connection to machine hardware under the Windows NT operating system, with the non-real-time aspect of the operating system accounted for, e.g., by buffering of packets sent. As Windows OS is not guaranteed to provide real-time performance, the use of RTLinux for a software-oriented CNC system with a prototype controller is presented in [11].

A major new development in computer technology is the availability of low-cost open source hardware, such as the Arduino microcontroller platform [12] and the Raspberry PI single board computer [13]. An advantage of open source hardware is that a wide variety of ready-to-use software is available for them on the Web, therefore the prototyping and development times are drastically reduced. Moreover, a wide range of low-cost interfaces, sensors, and accessories such as Arduino shields are also available on the Internet, along with clear instructions, examples, and applicable program code.

Predating the open source hardware, several useful open source software tools have been available in the area of CAD/CAM/CNC software, though these are not so versatile or powerful as the well-established commercial versions. However, for the development of low-cost educational models of CNC machines, such tools may be quite adequate from the viewpoint of machine control. Therefore, in this paper, the development of a prototype 3-axis desktop CNC mill using Arduino-based control system is presented.

## III. PROTOTYPE 3-AXIS CNC MACHINE

### A. Mechanical System

To speed up the development of the CNC prototype system, a ready-to-assemble CNC carving machine kit from Zen Toolworks, USA has been used in this work [14]. The kit is supplied with three stepper motors for the three axes, the frame parts, the lead screws, guide rods, anti-backlash falans and springs, and related accessories. The body of the machine is made of high density PVC boards. It has a fixed gantry and a mobile bed, and therefore a limited working range which however compares well with the specifications of the commercial CNC mill currently under use in our laboratory.

The main specifications of the assembled CNC machine are listed below:

Table 1. CNC machine characteristics

| | |
|---|---|
| X axis travel | 178 mm (7") |
| Y axis travel | 178 mm (7") |
| Z axis travel | 50 mm (2") |
| Stepper motors | 3xNema 17, 1.8$^{o}$, 200 step/rev, 2-phase, 4 wire, bipolar, 1.3A |
| Lead screws | Stainless steel, 3xM8x1.25, 20 tpi |
| Spindle motor | 24-36 V DC, 5000-8000 rpm, 0.3A no load |
| Power supply | 24 V, 15A, 360 W, switching power supply |
| Stepper motor drivers | 3xsingle axis, rated 3A, peak 3.5A, 24V DC rated, up to 1/16 |

| | |
|---|---|
| | microstepping, adjustable step, current, and half-decay |
| Microcontroller | Arduino Uno, R3 board, with ATmega328P @ 16MHz |

A photograph of the assembled CNC machine is shown in Fig. 1. The rotary tool shown is temporarily used for milling and carving, and is to be replaced by the spindle motor specified above.

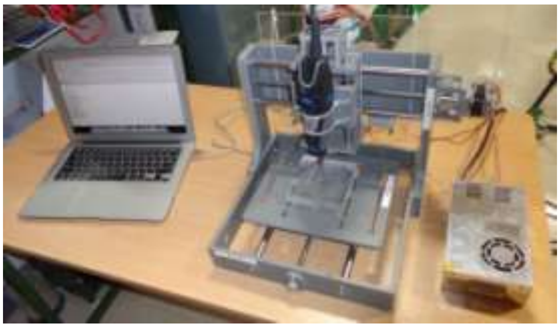

Fig.1. Assembled 3-axis CNC machine

B. Electronic Control System

Fig. 2 below shows the connections to the Arduino microcontroller and stepper motor drivers for controlling the CNC machine. For space saving convenience, the electronics assembly is mounted on the rear of the gantry.

The single-axis TB6560 stepper motor driver from SainSmart [15] is used each axis of motion, so that in the case of motor drive problems the single boards can be swapped out, without the trouble of replacing an entire multi-axis driver board. Of late, dedicated Arduino shield stepper driver boards to interpret the machine motion commands sent by the microcontroller are also available on the market.

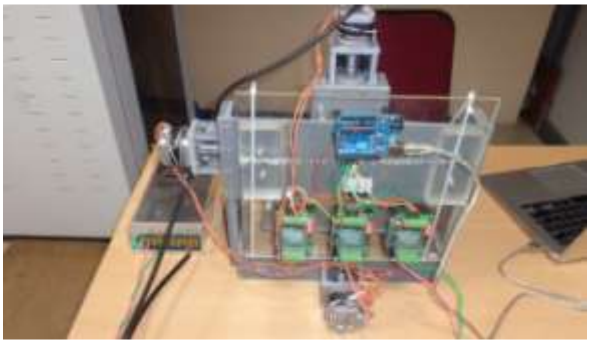

Fig. 2. CNC control electronics assembly

The basic configuration of the SainSmart single-axis stepper motor driver board is shown in Fig. 3.

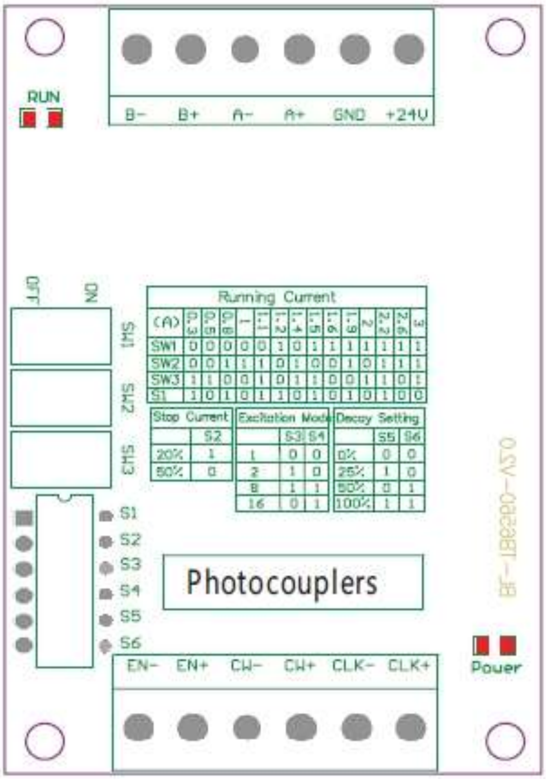


Fig. 3. Configuration of stepper motor driver [15]

The DC power supply is connected between +24 V and Ground, and the motor Phase A (B) windings are connected between A+ and A- (B+ and B-). The connections to CLK+ and CLK- pins control the stepping motion (known as pulse, PUL, in some other drivers), while the connections to CW+ (counterclockwise) and CW- (clockwise) pins control the direction of motion. The EN+ (disable) and EN- (enable) indicate the enable pulse connections, but it is not necessary to use them in the case of Arduino program based control.

The slide switches SW1 to SW3 in connection with dip switch S1 are used for controlling the running current from 0.3 A up to 3A. Switch S2 is used to control the stop current (ON: 20%, OFF: 50%), S3 and S4 are used to set the excitation mode (from whole to 1/16 steps), and S5 and S6 are used to control the decay setting.

C. Arduino-based Control

The Arduino board is programmed in a C++ like language in an integrated development environment (IDE), and comes with built-in example codes known as sketches. The sketches can be used as basis for performing basic tasks such as analog and digital input/output, and for operations using various Arduino shields which are expansion modules that can be stacked on top of the Arduino. Some of the shield applications are GPS, GPRS/GSM, Wi-Fi/Ethernet, SD card storage, LCD/TFT displays, servomotor and stepper motor controls, and so on. Extensive built-in libraries are available online with custom code for various applications and compatible hardware is made available by the open source user community.

Table 2. Main Arduino Uno specifications

| | |
|---|---|
| Microcontroller | ATmega328 (8-bit) |
| Operating voltage | 5 V |
| Input voltage | 7-12 V |
| Digital I/O pins | 14 (6 provide PWM output) |
| Analog Input pins | 6 |
| DC current per I/O pin | 40 mA |
| Clock speed | 16 MHz |
| PC connection | USB |
| External power jack | Yes |

Unlike the Mach3-based CNC systems reviewed earlier which need a parallel/printer port and therefore an older model desktop PC, the Arduino board is interfaced to the PC with a USB connector and therefore the developed CNC machine can also be controlled from a laptop PC. This enables portability in student operations on the machine. In this work, the CNC mill has been successfully able to machine using both Apple (MacBook Air) and Windows PCs.

There are several motor shields available for the Arduino, e.g., from Adafruit Industries [16], but they typically have lower rated and peak current ratings for Nema 17 and more powerful stepper motors. Similarly, the Arduino Uno does not have direct analog output capability and needs modified PWM output for speed control of spindle motor. Therefore, it is planned to port the machine control software and interface to the recent, more powerful Arduino Due board. The Due has a 32-bit microcontroller with an 84 MHz clock, 54 digital I/O pins (of which 14 can provide PWM outputs), 12 analog inputs, 2 analog outputs, and 4 UARTs (hardware serial ports). The Due board thus has ample scope for future expansion.

To avoid the axis motors going out of safe operating range, six limit switches have been tested - two for each axis - using the digital input pins on the Uno. An emergency stop button manual operation has also been tested for the machine. A clamping mechanism for the work pieces on the work table is to be installed in future.

## IV. CNC MACHINE CONTROL SOFTWARE

The basic process of CNC-based manufacturing is illustrated in Fig. 4. The part or good to be machined is designed in a computer-aided design (CAD) software, whose output is a drawing in one of many acceptable formats. This drawing is then fed to the computer-aided manufacturing (CAM) software, whose output is the machine readable code used for numerical control of the machine.


Fig. 4. Process of CNC machining

The machine readable code contains alphanumeric instructions to the machine in the form of G and M code [17]. Typically, it is expressed as N (followed by a three or more digit sequence number), G (followed by two digits, for preparatory functions such as motion commands), followed by X (position along X axis to move to), Y, Z. Other functions include F (for feedrate, or speed of the cutting tool in the cutting direction), M (for miscellaneous commands or functions, e.g., coolant on/off, tool change, etc.), T (tool function), and S (spindle speed function).

Since implementation of the G code is machine dependent, it is necessary to test out different choices for an open source G code interpreter for the Arduino, so that the correct motions are obtained for the machine axes through the stepper motor driver. We have used grbl, an open source G-code interpreter or milling controller for the Arduino developed by Simen Skogsrud [18], [19]. It implements in optimized C a subset of the RS-274/NGC (next generation controller) standard and has been tested to work with the G-code of several commercial CAM tools. It has up to 30 kHz step rate, and achieves precise timing and asynchronous operation. Accuracies of up to 0.1 mm have been reported by users of the software.

Compiled Arduino sketch or program files are in the form of .hex files. An open source Arduino hex uploader program called XLoader (available for download at http:// russemotto.com/xloader/) is used to upload the grbl hex file directly to the Arduino, without the need for a flash programmer. It is available for Windows only, but for Apple or other operating system, the uploading to Arduino can be done first using a Windows computer.

The interface of XLoader appears as in Fig. 5. The user needs to select the appropriate dropdown menus for Arduino Uno, the grbl hex file being loaded, and the correct COM port of the computer to which the Uno is connected, with the baud rate for the Uno being set at 9600.

The next and final step is to use a program to send the G-code for the specific machining job to the microcontroller loaded with grbl. For this purpose, we use another open source program called Universal-G-Code-Sender, which is a Java-based grbl compatible cross platform program [20].

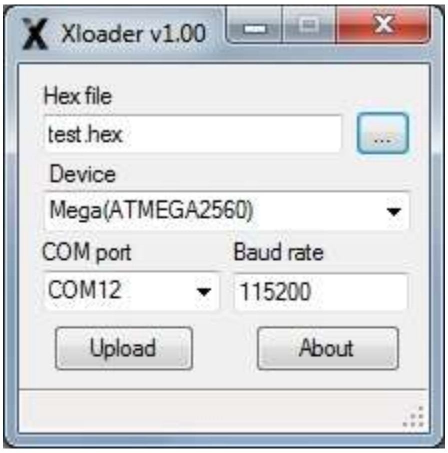


Fig. 5. Use of XLoader program for uploading grbl controller hex file to Arduino

A screenshot of the Universal G Code Sender program in use is shown in Fig. 6.

Fig. 6. Screenshot of Universal G Code Sender program

In this case, we set the correct serial port and baud rate, set line terminator to \r\n, and in the File Mode, select the G-code text file for the machining operation being undertaken. The program is quite versatile, in that it also has a Command Mode in which users can interactively enter G code commands, and a Manual Control Mode in which users can manually increment and decrement motions along the individual axes. The program provides options to reset the current coordinates to zero, or to return the machine to zero positions, as well as perform a homing operation.

An alternative to Universal G Code Sender that works directly with grbl shield for Arduino, is the GRBL Controller [21]. It also has the option to display in real time the current machine position coordinates and the current work position coordinates.

The authors have tested the prototype 3-axis CNC machine with various G code files for carving different shapes in acrylic and wood workpieces, e.g., square with curved edges, circle, and images. Satisfactory results have been obtained in all cases. For learning purposes, the Command Mode of the G Code Sender program prints out a list of options and settings, using which the specifications for the operation can be used and stored on the Arduino, e.g., steps per mm of each axis. Moreover, students can be encouraged to extensively try out the combinations of settings for the motor driver. The CNC kit maker also provides recommended feedrates and cutting depths for different materials.

## V. SCOPE FOR FUTURE WORK

It is planned to scale up the prototype CNC machine in terms of size, use more powerful motors, strengthen the frame and worktable with materials like aluminum or cast iron, and augment the CNC control software with software for simulation ahead of actual run.

For instructional purposes as well as for more precise operation, it is preferable to build CNC machines with DC or AC servomotors and encoder feedback using PC-based motion controllers [22]. The students can be encouraged to explore improvements to the system using alternative open source hardware like the Raspberry Pi, as well as shields. The open structure of the CNC machine will enable the students to gain a better understanding of the design and operation of the mechanical subsystem. Further, as students gain a solid understanding of the open source Arduino microcontroller platform and associated open source machining software, they can be encouraged to build their own prototypes at even lower cost, e.g., using cheaper lower-power stepper motors or recycled motors from old printers, construct the machine frame and work table with cheaper materials like plywood, and innovatively create actuation mechanisms from available stock like threaded rods, e.g., [23].

Machines in general, and robots in particular, are appealing to youth and children. Therefore, exposure to and experience with DIY robots and mechatronic system projects can render engineering education innovative through playful learning [24].

In some industrialized countries, school children are exposed to CNC programming and machining as early as middle school [25]. Therefore, with the power of the Internet, it is also planned to introduce neighborhood school children remotely to Web-based real-time operation of CNC machines, while imparting them basic knowledge of computer-aided art, design, and modeling through open source software such as Google SketchUp [26].

## VI. CONCLUSIONS

This paper has presented the results of development of a low-cost three-axis vertical CNC mill suitable for adoption in undergraduate mechanical engineering laboratory setting. The total cost of the developed system is just about 1/20th of the existing commercial CNC machine used currently in the laboratory, though pedagogically our model provides more scope for hands-on learning by the students and therefore better learning outcomes. It is hoped to extend this work in future to low-cost design and development of other CNC machines like lathe, router, and eventually a BYO or customized open source 3D printer.

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