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Implementation of an Economic Light Duty Three-Axis Computer Numerical Control Machine

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ABSTRACT

The Computer Numerical Control (CNC) is an advanced technology that has automated many manufacturing applications concerning parts machining as well as other applications. This work presents the implementation of a low-cost desktop size 3-axis CNC machine. It has been built from free software and cheap components. It is able for light duty cutting, painting, carving, and drawing. The control system of the machine consists of a PC and a microcontroller running Grbl software, which is an open source free program. The PC has the task of loading files written in a special programming language for CNCs, which is called G-code. It sends the lines of this file to the microcontroller, which parses the code, interpolates the motion commands, and drives the stepper motors of the machine. The system is built and tested experimentally to prove its operation, robustness, and accuracy.

1. INTRODUCTION

Numerical Control (NC) is a programmable automation technology that controls a process by letters, symbols, and numbers. NC machines are mechatronic products composed of mechanical and electrical components in which physical movements in one axis or more are controlled by instructions [1]. NC machines come in a variety of kinds that serve different automated industrial needs such as drawing, cutting, engraving, plotting, 3D printing and others. NCs also provide advantages in digital fabrication of customized parts due to their accuracy and reduced time-to-market. NC machines controllers can be built using transistors, circuits, and logic elements. Modern NC controllers are optimizing the advanced technology of microprocessors and computers to implement NC control functions. NC functions implemented with microprocessors are called Computer Numerical Control (CNC). The CNC workflow starts with an engineered design using Computer Aided Design (CAD) software. The CAD file is processed with a Computer Aided Process Plan (CAPP) that generates the machining necessary information such as machine tools selection, jig and fixture, cutting conditions, and machining sequences. Based

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on the information provided by CAD and CAPP, the Computer Aided Machining (CAM) is carried out to generate the tool paths. The generated tool paths are coded with a special programming language standard (ISO 6983-1) which is known as G-code [2]. G-code contains information that guides the motors of the system and sets some parameters of the CNC control system. CAM software can generate a wide range of G-code extensions based on the type and manufacturer of the CNC machine. Generally, the CNC system composed of Man Machine Interface (MMI) unit, Numerical Control Kernel (NCK) motors and drivers unit.

MMI: composed of a Graphical User Interface (GUI) application that offers the interface between the motion controller and the user. It provides the facilities for the user to load the part program, display the machine coordinates and tool paths, and a command line to send single instructions to the motion controller.

NCK: the part that is responsible for reading the G-code lines, extracts the motion commands, determine the tool paths, and position control the motors by delivering the motors driver units with appropriate signals.

Motors and drivers unit: Includes servomotors or stepper motors and their respective drivers.

Figure 1 shows a typical CNC structure with labels for the key components. It also indicates the 3 axes of movement (X, Y and Z). This is an example of a simple category of the available CNCs. There are tremendous numbers of configurations that differs in the number of supported axes of movements, sizes, and other machining features.

2. SYSTRM DESCRIPTION

The constructed machine composed of a GUI running on a Windows operated PC. It transmits G-code lines to a microcontroller, which is the core of the machine. It runs software that receives G-code lines, processes them, and generates the appropriate signals for the motor drivers. The motor drivers operate the machine stepper motors.

2.1. STRUCTURE

Figure 2 (a) shows the hardware of the designed CNC. In this work, the three primary linear axes X, Y, and Z are considered.

A ball screw shown in Figure 2 (b), which is a lead screw operated by a ball bearing, takes the role of converting the rotation of the motor to linear movement. It also determines the Basic Length Unit (BLU) of the machine tool. Here, three ball screws are coupled with each of the three stepper motors shafts using a plastic tube to reduce the sensitivity to misaligned rotation centers.

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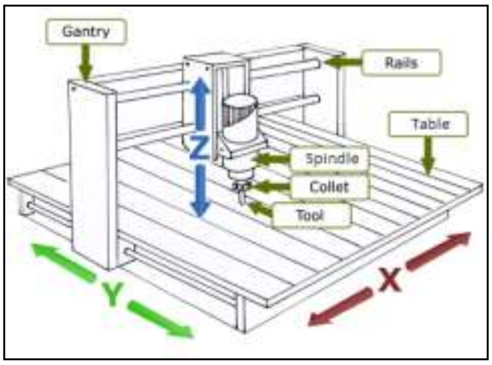

FIGURE 1. 3-axis CNC structure

FIGURE 2. a) The CNC System (left), b) Ball Screws (right)

In order to increase the linear movement accuracy and smoothness, aluminum drawer slides shown in Figure 3 (a), have been proposed as the linear movement guide of the table (Y), the gantry (X) and the spindle (Z).

The work area of the machine is 30x20 cm, and various options of light weight drills or low watts laser diodes can be used as cutting tools.

FIGURE 3. (a) Drawer Slide (left), (b) Stepper motor coupling with slide (right)

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2.2. MOTORS

Generally, CNC machines movements can be accomplished through the usage of stepper motors or servomotors. The control system is of open loop type when stepper motors are used. While in the case of servomotors, the control system would be a closed loop system.

Servomotors work in a closed loop setting where they continuously receive feedback signals forms the encoders. These signals dictate the current position and check whether the control signals executed properly. This setting gives the servomotors advantage over stepper motors in that there is no possible way of losing steps. In addition, servomotors offer high torque and speeds.

Stepper motors are DC motors move in discrete steps. Very precious speed and positioning control can be obtained using stepper motors. They are good for low speed/high precision applications, but their torque is less at high speeds. Stepper motors do not have position feedback. They operate in open loop control system. Figure 3 (b) illustrates the coupling of the stepper motor shaft with the ball bearing screw.

In this work, the used stepper motors are of size NEMA-17 and operated by 12 volt DC power supply.

2.3. STEPPER MOTORS DRIVERS

According to the way of energizing stepper phases, there are two distinct types of stepper drivers, namely, bipolar and unipolar. Unipolar drivers could be implemented with simple transistors circuitry. Their disadvantage is less available torque. Bipolar drivers use more advanced circuitry (H-bridge) that actually energizes all the coils of the steppers which deliver higher torque.

In this work, the A4988 micro-stepping motor driver is adopted. This driver operates bipolar stepper motors in full, 1/2, 1/4, 1/8, and 1/16 step modes [3]. The minimal wiring needed to connect the driver to the microcontroller is shown in Figure 4.

2.4. MOTION CONTROLLER

Grbl motion controller is a C program optimized to utilize all the tremendous features of the Atmega328p chips used in Arduino UNO microcontrollers boards. It is a high performance, free, open source software, and available for three-axis machines (X, Y, and Z). It interprets the G-code lines received serially from the GUI running on a PC, processes them, and delivers the control pulses to the motor drivers. G-code file is of ASCII format, and is composed of blocks. Each block contains a number of words [4]. A word consists of two parts: an address, which is an alphabetical character, and a numerical value. The incorporated G-code interpreter follows a subset of the Linux CNC standard. Grbl (last version is v1.1) supports arcs, circular and helical moves [5] and also capable of processing commands that are related to the coolant system and spindle control.

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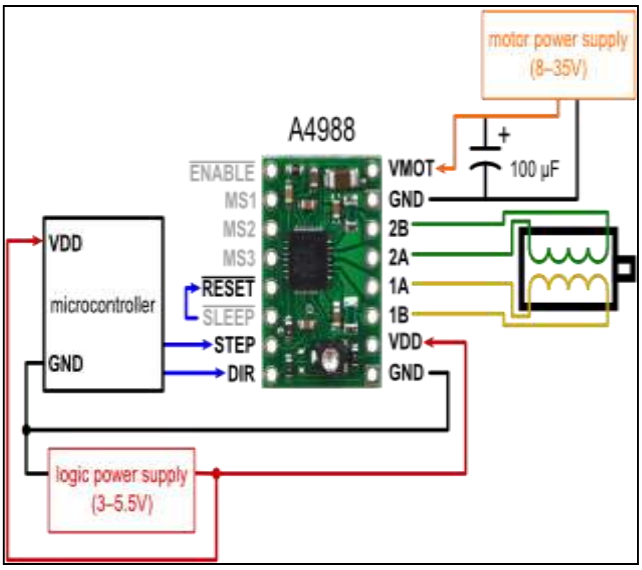

FIGURE 4. A4988 connection diagram

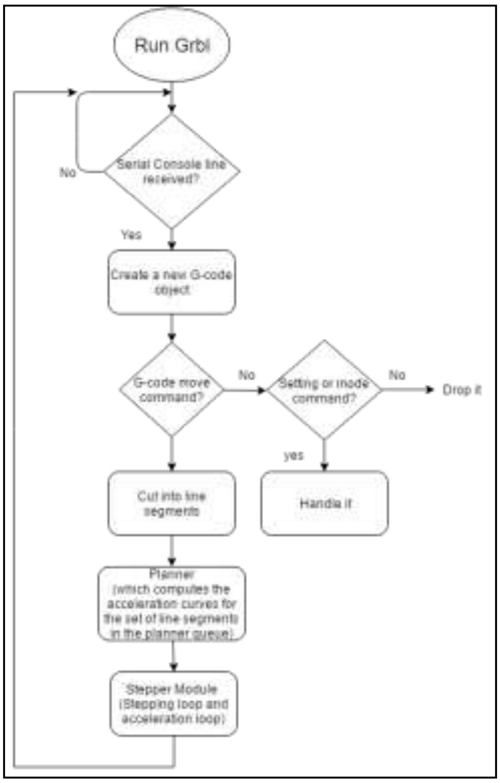

FIGURE 5. Grbl main processing steps

Table 1 lists some of the G and M commands that Grbl v1.1 can handle [5]. The processing steps of Grbl are illustrated in the flow chart shown in Figure 5.

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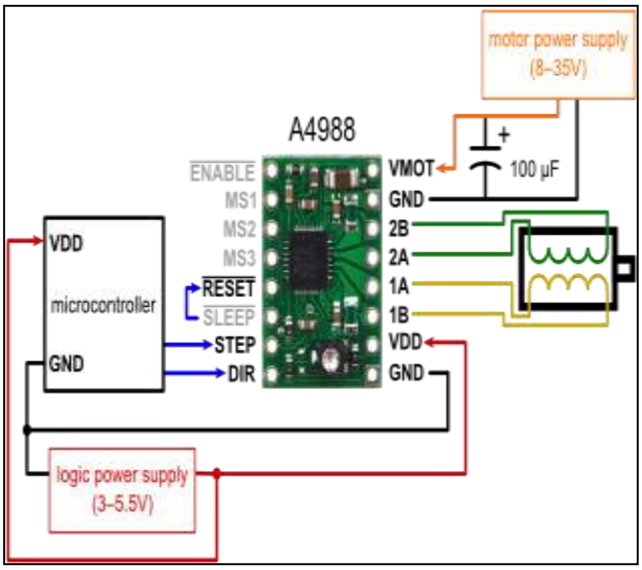

FIGURE 4. A4988 connection diagram

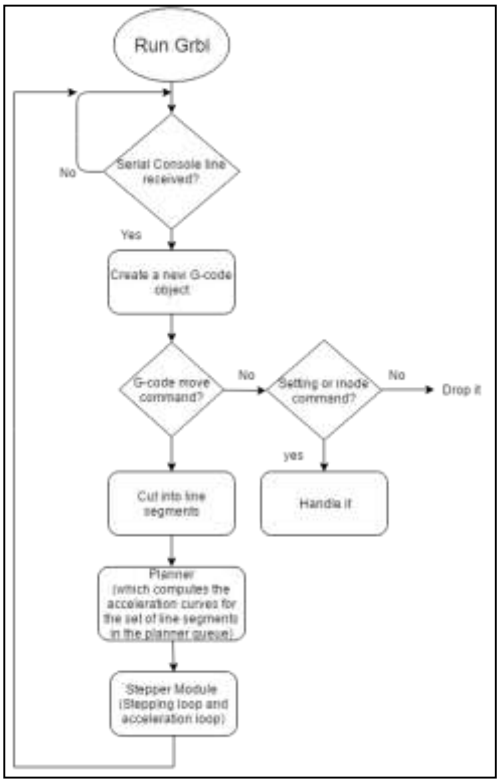

FIGURE 5. Grbl main processing steps

TABLE 1: Supported G-codes in Grbl v1.1

G0, G1	Linear Motions
G2, G3	Arc and Helical Motions
G4	Dwell
G10 L2, G10 L20	Set Work Coordinate Offsets
G17, G18, G19	Plane Selection
G20, G21	Units
G28, G30	Go to Pre-Defined Position
G28.1, G30.1	Set Pre-Defined Position
G38.2, G38.3, G38.4, G38.5	Probing
G40	Cutter Radius Compensation Modes
G43.1, G49	Dynamic Tool Length Offsets

2.5. MACHINING TOOL

Various types of CNCs are classified based on the tools that are used for machining. Laser diodes can be used as a tool for engraving and cutting materials. Drills can be attached to the tool holder and do various cutting and carving operations. Grbl v1.1 offers modes for using drills and lasers. It supports a set of commands that controls the laser power or the spindle speed. The spindle tool of the proposed machine is a 745 mW laser diode that is suitable for cutting and engraving thing materials.

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2.6. SYSTEM INTERFACE

Figure 6 gives an abstract view of system connections while Figure 7 shows the Grbl Controller application. Grbl Controller provides a simplified graphical user interface with all basic functions needed to communicate with it. It opens a USB port with the Arduino UNO at a specific baud rate e.g. 9600 is taken in this work. It offers a single line command that gives users the ability to manually give commands to the machine besides the ability to load a stored G-code file. It also offers a visualizer that shows the tool path of a loaded file. Figure 8 illustrates the G-code file that is loaded to the Grbl Controller GUI. G-code file is obtained from Aspire software which is CAD/CAM software.

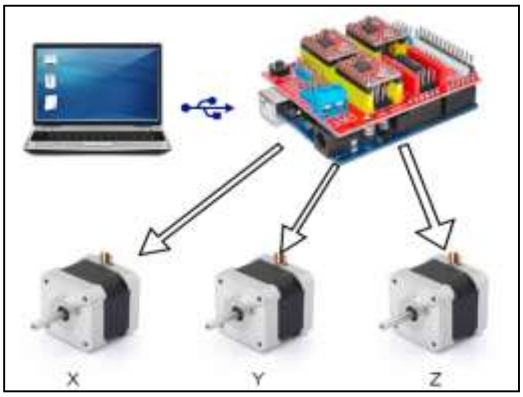

FIGURE 6. System Interface

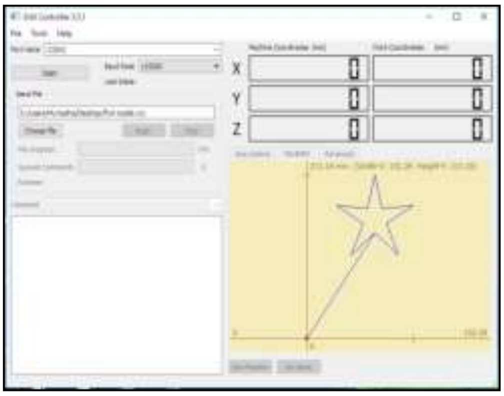

FIGURE 7. Grbl Controller

A CNC shield has been utilized to simplify the wiring of the system. CNC shield as shown in Figure 9 is a breakout board that has been designed specifically to work with Grbl CNCs. It has four sockets that are compatible with A4988 driver, which provides the ability to drive 4 stepper motors, namely, X, Y, and Z, plus one auxiliary motor. It also has additional connectors that facilitate the connection of limit sensors and control buttons.

```
G0X97.501Y137.823Z5.000F150
G1Z0.000F10000
G1X63.646Y108.984F150
X80.611Y150.094
X42.722Y173.381
X87.063Y169.949
X97.501Y213.180
X107.939Y169.949
X152.280Y173.381
X114.391Y150.094
X131.356Y108.984
X97.501Y137.823
G0Z5.000F10000
G0X0.000Y0.000F150
```

FIGURE 8. Typical G-code file

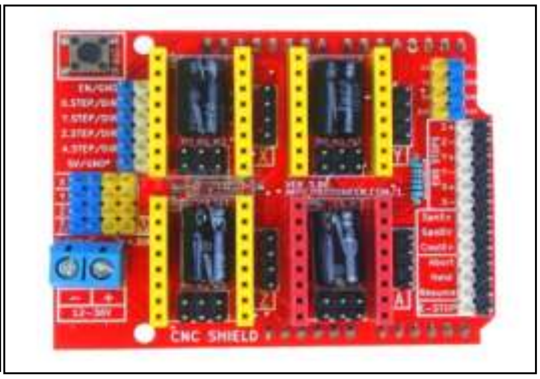

FIGURE 9. CNC Shield

3. PRACTICAL RESULTS

A designed part using 3DMAX, which is CAD software, is shown in Figure 10. This design is saved as a 2D vector file. This file is opened with Aspire, which is CAD/CAM

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software, to create accurate and efficient toolpaths to cut the designed shape, as indicated in Figure 11.

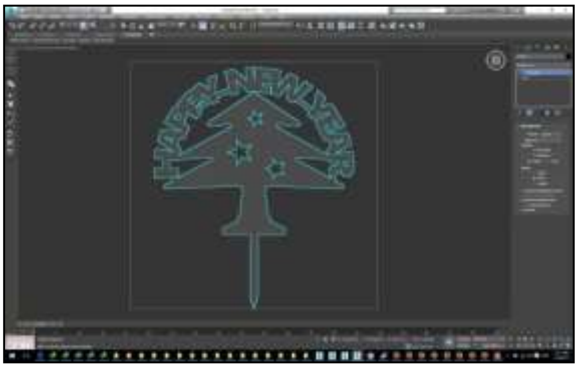

FIGURE 10. A 2D design using Aspire.

FIGURE 11. Tool paths generation with Aspire

The final product after cutting using a laser diode attached to the machine spindle is shown in Figure 12.

FIGURE 12. Designed shape engraved by laser on acrylic material

4. CONCLUSIONS AND FUTURE WORK

In this paper, a light duty 3-axis CNC machine structure and control system have been discussed. The machine has been built using wood, drawer sliders and ball screws. Three stepper motors have been used to move the axes of the machine in the X, Y, and Z directions. The core control of the CNC is achieved by utilizing the considerable features of Grbl v1.1. The system has been tested to draw different shapes designed with CAD software (3D MAX). CAD and CAM software are embedded in current available programs such as Aspire. This program offers the facilities to design the parts and generate the tool paths based on the available profiling options. The generated tool path file, which is called G-code, is loaded to Grbl through serial communication with a Grbl Controller application running on a personal computer. The constructed machine can be utilized in drawing, laser engraving and carving on several types of material such as wood and plastic. This gives the ability to invest this

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machine in producing numbers of products that could be marketed for small business projects.

Through utilizing the advanced technology of System on Chips (SoC), the CNC control system can be integrated in a single chip. Integrated control system of CNC omits the need for external PC and provides more portability and speeds processing of the system.

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