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Design and Build Microcontroller-Based Computer Numerical Control (CNC) Machine

Iqbal Rasyidin[1], Hamdani[2], pristisal[3]
[1,2,3]Department of Electrical Engineering, Universitas Pembangunan Panca Budi , Indonesia

ABSTRACT

Computer Numerical Control (CNC) machining is a system that allows automatic control of machine tools using graphically depicted commands. This study was conducted to determine and create microcontroller-based CNC machines for material processing. It is expected that the use of microcontrollers as the main control instrument will allow CNC machines to operate more flexibly and efficiently. The approach to conducting research includes conceptual planning, component selection, electronic system development, operational management, and performance evaluation. CNC machines are designed to use microcontrollers to drive stepper motors and control the motorization process using G-Code data. The findings of the study show that microcontroller-based CNC (computer numerical control) machines can produce outputs with the accuracy and pressure required for material processing applications. According to the results of the performance evaluation, the machine can operate in different time spans and customer types while providing consistent results. As a result, the use of microcontroller-based CNC machines has the potential to be an effective alternative in the development of material processing technologies with automatic controls that can be accessed and adapted for a wide range of industrial applications.

Keywords: plan; Computer Numerical Control; Microcontroller.

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Corresponding Author:
Iqbal Rasyidin
Department of Electrical Engineering
Panca Budi Development University
Jl. Gatot subroto km 4.5 medan, 20122, Indonesia.
Email : iqbalrasyidin@gmail.com

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1. INTRODUCTION

Modern technology has transformed instrumentation and control systems, among other sectors. High-capability electronic components are used as hardware and software, respectively. The control system regulates, manages, and supervises the conditions that generate certain value as revenue, improving system performance by reducing production costs, improving product quality, and improving time management.

Control and instrumentation systems have evolved since 1930 due to user needs and technological advancements. Computer-based automatic control systems in printing machines are examples of technical improvements. These machines can handle many heavy tasks in a short period of time, helping humans do a lot of things.

CNC machining is an automatic control system that uses abstracted and stored programming instructions to improve the printing machine. This is different from the past, when machines were operated manually or automatically via CAM. (Muchlis et al., 2021). CNC machines replace less efficient and time-consuming printing machines. (Imran et al., 2019).

CNC Plasma machines use laser or flame media, CNC Router machines use media cutters or drill bits, and more. (Anrinal et al., 2022). CNC Router Machine combines CNC machine and router machine. (Sujadi, 2019). The router controls the cutting, while the CNC rotates the cutting tool. CNC Router machines saw, engrave, and cut using the indentation of the cutting edge (Ma'arif et al., 2021).

CNC is one example of the development of machine tool technology. CNC machining is an innovative manual machine that is automatically controlled by an abstract program and stored in a storage medium, in

contrast to ordinary manual machines that are controlled by manual input or simple manipulation using Computer-Aided Manufacturing.
There are different types of CNC machines. CNC Plasma Machines use laser or fire media, whereas CNC Router machines use cutting or drill media. CNC routers combine CNC technology with Router technology. CNC technology drives the machined parts, while Router technology moves the workpiece. There are many ways to use computer numerical control (CNC) machines, such as milling, engraving, and cutting.
When you look at a new CNC machine alongside a standard CNC machine, you'll see that the new machine is more accurate, flexible, and intelligent. There are separate control system parts that are connected to the machine's operational system and then to the next set of electronic parts. This makes the numerical control system on CNC machines work well. At the same time, CNC machines are excellent at mass production, changing dimensions, and making components as small as possible.
In order to improve the quality and precision of the products produced by CNC machines, some researchers have used stepper motors and microcontrollers to make CNC routers more powerful. They are the Mach 3 USB Board and the Arduino Uno R3 which are most often used to build CNC machines. Scientists have found that the Arduino Uno R3 microcontroller works well and accurately. However, it takes a long time to work on and comes up with a lot of things.
To learn more about this issue, more research needs to be done regarding the design and construction of 4-axis CNC Router machine control systems with high accuracy and precision. The CNC router will be 50 cm long, 70 cm wide, and 15 cm high. It will use a Mach 3 USB controller that can use Mach 3 software to control up to 4 axes simultaneously. The Nema-23 stepper motor will be used to control the rotation of the shaft with high success. Compared to the TB6600 series motor driver which has a closer peak current. It is expected that this study will help create CNC routers with high precision and pressure, which will make such products better and more useful.

2. LETERATURE REVIEW

Computer Numerical Control (CNC)

Computer Numerical Control Machine, or commonly called CNC machine, is a term used to describe a machine operating system that is controlled by an internal computer. CNC technology is the best method today to meet the market demand for manufactured components due to the precision and efficiency it possesses (Firsa et al., 2015). In general, a CNC machine is a machine controlled by a numerical and letter code that automatically executes manufacturing operations according to the commands arranged in the numerical code (NC Code).

CNC technology is the best method today to meet the market demand for manufactured components, thanks to the precision and efficiency it has. The working system of CNC technology is more synchronous between computers and mechanics, so that when compared to similar tool machines, CNC machines are more reliable, more precise, and more flexible (Pratama et al., 2022). The reliability of CNC machines is inseparable from its supporting components, such as the operator (brainware), hardware (hardware), and software (software). These components must support each other to obtain satisfactory work results (Syahriza, 2015).

CNC has various types based on the medium used, including: CNC Router (using cutter media or drill bits), CNC Plasma (using laser or fire media), and others (Anrinal et al., 2022).

CNC Router Machine

CNC Router is a tool that is widely used in the cutting and engraving processes in small to medium-scale industries. CNC Router machines are computer-controlled work machines using numerical language (numbers and letters) (Budhi et al., 2021) that produce unique components that are precise and complex parts (Firdaus and Yuhas, 2022).

CNC Router Machines combine CNC and Router technology, with cutters that are able to cut the shapes of wood sheets or other soft materials that have complex shapes and require precision in manufacturing. This combination then forms a computer-controlled cutting machine, using a router machine to cut various

materials such as wood, composite, aluminum, soft steel, acrylic glass, plastic, and foam, by adopting CNC technology.

The cutting movement and cutter trajectory for the X, Y, and Z axes and the A and B axes come from a computer program based on the drawings or contour designs that have been created (Salam et al., 2019).

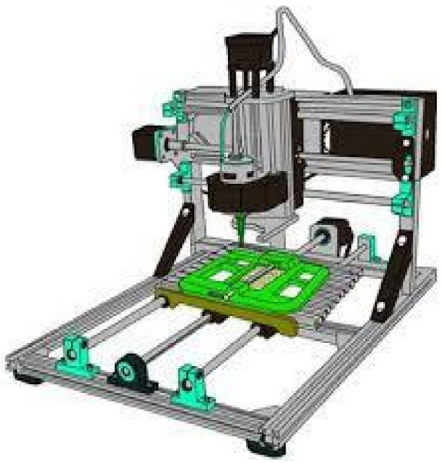

Figure 1. CNC Router Machine (Nayorama, 2016).

CNC Router Machine

The main tool used in CNC Router machines is a blade that is shaped similar to a drill bit. This knife will rotate at a predetermined speed and will cut the wood until it is shaped according to the desired workpiece. Based on their shape and function, Router blades are divided into four types:

1. **Groove Maker Knife**: This knife is used to make a wide variety of grooves and can be used to make joints.
2. **Wood Shaping Knife**: This knife is used to form the edges of wood.
3. **Edge Leveling Blade**: This knife is used to level the edges of wood.
4. **Small Groove Making Knife**: This knife is used to form a variety of decorative indentations on the edges of wood (Nayorama, 2016).

CNC Router Machines have three main functions:

1. **Cutting**: This function allows the machine to cut the material according to the wishes of the operator who operates it using a computer. This minimizes errors in cutting.
2. **Engraving**: This function allows the machine to decorate the material so that it looks nicer and more unique. The resulting product will be very satisfying and beautiful.
3. **Marking**: This function allows the machine to mark the wood to be used. That way, the finishing will be more appropriate and neat.

CNC Laser Machines

CNC Laser (Light Amplification by Stimulated Emission of Radiation) is a tool that has the function of engraving or printing various writing and calligraphy automatically on various media such as acrylic, fiber, aluminum, and wood (Muchlis et al., 2021). CNC laser machines are capable of performing two types of machining processes, namely cutting and engraving.

The cutting process is a process used to cut materials, while the engraving process is a process used to scratch the surface of the material so that the result resembles carving (Marcelina et al., 2021). The CNC

laser machine uses laser technology to cut the material with the working principle of directing the high-power laser to the material to be cut, and its movement is controlled by the computer.

CNC laser machines are widely applied in the manufacturing industry due to their ability to cut and engrave with high precision and efficiency.

CNC Plasma Cutter Machine

A CNC plasma cutter machine is a machine used to cut metal or wood in two dimensions. CNC plasma cutters use plasma torches to pierce wooden or metal sheets. The power required by the CNC plasma cutter is not as much as the power used in the CNC Router.

Plasma is a form of the fourth phase of matter after the solid, liquid, and gaseous phases. If heat is added, ice will change its form from solid to liquid, and if given excess heat, the liquid substance will turn into steam. If the steam is added to the heat again, it will turn into plasma. High electrical voltage is needed to apply force to the electrons of electric current so that it can pass through metals that have high resistance, where as a result of the addition of electrical voltage there is heat (Rahman et al., 2019).

Driver CNC

Parallel ports or known as Line Print Terminals (LPT) are used as a communication medium between CNC machines and computers. Parallel ports have the advantage of communication between computers and other devices controlled using computers, namely being able to send and receive data simultaneously at the same time. The use of parallel ports allows for real-time data communication.

In addition to the use of parallel ports, the operation of CNC machines can use another platform, namely microcontrol which can be used as the main control of CNC machines by using the Universal Serial Bus (USB) which is more flexible in its operation. The use of USB as a communication medium ensures that high-spec computers are not a problem, with several advantages such as hosts/senders and the design process being done on the same computer. USB communication is much faster and in real time compared to parallel communication (Nugroho et al., 2020).

Mach CNC USB Module is a hardware to control CNC machines by managing the G-Code data from the computer and providing a protection system. Meanwhile, Mach 3 works with parallel communication to ensure the speed of data sent and received in real time (Febryanto and Kartikasari, 2022).

Driver Motor Stepper TB6600

The stepper motor driver is a component that functions to communicate the controller with the actuator and amplify the output signal from the controller so that it can be read by the actuator. Stepper motor drivers are used to regulate the direction and rotation speed of the stepper motor. This driver controls the source of voltage that goes into the stepper motor coming from the microcontroller (Choirony et al., 2021).

In this study, a TB6600 driver board motor was used for 4-axis CNC. This motorcycle driver has several ports that will later be connected to each port such as input signal, stepper motor, driver switch setting, and DC power supply (Harrizal et al., 2017).

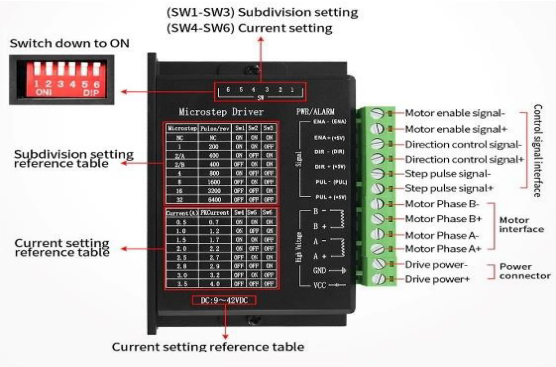

Figure 2. Pin Layout Driver Motor TB6600

Explanation of the TB6600 Driver Pin Layout In the image above, the TB6600 driver layout pin is shown which is divided into three interface control signals. The control signal consists of:

- Positive Pulse Signal Input (PUL+)
- Negative Pulse Signal Input (PUL-)
- Positive Directional Signal Input (DIR+)
- Negative Directional Signal Input (DIR-)
- Enabling Offline Positive Signal Input (EN+)
- Enabling Offline Negative Signal (EN-)

The power connector consists of DC (+) and D (-) which are connected by a power supply with a voltage of 12 – 48VDC. The motor interface consists of phase B-, B+, A-, and A+ motors connected to a two-phase hybrid stepper motor (Anonymous, 2021).

In Table 1. The following explains the specifications of the TB6600 motorcycle driver.

Type	TB6600
Interference capabilities	Anti-high frequency
Input flow	0-5.0A
Output current	0.5-4.0A
Maximum power	160W
Micro step	1, 2/A, 2/B, 4, 8, 16
Temperature	-10~45°C
Moisture	Non-condensing
Heavy	0.2 kg
Dimension	96x56x33 mm

Motor Stepper

Stepper motor is one type of motor that is widely used as an actuator, such as a read or write head drive on a disk drive to set the position of the read or write head on the surface of a diskette, a head drive on a printer, and a robotic linefeed. With the help of a microcontroller or microprocessor, the rotation of the

motor can be precisely and programmatically controlled. Stepper motors work to convert electrical energy into mechanical energy in the form of discrete (intermittent) motor movements called steps using electromagnetic principles (Supriyadi et al., 2020).

The main difference between stepper motors and DC motors is that DC motors have fixed magnets on the stator, whereas stepper motors have fixed magnets on the rotor. By applying the voltage to each phase in sequence, the stepper motor will rotate step by step. This step can be adjusted using a computer to achieve the right position and control the speed, so stepper motors are suitable for work that requires high precision (Fatoni, 2022). In addition, stepper motors are chosen because they can be controlled easily and have high precision (Harrizal et al., 2017). At low speeds, stepper motors will produce large torque. To drive a stepper motor, a stepper motor controller is needed that generates periodic pulses, such as a motor driver.

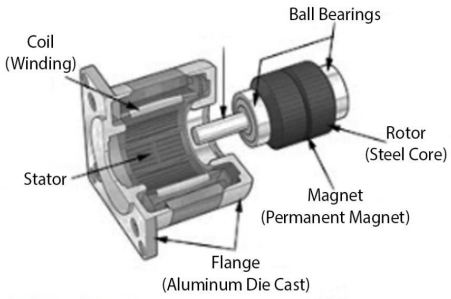

Figure 3. Stepper Motor Construction

In this study, a Nema-23 stepper motor was used. The Nema-23 stepper motor has a torque of 178.5 oz-inches (1.26 Nm), which is suitable for driving materials such as PCB, acrylic, wood, and aluminum.

3. Research Methods

In the design research of the 4 Axis Router CNC machine, the research method involves a series of systematic stages to ensure the successful implementation and evaluation of the machine. And it consists of several systematic stages to ensure the success and evaluation of the machine:

1) Machine Design: Designing all engine components in detail, including material selection and technical specifications such as stepper motor driver and USB Mach 3 controller.
2) Mechanical System: Making the machine frame using holo iron to guarantee the stability and reliability of the machine when operating.
3) Control System: Using Mach 3 USB board as the main controller connected with the stepper motor driver to control the engine's motion axis.
4) G-Code Program Creation: Generate G-Code programs from designs using Aspire software to guide cutting and engraving operations on materials.
5) Axis Calibration: Tests and calibrates the X, Y1, Y2, and Z axes to ensure the desired precision and speed of movement.
6) Operational Testing: Conducting operational tests to observe the performance of the machine under real-world conditions, including cutting materials at varying speeds.
7) Data Analysis: Analyze test result data to evaluate the accuracy, speed, and reliability of the machine in meeting the set goals.
8) Conclusion: Summarize the results of the evaluation to assess the successful implementation of the 4 Axis CNC Router machine as well as provide recommendations for future development.

With this approach, research can be conducted in a structured manner and provides a solid foundation for the development of better and more efficient CNC machining technology.

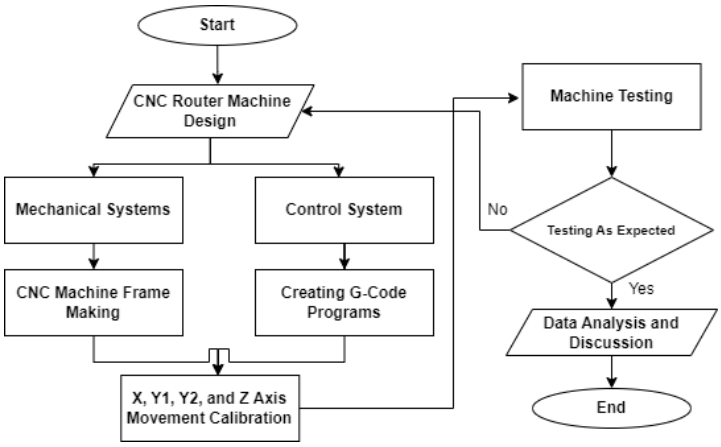

Figure 4. CNC machine designing flowchart

The following is a block diagram of the control system design that will be used on a 4 axis CNC Router machine shown in Figure 5.

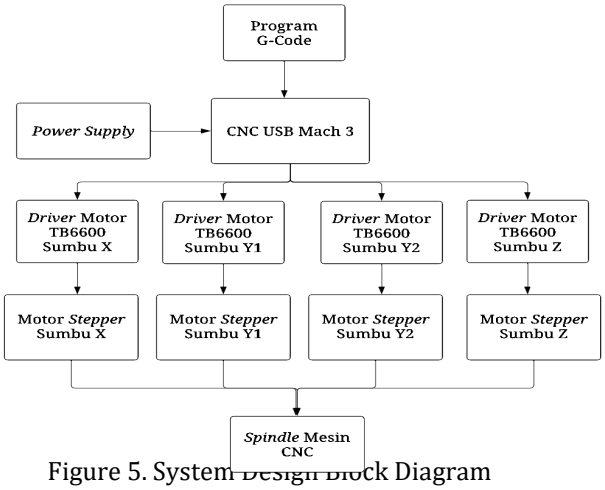

Figure 5. System Design Block Diagram

4 Axis Router CNC Machine Control System

This 4 axis CNC Router machine control system uses USB Mach 3 as a controller to control the whole system, from input, output, to data transmission to stepper motors and spindle motors. The power supply is used as a power source on the network. The input from the Aspire software is in the form of G-Code to be read by the CNC module. The incoming data will be sent to the Mach 3 microcontroller via serial USB. USB Mach 3 is connected with the TB6600 stepper motor driver. This driver functions to receive and read data, then generates an output to control the four stepper motors. The four stepper motors drive the X, Y1, Y2, and Z axes and give commands to the DC motor to drive the drill bit. The Mach 3 USB board is also connected with a limit switch that functions to provide a limit on the stepper motor so that it does not pass through the predetermined work area.

The following are the stages in manufacturing a 4 axis CNC Router machine:

Control System Design:

This stage begins with creating a circuit schematic and hardware design of a 4 axis CNC machine. The motor drivers used are TB6600, Nema-23 type stepper motor, and Mach 3 USB Board.

Programming:

This stage aims to run the axis of motion of the CNC machine using Aspire software for design and Mach 3 software to convert images into G-Code with Mach 3 USB Board controllers.

Accuracy Testing and Calibration:

This stage aims to test the ability, accuracy, and precision of the 4 axis CNC Router machine. Testing is performed on all axes used (X, Y1, Y2, and Z axes). Calibration is performed against the movement of the machine to ensure that the size of the movement of the machine is in accordance with the commands given by the computer. Measurement of the distance of the machine's movement is carried out after moving the axis using software with a predetermined distance.

By systematically carrying out these stages, it is hoped that the 4 axis CNC Router machine can operate with high efficiency and precision according to the needs of various industrial applications.

Results and discussion

Machine Design and Design
In this study, a 4 axis CNC Router machine was designed and designed using holo iron material and the control system used a Mach 3 USB board module as a controller, a TB6600 motor driver, a Nema-23 stepper motor, and Mach 3 software. The following is the design of the 4 axis CNC Router machine presented.

For this research, a 4 axis CNC Router machine was designed and designed using hollow iron material with a control system that relies on a Mach 3 USB board module as the main controller. This engine uses a TB6600 motor driver and a Nema-23 stepper motor, as well as Mach 3 software. Here is the design description of the 4 axis CNC Router machine:

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4 Axis Router CNC Machine Design

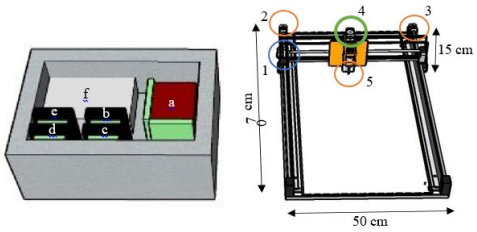

Figure 7. 4axis cnc machine design and electronic component box

- **Construction Material:** The material used is hollow iron with a machine size of 50 cm x 70 cm x 15 cm.
- **Main Components:**
  1. **TB6600 Stepper Motor Driver:** Connected with a Nema-23 stepper motor mounted on the engine frame for each axis.
  2. **Stepper Motor:**
     - X-Axis
     - Y1 axis
     - Y2 Axis

- Z-axis

3. **Blade Blade:** Used for the process of cutting or engraving on the material being machined.

- **Electronic Components Box:**

  - Located on the machine and containing the components of the CNC machine controller, including: a. CNC microcontroller board Mach 3 USB b. TB6600 motor driver for X c axis. TB6600 motor driver for Y1 axis d. TB6600 motor driver for Y2 e axis. TB6600 motor driver for Z f-axis. Power supply g. Fan for cooling.

With this design, it is hoped that the 4 axis CNC Router machine can operate stably and can produce precise work results according to the needs of various manufacturing applications.

Schematic of Mach 3 Board Control System Circuit

In this study, a USB Mach 3 motion card was used as a microcontroller board. TB6600 motor driver is used to control the direction and speed of the stepper motor. The Nema-23 type stepper motor will be used to convert electrical energy into mechanical energy in the form of DC motor movement. The TB6600 motor driver is chosen to regulate the direction and speed of the stepper motor, while the Nema-23 type stepper motor functions to convert electrical energy into mechanical movements necessary for machine operation. The Mach 3 Board control circuit used in this study has been designed to integrate all components efficiently, including pin settings for each motor driver and connections to auxiliary devices such as limit switches, emergency stops, and relays for external device control.

The control system circuit of the Mach 3 CNC Router 4 axis machine, which was used in this study is shown in this Figure:

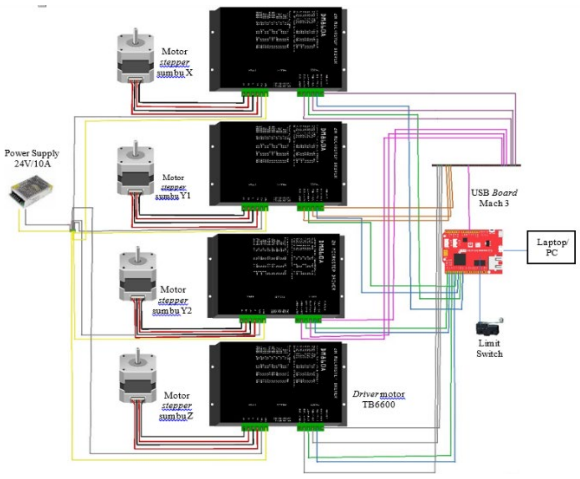

Figure 8. CNC Machine Control System Series

Here is an explanation of the schematic of the CNC machine control system circuit shown in Figure 8:

1. X-Axis Motor Driver:
   - The DIR pin (-) is connected to the XD pin on USB Mach 3.
   - The PUL pin (-) is connected to the XP pin on USB Mach 3.
   - Requires a voltage of 24V to operate the X-axis motor driver.
2. Y-Axis Motor Driver:
   - The DIR (-) pin is connected to the YD pin on USB Mach 3.
   - The PUL pin (-) is connected to the YP pin on USB Mach 3.
   - Requires a voltage of 24V to operate the Y-axis motor driver.
3. Z Axis Motor Driver:

- The DIR (-) pin is connected to the ZD pin on USB Mach 3.
- The PUL pin (-) is connected to the ZP pin on USB Mach 3.
- Requires a voltage of 24V to operate the Z-axis motor driver.

4. A-Axis Motor Driver:
   - The DIR (-) pin is connected to the AD pin on USB Mach 3.
   - The PUL pin (-) is connected to the AP pin on USB Mach 3.
   - Requires a voltage of 24V to operate the A-axis motor driver.
5. Power Interface Motor Driver:
   - Pins A+, A-, B+, B- are connected on the 2-phase hybrid stepper pins of the Nema-23 motor to determine the direction of rotation of the stepper motor.
6. Limit Switch:
   - The Mach 3 USB motion card 3 input pins are connected with a limit switch pin arranged in parallel for each axis, serving as a restriction of the movement of the machine.
7. Emergency Stop:
   - The Mach 3 USB motion card 4 input pins are connected with the emergency stop pin, to stop the operation of the machine instantly in an emergency.
8. Relay:
   - Pin out 4 USB motion card Mach 3 is connected with a relay pin, used to control external devices such as coolant pumps or sprayer systems.
9. USB Port:
   - The USB port on the USB motion card Mach 3 is used to connect the machine with a laptop/PC to send G-Code data and control the operation of the machine.

With this configuration, the CNC machine control system can work effectively in moving all axes (X, Y, Z, A) according to commands given through software such as Mach 3, maintaining safety with limit switches and emergency stops, and regulating auxiliary devices using relays.

To perform the analysis of observation data of the test results of the 4 axis CNC Router machine on a rectangular shape, here are the adjustments and revisions on the tables and graphs mentioned:

Table 3. Rectangular Shape Results

It	Feedrate (mm/min)	Measurement Input Value (mm)	Measurement Result Value (mm)	Accuracy (%)	Process Time (minutes)
1	50	50 70	50 70	100	3
2	100	50 70	50 70	100	3
3	150	50 70	50 70	100	3

Observational Data Analysis

After testing and calibrating the machine, the measurement results on a rectangular shape with a length of 50 mm, a width of 30 mm, and a depth of 5 mm show that the measurement result value (X, Y, Z) corresponds to the measurement input value with an accuracy of 100%. The processing time for each trial is 3 minutes.

Curve Graph

A curve graph reflecting the observation data of the test results can be presented to visualize the consistency and accuracy of the 4 axis CNC Router machine in carrying out cutting and engraving

operations. Thus, this data provides an overview of the machine's performance and facilitates evaluation to ensure that the machine can produce precise shapes according to the desired design.

Discussion

This study examines the design and implementation of a 4 axis CNC Router machine that uses a USB Mach 3 board module as the main controller, supported by a TB6600 motor driver and a Nema-23 stepper motor. The machine is designed using hollow iron construction materials with compact dimensions of 50 cm x 70 cm x 15 cm. The integrated control system includes detailed configurations for each motor driver and connections to additional components such as limit switches, emergency stops, and relays. The test was conducted with a focus on the accuracy and precision of cutting on acrylic materials, showing that the machine was able to achieve an average accuracy level of 99.59% for the X-axis, 99.21% for the Y1 and Y2 axes, and 97.17% for the Z-axis. In conclusion, these CNC machines are successfully designed and implemented for manufacturing applications with high precision requirements in material cutting and engraving, offering an effective solution in the modern production industry.

Conclusion

This research has successfully designed and implemented a 4-axis CNC Router machine based on a USB Mach 3 board module, a TB6600 motor driver, and a Nema-23 stepper motor. Based on the results of testing and data analysis, several conclusions can be drawn:
Machine Performance: CNC Router machines are able to maintain a high level of accuracy with an average of 99.59% for the X-axis, 99.21% for the Y1 and Y2 axes, and 97.17% for the Z-axis.
Control System Reliability: The use of the Mach 3 USB board module as the main controller is proven to regulate the movement of all axes efficiently and consistently. The well-integrated configuration of the electronic circuit provides ease of operation and programming.
Manufacturing Applications: These machines are suitable for manufacturing applications that require high precision in cutting and engraving materials such as acrylics. The test results show that the machine can be used for various types of projects with consistent and satisfactory results.

Recommendations
Software Optimization: Performs updates and optimizations to Mach 3 software to improve operational efficiency and expand machine programming capabilities.
Safety Development: Strengthened safety features by adding more advanced safety sensors and monitoring systems to reduce the risk of accidents during machine operation.
Materials Research: Conduct further research on the ability of machines to cut harder and more complex materials, such as metals or composite materials.
Increased Production Capacity: Increasing machine capacity to expand production capabilities on a small to medium industrial scale.
By implementing these recommendations, it is hoped that the 4 axis CNC Router machine can continue to improve its performance and become a more effective solution in the modern manufacturing industry.

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