Design and Construction of CNC (Computer Numerical Control) Machines Based on Microcontrollers

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ABSTRACT
The development of technology in the manufacturing sector has driven innovation in the development of microcontroller-based CNC (Computer Numerical Control) machines. This study aims to design and build a CNC machine with an Arduino Uno microcontroller that is capable of carrying out the engraving process on materials with a high level of precision. This machine uses components such as stepper motors, limit switches, and motor drivers to drive the X, Y, and Z axes. The design process includes hardware development, such as mechanical and electronic systems, as well as software for control using Grbl and the FlatCAM application for converting design files to G-Code. The test results show that the resolution of the X-axis movement is 375,000 steps/mm with an average error of 0.86%, while the Y-axis has a resolution of 395,153 steps/mm with an average error of 0.95%. The Z-axis shows a higher error due to the limitations of direct measurement of spindle movement. In addition, the machine is capable of producing precise engraving paths with a path thickness of T10 to T50, using a 10-degree router bit with a 0.1 mm tip at a DC motor speed of 6000 RPM. This microcontroller-based CNC machine successfully meets the needs of efficient and precise production processes, especially in the manufacture of complex designs such as PCB paths. The application of this technology offers an affordable solution for the needs of small and medium industries.

Keywords: CNC, microcontroller, Arduino Uno, G-Code, engraving, precision.

Introduction

The manufacturing industry is one of the sectors that has a strategic role in the global economy. One of the main challenges in this industry is increasing precision and efficiency in the production process. CNC (Computer Numerical Control) machines are one of the most effective solutions to achieve both. CNC machines allow automatic machine operation based on computer commands, resulting in a very high level of precision in various applications such as cutting, drilling, and engraving (Liu, 2020).

CNC technology has evolved rapidly since it was first introduced in the 1950s. The development of this technology is driven by advances in computerization and automation, which allow CNC machines to control multiple machine axes with very high precision and accuracy. However, the use of complex conventional CNC machines often requires expensive hardware and complicated operations (Zhang & Lee, 2019).

On the other hand, microcontrollers have become one of the important components in the world of automation and machine control, including in CNC machine applications. Microcontrollers can function as the brain of a CNC machine control system, which regulates the movement of motors and sensors to ensure accurate and efficient machine operation. By using microcontrollers, CNC machine designs become more affordable, flexible, and easy to control, allowing the adoption of this technology by small and medium manufacturing industries (Kumar & Singh, 2018).

The development of microcontroller-based CNC machines can be a solution to overcome the challenges of high costs and operational complexity in conventional CNC machines. By integrating a microcontroller, CNC machines can be designed simpler but still able to provide results with high accuracy. In addition, microcontroller-based CNC machines can be more efficient in terms of energy and simplify the maintenance process and component replacement (Wang, 2021).

This research aims to design and build a microcontroller-based CNC machine that can control various machine axes with high accuracy and precision. This research also aims to develop an efficient control system, by utilizing the latest microcontroller technology in CNC machine design. It is hoped that the resulting CNC machine can improve the efficiency and quality of production in the manufacturing industry, as well as provide more affordable solutions for various industrial circles.

Formulation of the problem:

1) How to design and build a microcontroller-based CNC machine?
2) How to ensure the precision and accuracy of cutting tool movements on microcontroller-based CNC machines?
3) How to optimize the performance of microcontroller-based CNC machines in the production process?

LITERATURE REVIEW

1. CNC (Computer Numerical Control) Machine

CNC (Computer Numerical Control) machines are one of the important technologies in the modern manufacturing industry because of their ability to perform production processes with a very high level of precision. This machine can be used for various applications, such as cutting, forming, drilling, and engraving, with automation that reduces human error and increases production efficiency. In its development, CNC machines continue to innovate, and the use of microcontrollers in the design of microcontroller-based CNC machines is one of the breakthroughs that allows for cost savings and increased design flexibility (Kumar & Singh, 2018).

2. CNC Machine Working Principle

CNC machines work by converting commands from a computer system controlled by software to direct the movement of motors in the machine. These commands are generally in the form of G and M codes that control the position, speed, and other actions of the machine. CNC machines allow material processing with very high precision, so they are widely used in the manufacturing industry to produce products with tight tolerances (Zhang & Lee, 2019).

3. Microcontroller in CNC Machine

A microcontroller is an electronic system that can be programmed to control various hardware, such as motors and sensors, in a CNC machine. In a microcontroller-based CNC machine, the microcontroller functions as the brain of the system that regulates motor movements through digital or analog signals based on the received code. Microcontrollers enable simpler and more affordable designs compared to more complex and expensive traditional CNC machine control systems (Liu, 2020). Microcontroller technology provides advantages in terms of ease of programming, low cost, and flexibility in controlling various CNC machine axes (Kumar & Singh, 2018).

4. Development of Microcontroller-Based CNC Machines

Microcontroller-based CNC machines have shown rapid progress in recent years. More sophisticated and cheaper microcontrollers allow CNC machines with simpler but still precise control systems. Several studies have shown that the use of microcontrollers to control motors in CNC machines not only reduces production costs but also improves system accuracy and flexibility. Microcontrollers also allow the use of various sensors, such as position sensors and temperature sensors, to improve the accuracy of motion control (Wang, 2021). The application of microcontrollers in CNC machines also allows the use of a friendlier user interface, where operators can easily program the machine using computer-based software or even mobile devices. This makes microcontroller-based CNC machines easier to use, especially for small and medium industries that may have limited resources (Liu, 2020).

Switch (Push Button Switch)

A switch or push button switch is a device that functions to connect or disconnect the flow of electric current in a system. The "unlock" working system on this switch means that the switch will connect or disconnect the flow of electric current when the button is pressed. When the button is released (not pressed), the switch will return to its normal condition, namely in a position not connecting the flow of electric current.

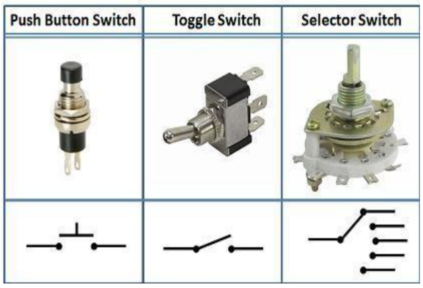

Figure 1. Types of Switches

Limit Switch

Automatic machine operation requires the use of switches that can be activated by machine movement. Limit switches are used to convert mechanical movement into electrical signals that are connected or disconnected. The limit switch shown in Figure 2 is a switch or electromechanical device that has an actuator lever as a terminal contact position changer, from Normally Open (NO) to Closed, or vice versa, from Normally Closed (NC) to Open. The contact position will change when the actuator lever is pushed or pressed by an object. Like most switches, limit switches only have two conditions, namely connecting or disconnecting the flow of electric current. In other words, limit switches have an ON or OFF condition.

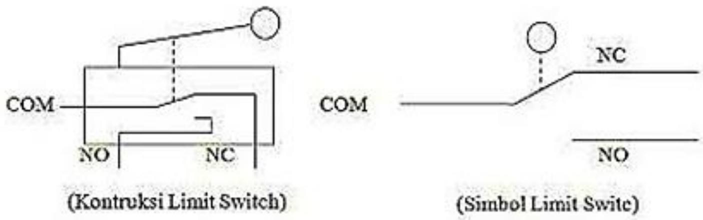

Figure 2. Limit switch and symbols

Arduino Uno

Arduino is a development board based on the ATMega 328P-200PU microcontroller, as seen in Figure 3. This board is equipped with 14 digital pins used for communication (I/O pins, input/output), with 6 of them can modulate the PWM (Pulse Width Modulation) output that allows analog output simulation. In addition, the Arduino Uno has 6 analog input pins that can be digitized using an internal ADC (Analog to Digital Converter).
The board also features a 16 MHz oscillator, a USB connector, a power supply jack, an ICSP (In-Circuit Serial Programming) header, and a reset button for easy operation and programming.

Figure 3. Arduino Uno

Stepper Motor

Stepper motors, or often called step motors, as seen in the Figure, are a type of motor that is similar to servo motors because the rotor position can be determined, but using a different approach. Stepper motors move based on a sequence of pulses given, where each pulse will cause the rotor to move in certain steps.

Figure 4. Stepper Motor

Research Method

Block diagram planning is the first stage in designing and compiling a circuit. Explanation of the information and function of the following circuit block diagram:

1) Abort Button: This button is used to stop the machine while it is running and displays an alarm notification on the software. This button gives a command to stop the process suddenly.
2) Hold button: This button is used to hold the tool while the process is running, which will temporarily stop the machine operation. A notification will appear on the application used to inform the user that the process has been paused.
3) Resume Button: This button is used to resume the performance of the tool after the Hold button has been pressed. This button allows the machine to continue the process after being paused.
4) Limit Switch: The limit switch functions as a marker for the maximum limit reached by the machine. When the limit switch is pressed, the machine will stop automatically to prevent further damage to the machine or workpiece.

5) Emergency Button: This button is used to stop the entire machine in an emergency situation without issuing an alarm notification to the software. This button allows for a quick stop of the machine to maintain safety.
6) Arduino Uno CNC Shield: Arduino Uno CNC Shield is a board that helps simplify the installation of inputs, outputs, drivers, and other components, allowing connections between components to be easier and more structured.
7) Arduino Uno: Arduino Uno functions as a data processing center from a computer or laptop to manage the input and output of the device. This Arduino controls the operation of the machine based on commands given through the computer.
8) Computer/Laptop: A computer or laptop functions as a device to input image files to be designed and run the creation application. This device also functions to control and monitor the processes that occur in the machine.
9) Stepper Motor Driver: The stepper motor driver functions as a command translator from Arduino to the stepper motor, to regulate the voltage and current required by the stepper motor to move according to the instructions given.
10) DC Motor: DC motors are used as spindle drivers and also for engraving processes. These motors drive rotating parts on CNC machines, such as spindles used for cutting or engraving.

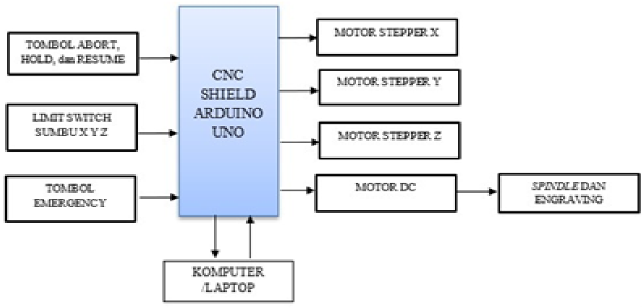

Figure: 5. Block Diagram

Results and Discussion

1). **Software Design**

a) Steps to Compile a Program for Arduino.
Programs created from Grbl use compilation from CV AVR and Arduino. However, the program used for the upload process uses Arduino IDE programming. To upload programs from a computer or laptop, you can use the Arduino IDE method. This method compiles the source code into hex code and automatically uploads it to Arduino. The .hex file cannot be compiled directly through the Arduino IDE.

b) Layout Design in Proteus.
Making a PCB (Printed Circuit Board) layout must be done carefully in making wire paths that connect the legs of one component to another. Therefore, in making a PCB layout, it is important to follow the planned path and adjust to the scheme that has been made so that the connection between components runs well and according to the design.

c) Gerber Files To G-Code Using Flatcam.
Flatcam is a software used to convert various designs into CNC router G-Code. The finished PCB design can be utilized through Gerber files to generate G-Code. The G-Code will be used to drive the CNC machine, allowing the process of cutting or creating PCB paths.

d) Candles.
Candle is a software used to control CNC machines. Candle is also a Grbl controller application that uses G-Code. Grbl itself is software to control CNC machine movements that can be uploaded to the Arduino library. Basically, Grbl is a hex file that is uploaded to Arduino so that Arduino can read the commands in G-Code and control the movement of the CNC machine according to the instructions given.

2). **Ensuring Precision and Accuracy of Cutting Tool Movements on Microcontroller-Based CNC Machines**

Precision and accuracy of cutting tool movements on microcontroller-based CNC machines are important to produce results that are in accordance with the design. One way to achieve this is to perform routine calibration on the machine control system, especially on the steps per millimeter (step/mm) of the stepper motor used to drive the X, Y, and Z axes. This calibration ensures that every command from the microcontroller is translated into precise movements by the motor. In addition, the use of high-quality components, such as stepper motor drivers with microstep settings, ensures smoother and more accurate movements.

Mechanical stability is also a major factor in maintaining precision. The machine frame must be sturdy and free from vibration during the cutting process. Limit switches are installed at the maximum limit of each axis to ensure that the cutting tool does not exceed the desired working area. In addition, parameters such as feed rate, spindle speed, and depth of cut in the G-Code must be adjusted to the material being cut to prevent damage to the tool or material. With proper setup and maintenance, the machine can achieve the optimal level of accuracy for various production needs.

Tool testing

Figure 6. X-Axis Testing

Table 1. Measurement and Percentage

No	Tool Measurement (cm)	Tool Movement (cm)	Percentage of Error (%)
	X-axis	Y axis	Z axis
1	0.51	0.52	0.49
2	1.01	1.01	0.99
3	1.5	1.51	1.48
4	2.4	2.52	1.97
5	2.47	2.52	2.47
6	3.01	3.01	2.97
	Average Error (%)		

Based on the print results shown in Figure 6, it can be seen that the engraving process uses a knife-shaped router bit with a size of 100 and a tip of 0.1 mm. The speed of the DC motor used is 6000 RPM with an X-axis resolution of 375,000 steps/mm. Based on the recorded data, the engraving results show that the X-axis has an average error of 0.86%.

This shows that despite minor errors, the CNC machine used has a fairly good level of accuracy in the engraving process, especially on the X-axis. These errors are likely caused by factors such as machine calibration, material quality, or other operational conditions. Based on the engraving print results using a 100-sized knife-shaped router bit with a tip of 0.1 mm and a DC motor speed of 6000 RPM, it shows that the Y-axis resolution is 395,153 steps/mm. From the results of this test, it can be seen that the Y-axis has an average error of 0.95%, which shows that the error on the Y-axis is slightly higher than the X-axis (0.86%).

In addition, and the test showing the results of the Z-axis test, it can be seen that the Z-axis has a higher percentage of errors compared to the X and Y axes. This is due to the fact that the movement of the Z-axis cannot be directly seen in the image, but rather refers to the movement of the spindle motor moving up and down. Thus, errors on the Z-axis are more difficult to measure directly through the printout, but are still detected through measuring the movement of the spindle motor on the machine.

Table 2. Average error on each axis based on engraving test results:

Axis	Resolution (step/mm)	Average Error (%)	Information
X	375,000	0.86	Lowest error, indicating accurate engraving results on the X axis.
Y	395.153	0.95	The error is slightly higher compared to the X axis.
Z	-	Higher	The error is greater because the measurement refers to the movement of the spindle motor.

This table shows that the lowest error is found on the X-axis, while the Z-axis has a higher error due to the measurement depending on the vertical movement of the spindle motor.

3). **Optimizing the Performance of Microcontroller-Based CNC Machines in the Production Process**

To optimize the performance of microcontroller-based CNC machines, technical and operational steps must be taken. Selecting a microcontroller that suits production needs is essential to handle the control process efficiently. Firmware such as Grbl used on Arduino Uno can be optimized to improve the ability to read G-Code faster. In addition, hardware optimization such as microstep settings on stepper motor drivers can improve motion resolution and reduce vibration.

Optimizing the cutting path or *toolpath* is also very important for time efficiency and material savings. Software such as FlatCAM can be used to generate more efficient cutting paths. In addition, routine maintenance such as lubrication of mechanical components, tightening of frames, and replacement of worn cutting tools helps maintain machine performance. The application of a cooling or lubrication system is also necessary, especially for hard materials or long production processes, to prevent overheating and maintain the quality of the cut results.

Integration of automation technologies, such as feedback sensors and remote control modules, can increase the flexibility and efficiency of the machine. These sensors allow automatic detection of the cutting tool position or automatic tool changeover, thereby reducing production downtime. With a combination of technical steps, maintenance, and technology integration, microcontroller-based CNC machines can work optimally to support precise and efficient production needs.

Conclusion

Microcontroller-based CNC machines have great potential to support precise and efficient production processes, especially in the field of design creation that requires a high level of accuracy, such as engraving and printing PCB paths. To ensure the precision and accuracy of cutting tool movements, steps are required such as system calibration, use of quality components, optimal parameter settings on G-Code, and routine mechanical maintenance. The use of limit switches and microstep drivers also play an important role in maintaining machine stability and accuracy.

On the other hand, optimization of machine performance can be achieved by integrating technologies such as feedback sensors, efficient cutting path management using software such as FlatCAM, and selecting the appropriate microcontroller. Regular component maintenance, including lubrication and replacement of cutting tools, helps maintain the quality of production results and extends the life of the machine. With a combination of these steps, microcontroller-based CNC machines can function optimally, produce high-quality products, and support various industrial needs .

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