Development of CNC Milling Machine for Small Scale Industry

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Abstract. The development of small-scale industry (SME) has increased the demand of small-scale CNC machines since the implementation of machine in production of small-scale product shown a profitable economic value. The use of machines in the fabrication of small part has been proven to increase product production efficiency as well as reduce product costs. This is able to increase the business profits of small companies and push the business development to a higher level. The main purpose of this paper is to discuss the development of 3-axis CNC machines using integration between microcontroller as main controller and spindle drill. The main application of this built machine is to cut and carve low-hard materials such as wood and acrylic material. The design product to be fabricate is sent to the microcontroller through a serial communication system. The microcontroller will control the movement of the spindle drill according to the point coordinates to perform the desired engraving or cutting according to the desired design. Three tests to determine the quality of product production are carry out. The tests are surface section, circular test and axial perpendicular test which can determine the accuracy of cutting geometry such as position, straight, roll, tone, evaporate and perpendicular to the work section under certain tool grooves and feed rate. The results of tests carried out on the products produced by the 3-axis CNC machine developed showed that this machine has a cutting and engraving accuracy of 98.5% and a depth accuracy of 100% for wood and archival materials. This machine is suitable for carving 2D and 3D objects with a maximum size of 30 cm x 30 cm.

1. Introduction

The manufacturing process has undergone dramatic changes since the last 30 years. This change is boost by the introduction of a manufacturing machine that was fully control by a numeric control system (NC). The introduction of numerical control technology has allowed machine work direction to be monitor via computerized control (CNC). In this system, a microcontroller is use to carry out all numerical controls of CNC machines.

CNC machines have been prove to play an important role especially in the manufacturing, automotive and oil and gas industries. Many parts used in this industry require high accuracy and fidelity to ensure the quality of the final product produced and the safety of the workers involved. Competency in controlling and operating CNC machines has been prove to provide high income for workers. Competency in operate and maintenance of CNC machining provides high employment opportunities for graduate students in engineering and technology field. Machines that use CNC working principles
are widely developed such as lathes, laser cutters and 3D printing machines. All of these machines have the same basic components, which consist of the integration of motor equipment, motor guides, main control components and computer software as a platform to control the motor spindle movement. The main differences are in the mechanical design and use of the means for the final operation.

With the advancement of numerical control systems, many CNC machines are develop for shaping objects especially for soft materials such as acrylic and wood. Most of these machines use a knife blade and laser as a cutter to form the desired product. The introduction of a control system driven by a microcontroller has allowed CNC machines to be produce at a low cost compared to CNC machines that use computer as a control system. The low cost of building CNC machines has allowed the SME industry to use these machines to produce their products. There are many investigators and researcher try to build a CNC machine at a minimum cost. Jayachandraiah [1] has made a comprehensive review regarding the construction of a low cost 3- Axis CNC machine. The results of his study found that using a microcontroller as a numerical guard can reduce the cost of development a CNC machine. He provided a mechanical built-in frame using easily available materials such as aluminium and carbon steel main frames.

In another study, Khanna et al. [2] have used LabVIEW as the main control system in fabricate 3-Axis CNC machine. The main purpose of the construction of this machine is to engrave objects for acrylic materials. There are other CNC machine study, [3] develop CNC machine specially to do the work of grinding, engraving and cutting PCB boards [4] [5] [6]. In addition, there are also studies that focus on algorithm development for CNC machines. [7] in his study have made improvements in the CNC machine control algorithm for linear and spherical interpolation. In another investigation, [8] has tried to optimize the selection of 3 - Axis CNC machine frame materials to ensure the low cost in order to ensure the SME industry can afford to buy the CNC machine. There is also researcher develop CNC machine whose main function is to do the work of draw objects [9]. The main objective of this machine development is to increase speed by minimizing errors and increasing the output of the resulting product.

In Malaysia, the development of CNC machines – 3 Axis particularly is still new. The increase in the number of machine fabrication companies capable of forming and building CNC machines is still low. In fact, many CNC machines used by SME are import from other countries. This is not good from the economic point of view since high price it also cause the outflow of money. In this regard, this study is to construct a low cost 3 –Axis CNC machine for use by SME manufacturing companies. The long-term implication of this study will give an impression of modernizing PKS in Malaysia with execution engines in their expenditure.

2. Structure Design
The structure of machine is an important component in the construction of a CNC machine. Machine structure must have high static and dynamic rigidity and have good machine tool damping response. This is because all the equipment involved in producing a CNC machine such as the motor and spindle motor will be integrate into the machine structure to form a complete CNC system. Therefore, a strong machine structure will ensure the machine can make precise movements and produce high quality products.

The structure designed in the development of this 3- Axis CNC machine is to ensure the structure has high rigidity. This is to ensure the CNC machine can produce a better lane width and can operate at higher fidelity. This high stiffness can also ensure the CNC machine operate at high speeds and so can produce better cutting and engraving quality. The CNC machine structure to fabricate is ensure to have the right joints and symmetry to reduce machine vibration during the cutting and engraving process.
Design of the 3-Axis CNC machine will have a working space dimension of 600 * 800 * 500 mm³. The target precision of the product to be produce is 50μm and the reproducibility in the environment is 10μm. The operating width path for the CNC machine is between (0-10Hz). This can ensure that the CNC machine has high efficiency.

The height of the CNC machine structure is 550mm without a spindle motor. 600mm structure width. The main frame of this CNC machine is fabricate using 6061 aluminium material. The built structure of this machine is connect using an M6 crew. The height of this machine is design to allow the machine have as much as 150mm of free movement when moving tin the Z-axis. The design of the 3-Axis CNC machine to be developed is as in Figure 1. The structural of the CNC machine design is purposely to using only one spindle mill to ensure the cost of producing this machine is at a minimum.

![Figure 1](image)

**Figure 1. Propose design of closed-frame support structure for CNC milling machine prototype**

In this structure, the contact surfaces with axes are purposely designed with allowances so a grinding process can be used on these surfaces to ensure good contact between axes module. All the angles are curved for better casting performance.

### 2.1 Machine assembling
The procedure of making the machine is listed below step by step. Each step has a corresponding figure listed in Figure 2.
After the machine structure is fabricate, the alignment of the movements of the X, Y and Z axis is carefully carry out. This is to ensure the cutting and engraving of the product can be carry out at high precision to produce a quality product. The X and Y-axis is install sequentially from top to bottom. If the screw installation is not in the correct position, it is difficult to make the alignment again when using the top to down method of mounting the frame. Therefore, it is important to ensure that the design is properly plan at the initial stage of the development of machines that is during earlier stages process of design CNC machine.

3. Controller Design and Setup
The microcontroller used to control the CNC machine is DDCSV2.1 500KHz CNC 4-Axis Engraving Machine Controller Motion Control System. This controller use for the purpose of to control the stepper motor and it is come with electronic hand wheel which makes it easy to control the movement of the movement of CNC machine. This controller has been develop by Faster CNC and has control speed for each position at 4 milliseconds. High accuracy of position is the main advantage of this controller. The highest uniaxial output pulse is 500 KHz and this controller can be used to control both stepper and servomotor. Figure 3 shown the DDCSDV2.1 controller that come with hand wheel.
Figure 3. Motion controller DDCSDV2.1 with hand wheel

The main advantage of the DDCSV2.1 controller is that it can be configure using a variety of software interfaces. DDCSV2.1 is compatible with the MASTERCAM software on Microsoft Windows environments. MASTERCAM provides a terminal for programming of G codes.

DDCSV2.1 provides settings for configuring and tuning the movement of the motor. It provides basic tools for tuning and set PID parameters, program servo algorithm, DAC selection and configuration open loop testing, filters, and real-time motor monitoring. A user interface of the work space is shown in Figure 4.

Figure 4. Interface of DDCSV2.1 setting parameter page

The DDCSV2.1 next page interface is distributed as a CNC human machine interface (HMI) with built-in customizable standard features. The DDCSV2.1 also can be customized with respect to number of axes, type of machine, tool offset display, custom messaging, etc. A screenshot of the workspace is shown in Figure 5.
While a complete CNC solution has been provided by the controller to control and operate our mini CNC machine, the cost of the DDCSV2.1 motion controller alone is almost one over third our total budget. The controller provides a set of powerful software tools. We can use these tools to test our machine’s precision and ensure everything is running properly.

3.1 Hardware connection and setup
Installation of the CNC machine is start by connecting all components with the DDCSV2.1 controller. The stepper motor is use to drive the CNC machine on the X, Y and Z-axes. The data from the decoder (pulse/rev) is use to determine the position of the motor spindle. For safety purposes, limit switch use as a indicator for the maximum motor movement of each axis. This switch serves as a sensor that will limit the motor spindle movement during the cutting and engraving process to be carry out by a CNC machine. All of these components connect to a 24V power source. The negative terminal is connect to ground on the same source.

After the component wiring connection complete, the motors that drive the machine’s CNC system are connected to the motor driver. The motor driver serves to move the stepper motor. It receives a signal from the controller and generates a signal in the form of a TTL quadrature that will drive the stepper motor. The encoder used in this machine build is an auxiliary type single-phase TTL signal encoder. It only has four channels: A +, B +, + 5V, and GND.

The encoder signal is use to locate the position stepper motor. X1-X4 is the encoding and quadrature mod. TTL cues are usually encode in quadrature mode and X4 mod can provide maximum resolution. In this machine, all coders are mount in their CW orientation across all axes. After properly configuring the encoding mode, we can roughly determine how many encoders the estimate corresponds to a 1cm step move.

4. Result and Discussions
The fabricated prototype mini-CNC machine is subjected to several different tests to determine its accuracy and repeatability. Three major tests are conducted in this study, that is surface flatness test and axes perpendicularity test.

4.1 Flatness test
Flatness test is done by machining a flat surface on a work piece and then measuring the flatness of the created surface. The flatness test can tell whether our XY axes are horizontal and moving in a plane as well as whether our working table is tilting or not.
Two different surfaces are created in two tool paths, one along X-axis and one along Y-axis, as shown in Figure 6 from the Mastercam simulation software. Theoretically machining a surface in two directions will not affect the surface feature. Therefore, any differences between two surfaces can tell the existence of error in Z-axis.

Figure 6. Flatness test X and Y direction tool path

For each surface created, six data paths are measured on the surface, three along X axis and three along Y axis, as shown in Figure 7.

Figure 7. Measure path on surface of X and Y direction tool path

Ideally, measurement paths in all directions should all have constant height in Z direction. However, due to errors in XY axes, the surface is slightly tilted. Figure 8 a) shows the same three paths in X direction but measured on surface created by Y direction tool path. Figure 8 b) shows the profiles of three paths in Y direction measured on surface created by X direction tool path. Figure 8 c) shows the same three paths in Y direction but measured on surface created by Y direction tool path.
Figure 8. Profiles of three paths: a) in X direction on X surface b) Y direction on X surface c) X direction on Y surface
Figure 8 shows the profile of surface measurements on the X and Y-axis. From this profile figure, it is clearly that the tool path on the X and Y-axis is at the tilt stage. The three data sets on the X, Y and Z-axis show their consistent surface profiles. The surface profile of the X-axis has a slope value of 0.005. This indicates that the surface profile is inclined towards the –X axis. Meanwhile, the surface profile in the Y direction has a slope value of -0.013. This represents -0.74 degrees of difference between the Y-axis direction and the horizon stage. The comparison of the surface profile show the Y-axis surface flatness are more consistent. Table 1 shows the residual norm of the linear fit model on both the X direction profiles and the Y direction profiles on the two surfaces. These data indicate that the surface profile in the Y-axis direction is smooth and flat. This comparison shows that the surface in the X direction axis is coarser than the surface in the Y-axis direction. For the path surface of the X tool, the cutting direction is less impressive, but the two profiles are still rougher than the Y direction profile on the path surface of the Y tool. On the other hand, the profile of this cutting direction is actually due to the Perspex fibre orientation of the material. The material used to carry out this surface profile analysis is plastic. Cutting plastics that do not follow the direction of alignment of the Perspex fibre material will result in rough cuts. The cutting process should align with plastic fibre orientation. Due to the inconsistent structure and density of the material, chip formation will vary along the cutting path, resulting in a non-uniform and uneven surface. This show in the Y-axis direction profile, which is parallel to the direction of the plastic fibre it produces a smoother and better profile of the cutting surface.

| Tool path | X direction | Y direction |
|-----------|-------------|-------------|
| X tool path | 0.030, 0.054, 0.041 | 0.05, 0.026, 0.051 |
| Y tool path | 0.033, 0.080, 0.084 | 0.0084, 0.012, 0.013 |

4.2 Perpendicularity test

The next test is perpendicularity test of X Y-axes. A tool path is created to cut the edge of a work piece purely in two directions: X and Y, as shown in Figure 2. After two flat vertical surfaces is created, the straightness of two surfaces can be measured using dial test indicator (DTI). The slope of two lines in XY plane can be measured. The angle between these two lines can be calculated using these two slope values.

Then, a linear fit was applied to these two sets of data individually. The slope of two straight lines can be measured. The norm of residuals of this linear fit also indicates the straightness of these two surfaces, which equivalently determines the straightness of XY axes movement. Figure 9 shows the linear fit of two measurements taken from two surfaces.
The path in X direction has a slope value of -0.0126. The path Y direction has a slope value of 83.199. The angle between these two lines can be calculated using:

\[
\text{angle} = \tan^{-1}(p11) - \tan^{-1}(p12) = \tan^{-1}(-0.012632) - \tan^{-1}(83.199) = 90.0351°
\]

Therefore, there are 0.0351° differences between the X-axis alignments and Y-axis alignments. This is a relatively small value. The perpendicularity of XY axes is within the acceptable tolerance. The straightness in Y direction is better than that in X direction. The linear fit in figure 6.13 gives a R² value of 0.9657 and the linear fit in gives a R² value of 0.9981. Both still move straight, and no obvious curvature is observe.

Conclusion

This paper discusses the fabrication of a small-scale three-axis CNC milling machine that is suitable for use in small industries (SME). In order to determine the accuracy of the CNC machine, flatness test and perpendicularity test are perform on the products produce by this CNC machine. This test is perform to analyze the precision of cutting and engraving. Perspex material is use as a test material. The test results on this material shows that a margin of 0.0351° is not perpendicular to the XY axis. The deviation of 0.28° tilt in the X-axis and -0.74° tilt in the Y-axis. This deviation is due to improper alignment of the CNC machined structure. Where the main cause of this alignment problem is the incorrect design of the CNC machine and the installation method that uses the top to down method. The circumference tests showed that increasing the feed rate decreased machining precision and surface quality. Cutting tests using other materials is need to be conduct for further performance analysis.

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