Effects of Design Parameters on Dimensional Accuracy of Parts Made on a Mini 3-Axis CNC Router

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Abstract

Computer numerical control (CNC) is a very broad term that encompasses a variety of types of machines used in industrial automation — all with different sizes, shapes, and functions. But the easiest way to think about CNC is to simply understand that it is all about using a computer as a means to control a machine that carves useful objects from solid blocks of material. Traditional CNC machines are expensive, complicated, and typically only found in large manufacturing companies that can afford them. Small hobbyist CNC machines can run anywhere from $7,000 and higher; professional machines can cost millions of dollars! Now, for a fraction of the cost — under $800 one can own a Mini 3-axis CNC machine and cut, drill, mill, and carve objects of one's imagination. In this paper, a Mini 3-axis CNC router was assembled and tested for machining different materials such as plastic and wood. Simple shapes of circles (diameter, d = 1") and squares (side, a = 1") were cut using the CNC router. G-Code programs were developed to cut the required circles and squares. A digital caliper was used to measure the diameter of the circles and the side of the squares. Data were collected for a 2^k factorial design experiments considering 2-levels for parameters: spindle speed, feed rate, cut depth, object shape, and material. Statistical analyses were performed to determine the effects of chosen parameters on the dimensional accuracy of the parts made. The results indicated that the parameters material, object shape, and cut depth have significant effects on the dimensional accuracy of the parts made.

1. Introduction

Numerical control, popularly known as NC is very commonly used in the machine tools. Numerical control is defined as the form of programmable automation, in which the process is controlled by the numbers, letters, and symbols. In case of the machine tools this programmable automation is used for the operation of the machines. CNC is the short form for Computer Numerical Control. The NC machine works as per the program of instructions fed into the controller unit of the machine. The CNC machine comprises of a mini computer or a microcomputer that acts as the controller unit of the machine. While in the NC machine the program is fed into the punch cards, in CNC machines the program of instructions is fed directly into the computer via a small board similar to the traditional keyboard. CNC machines were originally built for machining metals. They were subsequently adapted for other industries such as wood, fabric, foam, and plastic to name just a few. All these machines have some features in common which are: a program (instructions), a controller, and a machine tool (Groover, 2015).

CNC router is a computer-controlled cutting machine related to the hand held router used for cutting various hard materials, such as wood, composites, aluminum, steel, plastics, and foams. CNC routers can perform the tasks of many carpentry shop machines such as the panel saw, the spindle molder, and the boring machine. A CNC router is very similar in concept to a CNC milling machine. Instead of routing by hand, tool paths are controlled via computer numerical control. The CNC router is one of many kinds of tools that have CNC variants.

A CNC router typically produces consistent and high-quality work and improves factory productivity. Automation and precision are the key benefits of CNC router tables. A CNC router can reduce waste, frequency of errors, and the time the finished product takes to get to market (Albert, 2017).

This paper is one of the outcomes of the Mercer Summer Engineering Experience (MeSEE 2017), an Academic Training program, in which multidisciplinary student teams were trained in engineering labs and then worked on hand-on projects over a period of 10 weeks (30-40 hours/ week) in the lab environment, during 2017 Summer semester to complete the chosen projects. Three senior students (Abdullah Alfadel, Industrial Engineering; Kyle Trammell, Mechanical Engineering; and Riley Atkinson, Industrial Management) forming a multidisciplinary team worked on this project. The overall objective of this project is to assemble/build and test a mini 3-axis CNC router in a laboratory environment; and conduct experiments, collect, analyze, and interpret data within the ten weeks duration of the academic training.

In this project, the student team has built and tested a DIY CNC router for machining different materials, plastic and wood. Simple shapes of circles (diameter, d = 1") and squares (side, a = 1") were cut using the CNC router. G-Code programs were developed to cut the required circles and squares. A digital caliper was used to measure the diameter of the circles and the side of the squares. The measured data were used to perform statistical analyses using Minitab and/or Microsoft Excel. Results obtained from statistical analyses were presented and discussed.

2. Background/Literature review

2.1. CNC history

NC or simply Numerical Control was developed in the late 1940s and early 1950s by John T. Parsons in collaboration with MIT (Massachusetts Institute of Technology). It was developed to help in the post war manufacturing effort. Aircraft parts were becoming more complex and required a level of precision that human operators could not achieve. At first, machines were hardwired and then instructions were given via punched tape starting in 1952. Five years later, NC machines were being installed in metal working production environments all over the United States. By the mid 1960s, NC technology was playing a dominant role in the industry. Most machine programs were recorded on a punched paper or aluminum tape until about 1980. The growth of microprocessor technology in the 1970s and 1980s made it possible for computers to be connected directly to NC machines using cables and hence the term CNC (Groover, 2015).

There are two main types of CNC machine tools and the control systems used with them differ because of the basic differences in the functions of the machines to be controlled. They are known as point-to-point and contouring controls. Some machine tools for example drilling, boring and tapping machines etc., require the cutter and the work piece to be placed at a certain fixed relative positions at which they must remain while the cutter does its work. These machines are known as point-to-point machines. Other type of machine tools involves motion of work piece with respect to the cutter while cutting operation is taking place. These machine tools include milling, routing machines etc., and are known as contouring machines. A milling machine is a machine that has a spindle (a device similar to a router) with a special tool that spins and cuts in various directions and moves in three different directions along the x, y, and z axes (Hood-Daniel

& Kelly, 2009).

A DIY Desktop CNC Machine is a “personal” version of a CNC machine. It is controlled by a desktop computer and is designed for the hobbyist or enthusiast to create objects within a relatively compact space and at modest expense. To that end, the DIY Desktop CNC Machine is designed to provide a resolution of one thousandth of an inch (0.001”) per step in each axis, and was intended to be accessible and buildable by the average DIY'er with non-specialist domestic tools (DIY CNC Router Kit, 2017; Ginting, Hydiyoso, & Aulia, 2017).

A small CNC router (work area: 20 cm x 20 cm) was installed and tested in a small scale industry in Indonesia for cutting, engraving, and marking on wood, acrylic and PCB objects. When tested, this router was able to provide 98.5% of carving accuracy and 100% of depth accuracy (Ginting, Hydiyoso, & Aulia, 2017). An automatic mini CNC machine for PCB drawing and drilling based on low cost CNC system was designed and made by incorporating features of PC with ATMEGA 328 controller in an arduino board, an open-source electronics platform based on easy-to-use hardware and software (Mudekar et al, 2016).

A low cost CNC router was designed and fabricated to fulfill the demand of CNC routers in small scale to large scale industries with optimized low cost (Jayachandraiah et al, 2014). A mini CNC router which is compatible to extrude as 3D printer, less expensive and affordable, compact in size and less power consuming, with user friendly interface to operate very smoothly, was designed and fabricated (Dey, Mondal, & Barik, 2016).

Effect of machining parameters such as speed, feed, and depth of cut on surface finish on a CNC router were analyzed using Taguchi's robust design approach using orthogonal arrays and analysis of variance models. The results indicated that feed rate has the highest influence on surface finish followed by spindle speed and depth of cut (Patel & Patni, 2014).

3. Materials and methods

3.1. DIY CNC machine

DIY CNC Router Kit used in this project is a mini CNC for study and research. It requires self-assembling and certain mechanical skills to assemble. According to the product details "The machine can carve wood, plastic, acrylic, PCB CCL, soft metals like copper and aluminum and other materials: working area: 240 * 170 * 65 mm; positioning accuracy: 0.04 mm; and software: easy to use GRBL" (DIY CNC Router Kit, 2017). Figure 1 shows the components of the DIY CNC Router Kit.

3.2. Measuring device

In this project, a digital caliper was used to measure the diameter of the circles and the side of the squares (Fig. 2). A caliper is a device used to measure the distance between two opposite sides of an object. It has a rated accuracy of 0.001 inches (Digital Calipers, 2017).

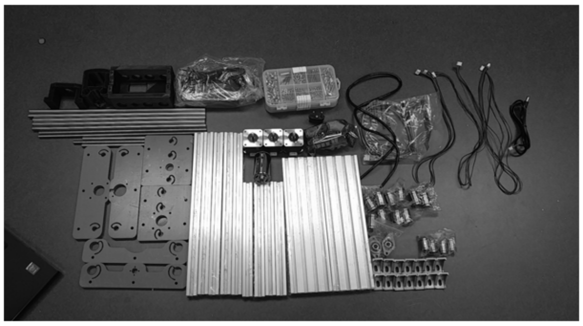


Figure 1. Components of DIY CNC router kit

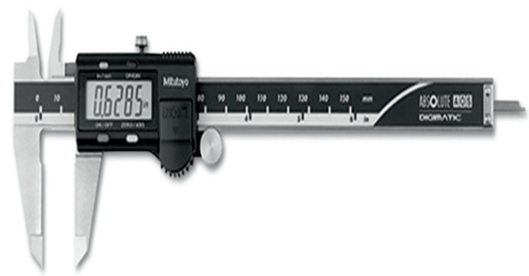


Figure 2. Digital caliper

3.3. G-codes for cutting circles and squares (Nanfara, Uccello, & Murphy, 1999)

The G-codes for cutting circles and squares are given in Table 1.

Table 1. G-codes for circles and squares

Circle	Square
G20 M3 S1000 G90 G00 X0 Y0 Z0 G01 Z-___ F__ G02 X0 Y0 I.446 J0 F__ G00 X0 Y0 G01 Z-___ F__ G02 X0 Y0 I.446 J0 F__ M30 G28	G20 G90 G40 G0 M3 S____ Z-______ G1 X.918 F__ G1 Y.918 G1 X0 G1 Y0 M30 G28

Two levels of spindle speed (S), feed rate (F), and cut depth (Z) were used to cut two simple shapes, circles and squares, on two different materials, plastic and wood.

3.4. The electronics of the CNC

Each CNC machine requires an electronic unit (Figure 3) to run the codes, move the shafts and the platform. It depends on the type of the CNC if it is 5 axes or 3 axes and also if there is a need to use coolant to cut aluminum parts. This DIY CNC requires an electronic unit to machine parts (DIY CNC Router Kit, 2017):

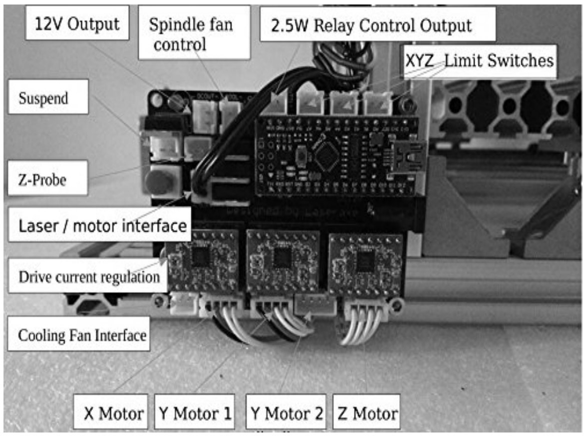


Figure 3. The electronics of the CNC router

- **Partmore:** 3 Axis CNC Controller Board (Fig. 3)
- **Compatible motor:** 2 Phase 4 Wire Stepper Motor
- **Working voltage:** DC 12V
- **Board size:** 100 x 80 mm (L*W)
- 3 **Stepper motor drivers**: A4988
- **Spindle drive chip**: MOSFET, the highest 60V
- **Support stepper motor:** 12V, maximum current of 2A or less is recommended within 1.5A and additional heat
- **Master chip**: Atmel 328P (Arduino Nano compatible)
- **Software**: GRBL controller, Universal G-code sender
- **Stepper motor specification:** Fuselage length 34mm; Current 1.33A, 12V; Torque 0.25N/m; and 4 lines

The assembled CNC router is shown in Figure 4.

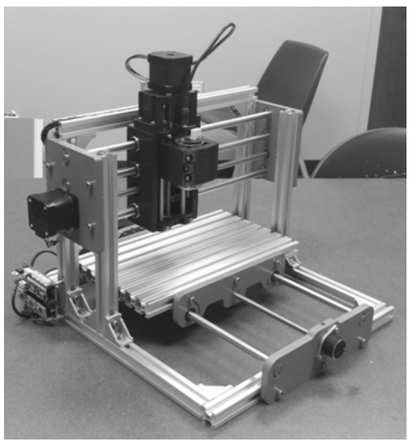


Figure 4. Assembled CNC router

3.5. Factors and Levels

To determine the accuracy with which the CNC router can cut parts, 25 factorial design experiments were designed with two levels for each factor under consideration (Montgomery, 2017): Speed: 800 and 1000 rpm; Feed Rate: 8 and 10 inches/min; Cut Depth: 0.08 and 0.1 inch; Material: Plastic and Wood; and Shape: Circle (d = 1±0.02") and Square (a = 1±0.02").

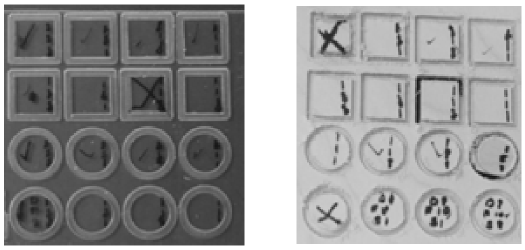
Experiments were conducted with two replicates. The data collected are shown in Table 2. All measurements were found to be within the tolerance limits 1±0.02" indicating that the CNC router is capable of cutting plastic and wood within the dimensional tolerance.

Table 2. Data collected

StdOrder	Speed	Feed Rate	Cut Depth	Materials	Shape	R1	R2
1	800	8	0.08	Plastic	Circle	1.011	1.006
2	800	8	0.08	Plastic	Square	1.02	1.015
3	800	8	0.08	Wood	Circle	1.008	1
4	800	8	0.08	Wood	Square	1.007	1.012
5	800	8	0.1	Plastic	Circle	1.014	1.011
6	800	8	0.1	Plastic	Square	1.002	1
7	800	8	0.1	Wood	Circle	1.007	1
8	800	8	0.1	Wood	Square	1.006	1.004
9	800	10	0.08	Plastic	Circle	1.005	1.01
10	800	10	0.08	Plastic	Square	1.015	1.012
11	800	10	0.08	Wood	Circle	1.009	1.001
12	800	10	0.08	Wood	Square	1.011	1.006
13	800	10	0.1	Plastic	Circle	1.015	1.015
14	800	10	0.1	Plastic	Square	1.005	1.01
15	800	10	0.1	Wood	Circle	1.005	1
16	800	10	0.1	Wood	Square	1.001	1.003
17	1000	8	0.08	Plastic	Circle	1.008	1.005
18	1000	8	0.08	Plastic	Square	1.019	1.018
19	1000	8	0.08	Wood	Circle	1.003	0.996
20	1000	8	0.08	Wood	Square	1.008	1.004
21	1000	8	0.1	Plastic	Circle	1.01	1.01
22	1000	8	0.1	Plastic	Square	1.007	1.002
23	1000	8	0.1	Wood	Circle	1.014	1.007
24	1000	8	0.1	Wood	Square	1.006	1.006
25	1000	10	0.08	Plastic	Circle	1.011	1.008
26	1000	10	0.08	Plastic	Square	1.015	1.013
27	1000	10	0.08	Wood	Circle	0.996	0.992
28	1000	10	0.08	Wood	Square	1.01	1.01
29	1000	10	0.1	Plastic	Circle	1.01	1.013
30	1000	10	0.1	Plastic	Square	1.006	1.005
31	1000	10	0.1	Wood	Circle	1.006	1.002
32	1000	10	0.1	Wood	Square	1.003	1.002

4. Results and discussions

Samples of square and circular parts (plastic and wood) were cut using the CNC router. They are shown in Figure 5. A completely randomized 25 full factorial designs were used to collect data (Montgomery, 2017). Minitab 17 software was used to analyze the data (Minitab 17, 2017). Table 3 shows the Minitab output of Analysis of Variance (ANOVA).



(a) (b)

Figure 5. Samples of square and circular parts made: (a) Plastic and (b) Wood

Table 3. Minitab output - ANOVA table

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significant?
Model	31	0.001735	0.000056	6.10	0.000	
Linear	5	0.000624	0.000125	13.60	0.000	
Speed	1	0.000007	0.000007	0.75	0.393	
Feed Rate	1	0.000007	0.000007	0.75	0.393	
Cut Depth	**1**	**0.000051**	**0.000051**	**5.53**	**0.025**	**S**
Material	**1**	**0.000512**	**0.000512**	**55.81**	**0.000**	**S**
Shape	**1**	**0.000047**	**0.000047**	**5.15**	**0.030**	**S**
2-Way Interactions	10	0.000775	0.000077	8.45	0.000	
Speed*Feed Rate	1	0.000007	0.000007	0.75	0.393	
Speed*Cut Depth	1	0.000029	0.000029	3.15	0.085	
Speed*Material	1	0.000001	0.000001	0.14	0.713	
Speed*shape	1	0.000015	0.000015	1.64	0.210	
Feed Rate*Cut Depth	1	0.000002	0.000002	0.21	0.653	
Feed Rate*Material	1	0.000026	0.000026	2.86	0.100	
Feed Rate*Shape	1	0.000000	0.000000	0.02	0.902	
Cut Depth*Material	**1**	**0.000047**	**0.000047**	**5.15**	**0.030**	**S**
Cut Depth*Shape	**1**	**0.000606**	**0.000606**	**66.11**	**0.000**	**S**
Material*Shape	**1**	**0.000041**	**0.000041**	**4.43**	**0.043**	**S**
3-Way Interactions	10	0.000219	0.000022	2.39	0.030	
Speed*Feed Rate*Cut Depth	1	0.000013	0.000013	1.43	0.240	
Speed*Feed Rate*Material	1	0.000001	0.000001	0.14	0.713	
Speed*Feed Rate*Shape	1	0.000004	0.000004	0.38	0.540	
Speed*Cut Depth*Material	**1**	**0.000070**	**0.000070**	**7.65**	**0.009**	**S**
Speed*Cut Depth*Shape	1	0.000013	0.000013	1.43	0.240	
Speed*Material*Shape	1	0.000000	0.000000	0.04	0.838	
Feed Rate*Cut Depth*Material	**1**	**0.000058**	**0.000058**	**6.34**	**0.017**	**S**
Feed Rate*Cut Depth*Shape	1	0.000004	0.000004	0.38	0.540	
Feed Rate*Material*Shape	1	0.000015	0.000015	1.64	0.210	
Cut Depth*Material*Shape	**1**	**0.000041**	**0.000041**	**4.43**	**0.043**	**S**
4-Way Interactions	5	0.000115	0.000023	2.51	0.050	
Speed*Feed Rate*Cut Depth*Material	1	0.000002	0.000002	0.21	0.653	
Speed*Feed Rate*Cut Depth*Shape	1	0.000003	0.000003	0.29	0.595	
Speed*Feed Rate*Material*Shape	**1**	**0.000041**	**0.000041**	**4.43**	**0.043**	**S**
Speed*Cut Depth*Material*Shape	**1**	**0.000044**	**0.000044**	**4.79**	**0.036**	**S**

Feed Rate*Cut Depth*Material*Shape	1	0.000026	0.000026	2.86	0.100	
5-Way Interactions	1	0.000003	0.000003	0.29	0.595	
Speed*Feed Rate*Cut Depth*Material*Shape	1	0.000003	0.000003	0.29	0.595	
Error	32	0.000293	0.000009			
Total	63	0.002029				

Table 3 indicates that with 5% level of significance and a p-value < 0.05, the following factors are found to be significant (highlighted bold with S after P-Value):

Main effects: Cut Depth, Material, and Shape
2-Factor Interactions: Cut Depth*Material, Cut Depth*Shape, and Material*Shape
3-Factor Interactions: Speed*Cut Depth*Material, Feed Rate*Cut Depth*Material, and Cut Depth*Material*Shape
4-Factor Interactions: Speed*Feed Rate*Material*Shape and Speed*Cut Depth*Material*Shape

Considering main effects and 2-factor interaction effects, it can be concluded that Cut Depth, Material, and Shape have significant effects on the diameter of circles and the side of squares cut using the CNC router. All five factors are found to have influence on the measurements when 3-factor and 4-factor interactions are considered.

The normal probability plot of the residuals, nearly linear, is shown in Figure 6. The fitted values versus residuals plots are shown in Figure 7. Figures 6 and 7 indicate that the residuals are normally distributed and there is nothing unusual about the residuals/errors.

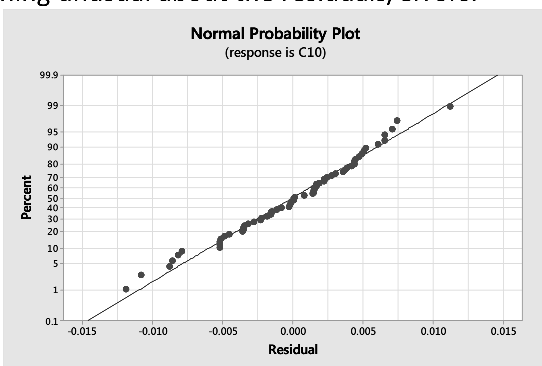


Figure 6. Normal probability plot

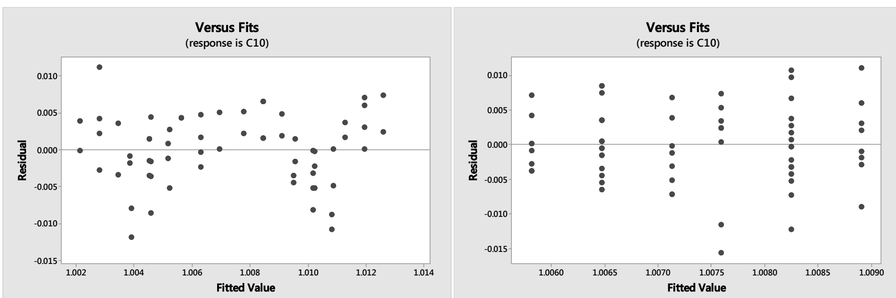


Figure 7. Fitted value versus residual plots

The main effects plots are shown in Figure 8. It is seen from the figure that:

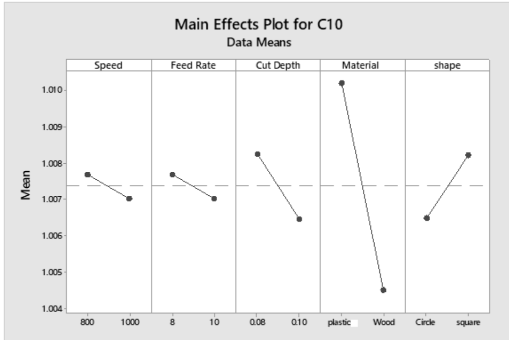


Figure 8. Main effects plot

1. The material factor is found to be the most significant factor;
2. The shape and cut depth factors are the next most significant factors;
3. The speed and feed rate factors have minimum effect.

The results are consistent with the p-values for the above factors in the ANOVA table (Table 3).

5. Conclusions and recommendations

The DIY CNC router assembled and tested by the student team is capable of cutting materials (plastic and wood) within the dimensional tolerances (1 ± 0.02"). The Minitab output shows that the normal probability plot is nearly linear indicating that the residuals/errors are normally distributed and there is nothing unusual about the residuals. Main effects and the 2-factor interaction effects indicate that material, shape, and cut depth have significant effects on the measured values. All five factors showed significant effects at higher order interactions (3-factor and 4-factor interactions). The main effect plots show that the material has the highest effects on the machining, as it was expected because the materials used, plastic and wood, have different levels of softness.

Through this hands-on project, the student team was trained in assembling and testing a CNC router, cutting simple to complex shapes using G-Codes, measuring the parts made for dimensional accuracy, collecting data for experimental design, and analyzing the data using Minitab/Microsoft Excel. This is an excellent hand-on learning experience for the student team. Using the DIY CNC router, other materials such as wax, acrylic, soft metals like copper and aluminum can be cut and tested for dimensional accuracy. The CNC router assembled and tested is now available for other students for further studies.

6. Acknowledgment

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