EXAMPLE OF CROSS-DISCIPLINARY APPROACH IN EDUCATION

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Abstract - Engineering education in the modern world requires a cross-disciplinary approach in order to better prepare learners for diverse and complex problems that engineers need to solve in a real industrial environment. In this paper, the process of the development of a Computer Numerically Controlled (CNC) machine is presented. CNC machines are commonly used for a variety of engineering manufacturing applications in many modern industries. It is, therefore, considered particularly important that students from various engineering streams be given adequate exposure to modern CNC machines, their design, programming and control. As a result of this project, a cost-effective CNC router with the application of engraving was developed. The CNC router can also be used as an educational tool to teach junior students or school learners the basics of modern manufacturing machines and systems. The synergetic combination of mechanical, electrical and software engineering is evident in the design of the CNC router. The design process follows the systems engineering approach to teach learners to adhere to the classical engineering methods and apply correct design tools and software. Following all the steps, from design to implementation and to testing, students can better understand the complexity and interdependability of tasks in engineering.

Keywords - Training and Education, Design, Engineering, CNC Machines

I. INTRODUCTION

Human Resource Development (HRD) plays an important role in the modern industrial economy that provides a means for improving living standards, which is recognised globally [1]. In developing countries, such as South Africa, there is a need to enhance education to speedup economic development and industry growth. Hence, a lot of emphasis is placed on specifically technical education and training [2, 3]. Modern engineering educational programmes need to be cross-disciplinary because there are no longer clear boundaries between engineering tasks and activities in the rapidly changing technological world. Therefore, students nowadays must be equipped with fundamental knowledge of many disciplines, which were traditionally considered as part of other engineering streams. Basic sciences and mathematics lay a foundation for engineering sciences, which need to reflect the latest developments in technology and commerce. In addition, with a rapid introduction of IoT and Industry 4.0, newly generated knowledge must be continuously integrated in current engineering education curricula.

Modern CNC machines and robots incorporate elements of many engineering fields because they consist of mechanical transmissions, electric motors, electronic circuits, computer-based controllers and communication modules for web access and control. Therefore, as part of the graduate engineering programme, it was decided to design a CNC router in order to demonstrate the synergetic combination of engineering fields, such as: mechanical, electrical, electronic and computer engineering.

Although engraving is essentially a two-dimensional process, a 3-axis machine is required to allow for the positioning of the tool in three-dimensional space [4, 5]. Dedicated software such as Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) allow one to design a desired profile or image and to generate the tool path using specific code, namely G-code, which contains the information to control CNC machine axes to engrave or cut the image on the surface of the material.

The design of a CNC router described below follows the cross-disciplinary approach, which can also be used as a practical demonstrator of various engineering sciences, technologies and practices, as well as an educational tool for basic training of CNC operators.

II. SYSTEM DESIGN

A. Mechanical Design

The mechanical design of the CNC router is of a Cartesiantype, which comprises of a baseplate, three linear axes and a high-speed spindle attached to the vertical Z-axis platform as shown in Fig. 1.

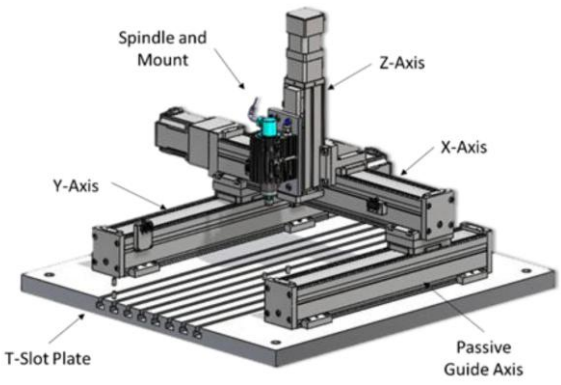


Fig 1. CAD model of the CNC router

To ensure accuracy and squareness, the baseplate is of crucial importance as it provides a platform to house all the components, ensure alignment between the axes

and allows a means to secure the workpiece while it is being machined, Fig 2.

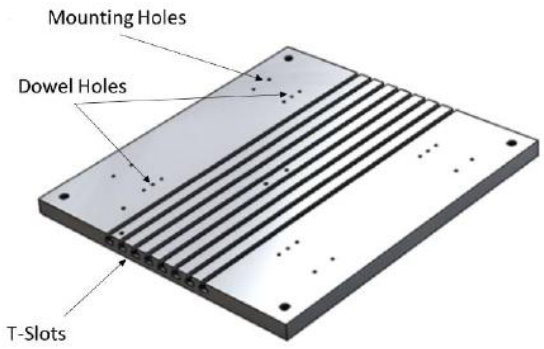


Fig 2. CAD Model of the baseplate

The baseplate was manufactured from a solid piece ofaluminium due to its strength, light-weight and rust-proof nature. A number of T-slot channels were machined in the centre of the baseplate. These allow for an industry standard means of clamping various sized workpieces to the base.

Mounting threaded holes are used to connect the clamping brackets and an enclosure to the baseplate. These brackets are situated on each side of the axes and are used to fix the axes drives. Furthermore, four dowel holes were machined in the baseplate to guarantee alignment of the inner connecting brackets of the Y-axis and its guide axis. This is paramount in obtaining a square and accurate system.

Motion along the X, Y and Z directions is provided by three ballscrews. Stepper motors were used to drive the respective axes. The drives were chosen due to their high accuracy, reliability and low cost.

The X-axis is connected to the Y-axis and corresponding guide axis by means of a connecting bracket. The driverless guide axis was used to provide support for the force and torque capacity of the system and helps to assist in reducing vibrations of dynamic loads. The Z-axis is connected to the X-axis using an angular connecting bracket to provide the correct orientation of the end-effector. Limit switches are used to limit the maximum travel positions for each axis and to provide automatic homing and safety.

The high-speed spindle enables the use of small diameter cutting bits for the engraving operation. The smaller the cutting bit used, the higher the required angular velocity to maintain the necessary cutting velocity.

B. Electrical and Control Hardware Design

The overall system architecture is shown in Fig. 3. The CNC router's electrical and control system makes use of a personal computer (PC) as the machine controller, implementing Mach3 CNC control software. A dedicated Mach3 breakout board is connected to the PC via universal serial bus (USB). The breakout board is used to manage the pulse and direction signals that are sent to the three stepper motor drivers as well as to control the inputs and outputs of the system, which include an emergency stop button and limit switches. The outputs consist of a spindle start signal and an analogue signal to control the spindle speed.

The stepper motors are controlled by Gecko stepper motor drivers powered by a 48VDC power supply.

The spindle frequency converter is supplied with a 24V start/stop signal and 0 to 10V analogue signal to control the spindle

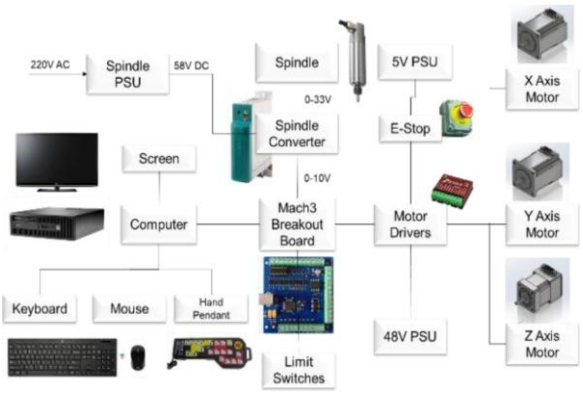


Figure 3. System architecture

speed between 5000 and 80000 rpm. The spindle is powered by an independent 58VDC power supply. The inputs and outputs are powered by a 24VDC power supply, which allows for the limit switches, E-stop and spindle control circuits to operate.

C. Control System Software

The controller's tasks consist of interpreter, interpolator, acceleration and deceleration control, position control as well as management of all inputs and outputs of the system. A PC with Mach3 software performs the control system functions.

Mach3 software allows for control of up to 6 axes with a visual G-code display and live simulation. It provides control for the spindle speed, feed rate, E-stop and limit switches via industry standard G-code interpretation. The control logic flow diagram of the CNC program is shown in Fig. 4.

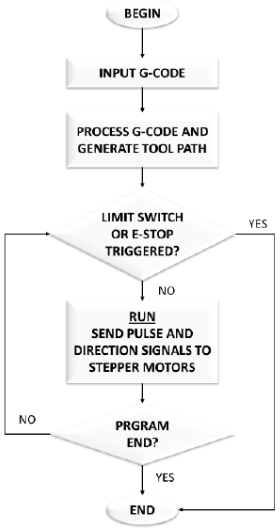


Fig 4. CNC control system flow diagram

D. System Integration

The designed CNC router is shown in Fig 5.

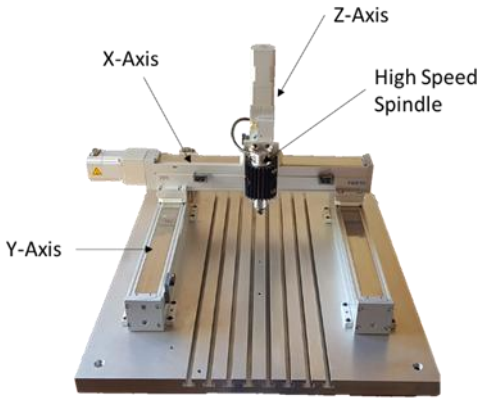


Fig 5. Photograph of the CNC router

The Y-axis and corresponding guide axis were attached to the baseplate by means of four pairs of connecting brackets. The X-axis was then placed across the Y-axis and guide axis and attached on both ends by means of the adapter kits. The Z-axis was then attached to the X-axis by an angular mounting bracket. The spindle mount is attached to the Z-axis by means of a connecting bracket.

The motors are all connected to each respective axis by means of motor couplings. Lastly, the limit switches were mounted using custom 3D printed brackets that fit in the grooves alongside each axis.

III. RESULTS

Various tests were performed on the system to verify its performance, repeatability, accuracy and squareness.

A. Preliminary Tests

Preliminary testing was performed after setup to ensure the system was performing adequately before further tests were performed to quantify the repeatability, accuracy and squareness of the machine. Before the spindle was attached, a pen was connected to the Z-axis and a G-code program was run to check whether the interpolation was working correctly. The system was deemed effective from the results of the drawing test and the spindle was then attached to the system. With the spindle connected, the performance could then be verified on wood, plastic and aluminium.

B. Repeatability Tests

The repeatability of a CNC machine is a measure of the closeness of the agreement between the results of successive measurements taken under the same conditions [6]. This gives an indication of how reproducible the positioning of the system is.

A dial indicator was used in the experiment to determine the repeatability of the system. The dial indicator was positioned to measure movement in the X, Y and Z axes respectively as seen in Fig. 6.

The tip of the tool was then jogged to touch the dial indicator so that a deviation was noted. This point was then set as the machine origin. Various movements were then



Fig 6. Photograph of the dial indicator setup for repeatability measurements

made in each respective axis and the machine was then sent back to the origin point at the dial indicator. Any deviations were then recorded, and the repeatability was calculated.

The pooled mean value for each test was calculated, as in [7]:

$$\langle \bar{x} \rangle = \frac{1}{M} \sum_{j=1}^{M} \bar{x}_j \qquad (1)$$

The pooled mean values for each axis were found to be:

$$\langle \bar{x}_y \rangle = \frac{1}{3}(0.007 + 0.00 + 0.00) = 0.0023 \text{ mm} \qquad (2)$$

$$\langle \bar{x}_x \rangle = \frac{1}{3}(0.007 + 0.0035 + 0.00) = 0.0035 \text{ mm} \qquad (3)$$

$$\langle \bar{x}_z \rangle = \frac{1}{3}(0.007 + 0.007 + 0.0035) = 0.0058 \text{ mm} \qquad (4)$$

The pooled standard deviation for each axis was then calculated using [5]:

$$\langle S \rangle = \sqrt{\frac{\sum_{j=1}^{M} (\bar{x}_j - \langle \bar{x} \rangle)^2}{M-1}} \qquad (5)$$

The pooled standard deviations for each axis were found to be:

$$\langle S_x \rangle = \sqrt{\frac{0.0000245}{2}} = 0.00350 \text{ mm} \qquad (6)$$

$$\langle S_y \rangle = \sqrt{\frac{0.00003267}{2}} = 0.00404 \text{ mm} \quad (7)$$

$$\langle S_z \rangle = \sqrt{\frac{0.00000817}{2}} = 0.00202 \text{ mm} \quad (8)$$

And the pooled standard deviation of the means was found with [5]:

$$\langle S_{\bar{x}} \rangle = \frac{\langle S_x \rangle}{\sqrt{M}} \quad (9)$$

The pooled standard deviation of the means for each axis were found to be:

$$\langle S_{\bar{x}} \rangle = \frac{0.00350}{\sqrt{3}} = 0.0020 \text{ mm} \quad (10)$$

$$\langle S_{\bar{y}} \rangle = \frac{0.00404}{\sqrt{3}} = 0.0023 \text{ mm} \quad (11)$$

$$\langle S_{\bar{z}} \rangle = \frac{0.00202}{\sqrt{3}} = 0.0012 \text{ mm} \quad (12)$$

An estimate of the true value of the repeatability can be found employing a 95% confidence interval [5].

$$x' = \langle \bar{x} \rangle \pm t_{v,P} \langle S_{\bar{x}} \rangle (95\%) \quad (13)$$

With $v = 9$ and $P = 0.95$

$$t_{9,0.95} = 2.262 \quad (14)$$

The repeatability of each axis is therefore found to be:

$$R_x = 0.0035 \pm 0.0045 \text{ mm} \quad (15)$$

$$R_y = 0.0023 \pm 0.0052 \text{ mm} \quad (16)$$

$$R_z = 0.0058 \pm 0.0027 \text{ mm} \quad (17)$$

C. Uncertainty of Measurements

The zero-order uncertainty is calculated as:

$$u_0 = \frac{\text{Resolution}}{2} = \frac{0.01}{2} = 0.005 \text{ mm} \quad (18)$$

The calculated uncertainty in the measurements of each axis can be combined using the root-sum-squared method as follows [4].

$$u_c = \sqrt{{u_x}^2 + {u_y}^2 + {u_z}^2} = \\ = \sqrt{0.0045^2 + 0.0052^2 + 0.0027^2} = 0.0074 \text{ mm} \quad (19)$$

The total uncertainty is then found to be:

$$u_T = \sqrt{{u_0}^2 + {u_c}^2} = 0.0089 \text{ mm} \quad (20)$$

The total repeatability of the system can be calculated by the root-sum-squared method whereby:

$$R_{total} = R_T \pm u_T \quad (21)$$

$$R_T = \sqrt{{R_y}^2 + {R_x}^2 + {R_z}^2} \quad (22)$$

$$\therefore R_{total} = 0.007 \pm 0.0089 \text{ mm} \quad (23)$$

D. Accuracy and Squareness Testing

The accuracy and squareness were verified using a technique called Optical Microscopy. A test pattern was designed and engraved in aluminium using the constructed machine as seen in Fig. 7.

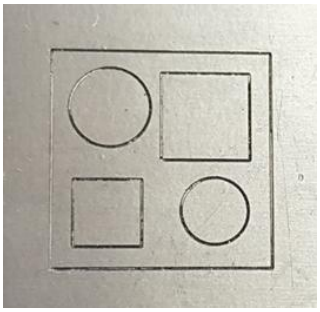


Fig 7. Photograph of the test sample

The sample was then imaged using the Olympus DSX510 Optical Microscope. Multiple images were taken and digitally stitched together to form a calibrated image of the test sample. Each pixel in the high-quality image resembles a specific length.
Therefore, measurements could be made on the calibrated image using specialised software to confirm the squareness and accuracy of the machine.

E. Squareness Testing

The squareness of the machine can be measured by checking the angles of the engraved squares and the roundness of the circles.
A corner angle of 90^0 would indicate perfect squareness and perpendicularity between the axes. The angles of the corners were measured, and average calculated as shown in Table 1.

No.	Measured Angle (°)	Variance from the Mean (°)
1	90.43	0.49
2	90.32	0.38
3	89.67	-0.27
4	89.77	-0.17
5	89.72	-0.22
6	89.71	-0.23

Table 1. Measurements for Squareness Testing

The mean angle is calculated as: $\bar{x} = 89.94°$
The standard deviation is found as follows [5]:

$$S_x = \sqrt{\frac{\sum_{i=1}^{N} (x - \bar{x})^2}{N-1}} = \sqrt{\frac{0.5876}{5}} = 0.34 \quad (24)$$

The standard deviation of the means was calculated as:

$$S_{\bar{x}} = \frac{S_x}{\sqrt{N}} = \sqrt{\frac{0.5876}{5}} = 0.14 \quad (25)$$

An estimate of the true value with a 95% confidence interval employed and $t_{5,95} = 2.571$, can be found to be:

$$\alpha = \bar{x} \pm t_{v,P} S_{\bar{x}}(95\%) = 89.94° \pm 0.36° \quad (26)$$

The deviation in circle roundness was also measured and is another indicator of the squareness of the machine, as shown in Fig. 8.
The mean of the deviations was found to be $\bar{x} = 56.77$ µm.
The standard deviation and the standard deviation of the mean were calculated to be: $S_x = 25.67$ µm and $S_{\bar{x}} = 12.84$ µm.



Fig 8. Measurements in the deviation of circle roundness

Therefore, with $t_{3,50} = 0.765$, the deviation can then be expressed as:

$$\delta = 56.77 \pm 9.82\ \mu m \quad (27)$$

The angle of 89.94° and deviation in roundness of 56.77µm indicate a relatively good squareness of the machine and good perpendicularity between axes for the purpose of engraving.

F. Accuracy Testing

To test the accuracy of the engraving, and subsequently the machine, measurements were made of the lengths of the sides of each square. These values were then compared with their supposed lengths to calculate their respective deviations. The results of measurements of the sides of the squares are shown in Fig. 9.

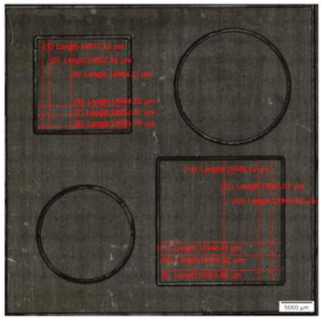


Fig 9. Measurements in the squares for accuracy assessment.

G. Accuracy in the X-Axis

The mean of the differences was found to be $\bar{x} = 51.52$ µm, the standard deviation was found to be $S_x = 13.47$ µm and the standard deviation of the means was foundto be $S_{\bar{x}} = 4.49$ µm.

Therefore, employing a 95% confidence interval and $t_{8,95} = 2.306$, the accuracy in the X-axis is found to be:

$$x' = 51.52 \pm 10.35\mu m \quad (28)$$

H. Accuracy in the Y-Axis

The mean of the differences was found to be $\bar{y} = 37.33$ µm, the standard deviation was found to be $S_y = 14.05$ µm, the standard deviation of the means found to be $S_{\bar{y}} = 4.68$ µm.

Therefore, employing a 95% confidence interval and $t_{8,95} = 2.306$, the accuracy in the Y-axis is therefore found to be:

$$y' = 37.33 \pm 10.79\ \mu m \quad (29)$$

The final accuracy of the machine can be considered to be that of the worst performing axis. Therefore, the accuracy can be said to be within a $= \pm 0.06$mm.

IV. CONCLUSION

The purpose of this project was to develop a cost-effective CNC router with an engraving operation to be used as an educational tool by applying the systems engineering approach, relevant engineering tools and software. The CNC router design is the result of a multi-disciplinary approach, which incorporates mechanical, electrical and computer engineering fields of knowledge.
The developed CNC router has a 3-axis Cartesian design architecture with ballscrews, driven by stepper motors, which allow 2.5D-axis machining. An incorporated vertical high-speed spindlewith up to 80000 rpm providesrequired cutting speeds for small diameter engraving tools. The CNC router work envelope is 200mm in the X-direction, 240mm in the Y-direction and 80mm in the Z-direction, and it can be considered as a desktop machine.
Mach3 freeware software for a PC platform, together with low-cost hardware, such as: stepper motor drives, breakout boards and frequency converters, provide an efficient, affordable and user-friendly control of the CNC router. The industry standard G-code is used for CNC programming.
The accuracy and repeatability of the CNC router were determined experimentally and using statistical calculations of the uncertainties they were found to be as follows: a positional accuracy of 0.06±0.01mm, a repeatability of 0.02mm with a resolution of 0.006mm for the X and Y axes and 0.005mm for the Z axis. As a result, the CNC router achieved high quality and good resolution engraving capabilities which was demonstrated with engravings performed on wood, plastic and aluminium.
The CNC router can be easily reconfigured as a laser cutting or a desktop milling machine. The engineering concepts employed in this project can be used to teach

students the basics of engineering design, manufacturing, control and CNC programming.

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