Evaluating the development and cutting capacity of a one-square computer numeric controlled milling machine

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ABSTRACT

Traditional subtractive technology is rapidly losing significance with the advent of digital manufacturing technologies, which offer affordable machining with high accuracy and repeatability. Computer numeric controlled (CNC) machining has been around for a while; however, it has been costly to own one. Since the concept of CNC machining is now broadly understood and open-source software is available for control, designers can make use of available local materials to develop cheaper CNC machines. Hence, this presents the evaluation of the design and development of a one-square-meter CNC milling machine. The control was implemented on Arduino Uno, while open-source Universal G-code Sender (UGS) and G-code reference block library (GRBL) were used for the G-code generation and machine control, respectively. The built CNC was calibrated and tested on wood and plastic materials, and the resulting products were acceptable in accuracy up to ±0.02 mm in the first trial, but attained perfect accuracy by the third trial. Multiple tests repeatedly showed that accuracy was maintained. Since the machine is reconfigurable, future work entails automation and incorporating laser cutting capabilities into the machine.

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1. INTRODUCTION

Computer numeric control (CNC) machining is a subtractive technology, as it works by systematically removing material from the parent material until the desired shape is formed. It is a sustainable manufacturing method which helps minimize carbon emissions in production processes. This is so because the operation process is optimized for a minimal but effective production process [1]. Digital manufacturing is taking a sharp upward growth, impacting all industrial practices and manufacturing. Most parts in manufacturing industries now seek to incorporate digital manufacturing into their operational line-ups [2]–[4]. Large scale production requires short production time; hence, the CNC automation comes in handy, where short production time with high volume and uniform products are integrated into the shop layout [5], [6].

Engineers and manufacturers continually face the challenge of determining the most effective production method. Similarly, the type and form of the desired product requires the task of deciding if CNC machining would be the optimal choice for the production [7]. Affordability and cost management in the fabrication and operation of CNC machines must be carefully considered, especially with the conversion into digital manufacturing [8], [9]. Rapid prototyping, high production rates, uniform quality, and customization require the need for customizable digital manufacturing machines. Similarly, size and shape constraints also provide a basis for self-made manufacturing machines [5]. These are important aspects of digital manufacturing because not only should these factors be considered, but the types of materials used for production or to be produced should be included in the design of these machines. Wood, plastics, metals, glass, foam, and composites are among the materials that can be CNC machined and are used in the aerospace, automotive, and medical industries.

The rapidly changing product requirements, technology, advocacy for sustainability, and affordability, in line with SDG goals 8, 9, 11, and 12, advocate individualized participation in digital manufacturing using CNC technology [6]. Ali *et al.* [10], in order to conveniently interact with digital manufacturing, they developed a high speed mini CNC machine with low power consumption and ± 0.01 mm accuracy. Some of these customized machines are for private use, but recently, Sneinel *et al.* [9] developed a CNC wood carving machine for artisans, which achieved an accuracy between ±0.1 and ±0.15 mm. In [11], a mini CNC milling machine, developed that will be accessible for training students, was presented. This machine is made available for students to operate, as most institutions do not give students individualized access to such machines. In addition, since the cost of acquiring CNC machines is high, the progressive knowledge of electronics has increased participation in digital developments. Open-source software and codes are available, and there is much familiarity with the operational sequence, hence enthusiasts as well as machinists can upgrade existing traditional machines to computer controlled or build new ones. On this background, Ayala-Chauvin *et al.* [12], developed a mini, low cost CNC milling machine for woodworking. Usually, most self-made CNC milling machines are mini and are limited to wood cutting. It is necessary to extend the range of materials and the size of these non-commercial machines, which will increase their application.

In CNC machining, time, energy, and cost savings are very important. This can be achieved by optimizing the process parameters [13]. Optimizing or controlling process parameters has been deemed one of the most important aspects of computer-controlled or digital manufacturing [14]. Process parameters can be material- or shape-specific; hence, a generic process parameter cannot be used for all materials. Precision is germane in producing parts and products, and it is the basis for computer numeric control [15]. Alterations and changes in process parameters in CNC machining result in variations in the outcome of the machined part.

Theoretical modelling of the CNC is crucial to developing customized solutions to its design and control strategy [16]. The modeling provides the designer with the structural configurations and how they interact. This resource is a good input for the automation and remote control of the systems [17]. It was also suggested to be helpful in the case of digital twin applications. CNC machining is a computer aided manufacturing (CAM) technology that requires a good knowledge of computer aided design (CAD), according to Gui *et al.* [18] who developed a draw-to-cut CNC application for artefacts. This customized application uses drawing language that converts hand sketches on materials to machine language for the cutting operation.

The life cycle of a machine includes the design, manufacture, installation, and commissioning [19], [20]. This work presents the life cycle of a one-square-meter CNC milling machine. It was inspired by the recurrent need for high-volume precision cutting for projects in the department. However, the department cannot afford a new CNC milling machine, so the additive manufacturing laboratory raised a team mainly from the additive manufacturing research group to develop one. The detailed design, manufacturing, and testing of the CNC machine are presented. Similar research has been conducted in response to the need. For example, Bukhari *et al.* [21] and Ngadiyono *et al.* [22] presented custom-sized CNC engraving machine for acrylic products, underscoring the peculiarity of application and need based CNC machine development.

2. METHOD

This section discusses the materials and methods used to design and develop the CNC milling machine. It also presents the calibration and testing procedures. These descriptions ensure clarity in the development process and reliability in the evaluation results.

2.1. Materials

The CNC milling machine was made of mechanical, electrical, and electronic parts. Mechanical parts, which are the bulk of the materials used, form the structural frame, ensure stability, and guide the movement of the axes. The electrical and electronic parts give power to the moving parts and the cutting operation. These parts were interconnected with miscellaneous parts to form the complete machine. However, the major materials used are described in Table 1.

Table 1. Major materials used for the development of the CNC milling machine

Part	Description
Nema 23 stepper motors	For navigation and controlled movement of the axes
Lead screw	Movement of the x and Y axes
Xtreme polycarbonate C-wheels	End supports for the Y-axis
C-Beam aluminium profile	Guide and support for the Y and Z axes
Arduino	Microcontroller
Lead plate	Frame for the vertical structure
Spacers	To hold parts together for easy relative movements
SBR linear rails	Guide rail for the Y-axis
Limit switches	Set boundaries for the axes' movements
Linear rail blocks	Guide rail for the X-axis
SBR16 linear rail	Guide rail for the Z-axis
Emergency stop switch	To alt the operation in case of an emergency
Thrust bearing	To support the rails and beams
C-Beam end plates	Support for the C-beams

2.1.1. Detailed 3D modeling and assembly simulation

The CNC milling machine was conceptualized as a 3-axis configuration with a moving gantry, designed for movement and operation through a screw-driven mechanism that is of the right size. The detailed view of the 3D model is presented in Figure 1.

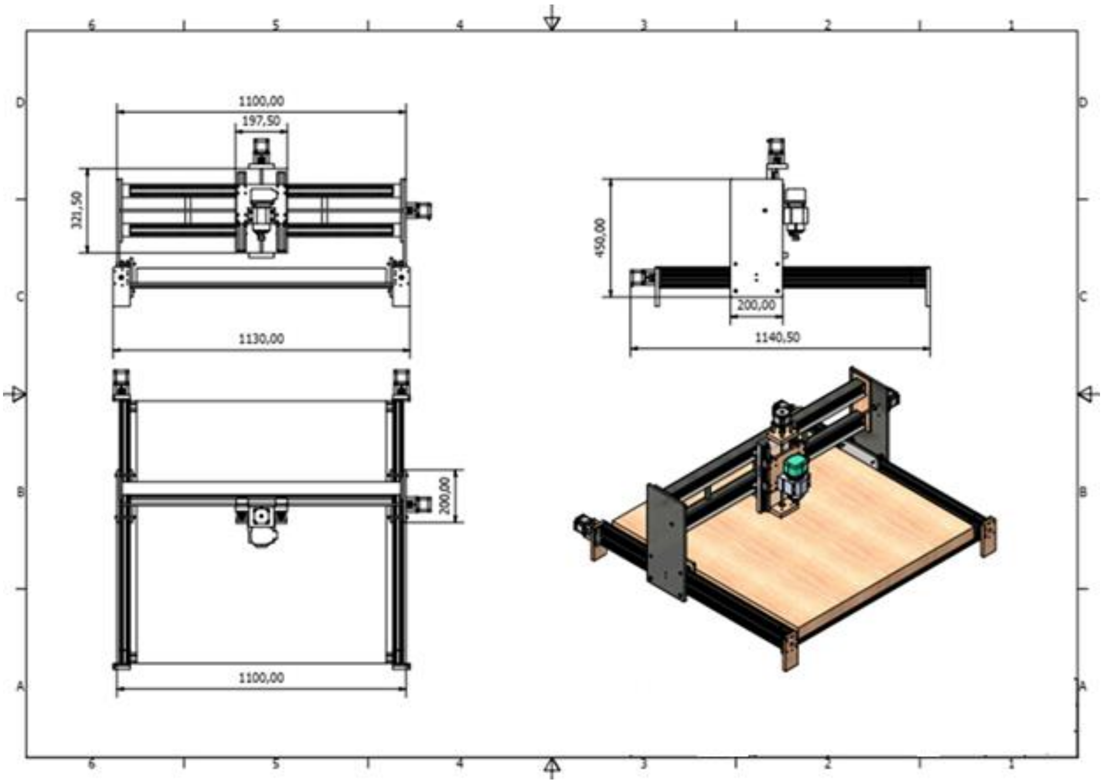

Figure 1. Orthographic view of the CNC milling machine model

2.2. Design workflow

Exceptional design is not an instantaneous achievement. It emerges through iterative refinement and rigorous testing to assure its practicality. This section details the electrical design and design calculations.

2.3. Electrical design

The electrical design involves choreographing the exact movements of stepper motors to implement safety protocols and embedding user interfaces. This intricate interplay of electrical design serves as the keystone, guaranteeing the CNC milling machine's harmonious operation and achieving the pinnacle of functionality and efficiency.

Figure 2 shows the electrical design wiring, which encompasses a range of vital components that include four Stepper motors, four TB6600 stepper motor drivers, an Arduino Uno, an Arduino Uno shield, a power supply, an emergency stop switch, a router, power switches, and an AC power connector as shown in Figure 3.

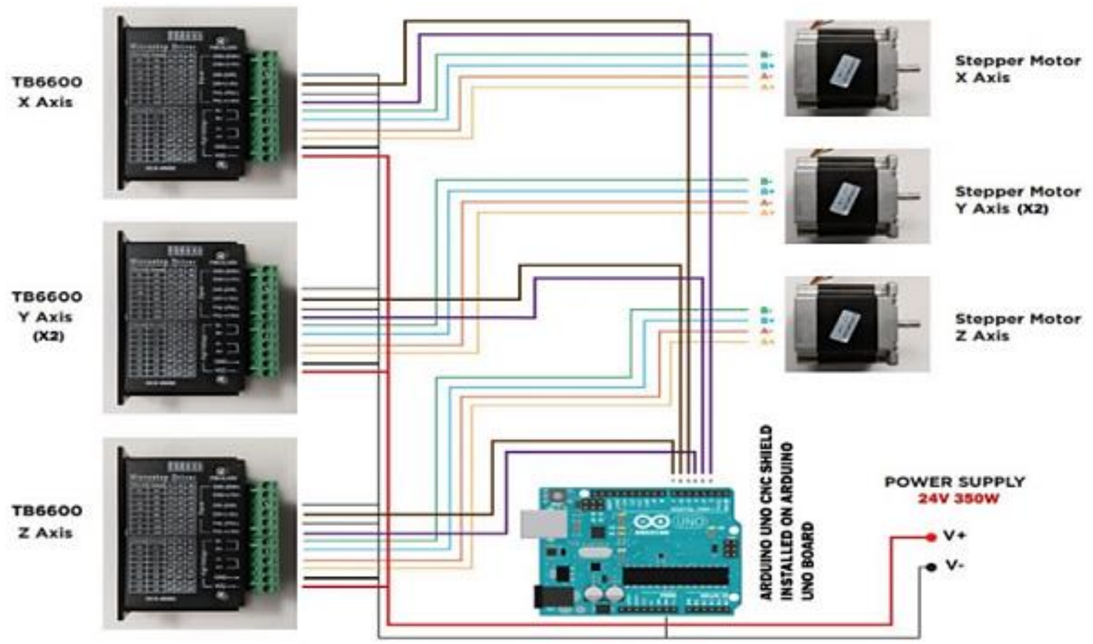

Figure 2. Wiring schematics

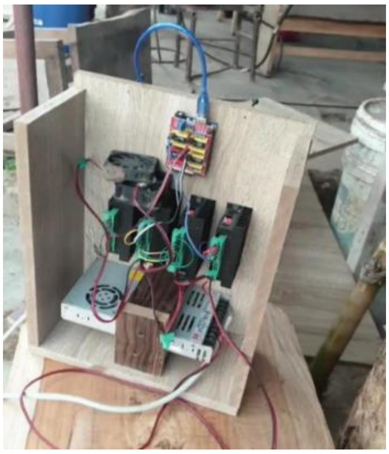

Figure 3. Electric box

2.4. Design calculations

The design for parts, electrical circuit, lead screws, and power requirement are presented in this section. Each component is explained to highlight its function and contribution to the overall system. The descriptions aim to provide a clear understanding of the machine's structure and operational needs.

2.4.1. Mathematical calculations for parts requirements

This section presents the mathematical relations for the design. The mathematical calculation is summarized in Table 2. The structural analysis of the frame was designed for stability, load bearing, and vibration prevention.

Table 2. Mathematical calculations for part designs

Activity	Equations	Value
Motor selection	$Velocity\ ratio = \frac{Displacement\ of\ effort}{Displacement\ of\ load}$ $= \frac{\pi D}{pitch} = \frac{\pi \times 8}{2}$	12.5664
	$Efficiency = \eta = \frac{tan\alpha}{tan\beta} = \frac{tan4.5499}{tan16.6992}$	$\mathbf{0.265}$
Torque requirement for the Z axis	Total weight transverse for Y axis, which includes router, router holder, backplate and SBR12UU block, is 5 kg The maximum load would be the net axial force during upward motion. $Torque = \frac{Net\ axial\ force \times Pitch}{2\pi\eta} = \frac{\mathbf{59.05 \times 2 \times 10^{-3}}}{\mathbf{2\pi \times 0.265}}$	$0.071Nm$
Torque requirement for the X axis	The maximum load would be the axial force during constant acceleration on the X axis. $Torque = \frac{Net\ axial\ force \times Pitch}{2\pi\eta} = \frac{54.373 \times 2 \times 10^{-3}}{2\pi \times 0.265}$	$0.0653Nm$
Torque requirement for Y axis	The maximum load would be the axial force during constant acceleration on the Y axis. $Net\ Axial\ force = \mu mg + ma = (0.3 \times 31 \times 9.81) + (31 \times 2)$ $Torque = \frac{Net\ axial\ force \times Pitch}{2\pi\eta} = \frac{153.233 \times 2 \times 10^{-3}}{2\pi \times 0.265}$	$0.184Nm$
Power requirements	Having 4 Nema 23 motors rated at 2.8 A in a parallel connection therefore: $Total\ current\ required\ for\ the\ supply = 4 \times 2.8$	$11.2\ A$
	A common practice is to add a 10-20% margin to the calculated power requirements. Adding a safety margin of 20% = 1.2 × 11.2 Since this is the power supply needed, we used a power supply rated at 24 W, 14.68 A, which is sufficient for our motors' need.	$13.44\ A$

$g = acceleration\ due\ to\ gravity = \frac{9.81m}{s^2}, a = linear\ acceleration = \frac{2m}{s^2}$.

2.4.2. Design of lead screws for Y-Axis

A lead screw length of 1000 mm was considered. The weight of the motor will act vertically downward towards the shaft. The force acting on the lead screw is the weight of the router and the weight of the block to mount the router, which act on the lead screw at the center. The weight of the block on which the router is mounted is 31 kg. the design calculations are presented in (1)-(6). Hence, Total weight=Weight of the router + Weight of the block on which the motor is mounted (Gantry)=31 Kg=304.11 N.

$$\sum F_y = 0 \quad (1)$$

$$R_A + R_B = 31 \times 9.81 = 304.11\ N \quad (2)$$

$$\sum F_y = 0 \quad (3)$$

$$304.11 \times 500 - R_B \times 1000 = 0 \quad (4)$$

$$R_B = 152.055 \quad (5)$$

$$R_A = 304.11 - 152.055 = 152.055 \quad (6)$$

2.4.3. Design of lead screws for X-Axis

The lead screw guides the drilling head in x direction, i.e., in the horizontal direction. Forces acting on the lead screw are the weight of the Z Axis build (i.e., the motor of the Z axis, Router, SBR rails, and Guided rails). The design calculations are presented in (7) to (12).

Weight of the Z Axis=11 kg=107.91 N

$$\sum F_y = 0 \quad (7)$$

$$R_A + R_B = 107.91\ N \quad (8)$$

$$\sum M_A = 0 \quad (9)$$

$$107.91 \times 500 - R_B \times 1000 = 0 \quad (10)$$

$$R_B = 53.955 \quad (11)$$

$$R_A = 107.91 - 53.955 = 53.955 \quad (12)$$

2.4.4. Power requirement

The primary power consumers in a CNC milling machine are the motors responsible for moving the various axes (X, Y, Z). CNC machines require control electronics, including a microcontroller, motor drivers, and other auxiliary components. It also consists of cooling systems to maintain the optimal temperature of the motors and cutting tools. It is advisable to include a safety margin for power calculations to account for unexpected power surges, start-up currents, and other variations.

3. RESULTS

3.1. Machine performance evaluation

Machine performance evaluation entails analyzing the CNC milling machine's capabilities in terms of precision, speed, repeatability, surface finish, and overall output quality. This assessment involves testing the machine's ability to meet design specifications, achieve desired tolerances, and produce consistent results across various materials and machining operations. GBRL open software is used to extract the G-code from the CAD drawing, which is then sent to the CNC machine for the required operation. The specification of the major parts based on the design calculations is presented in Table 3.

Table 3. Specifications of parts

S/N	Components	Specifications
1	Lead Screw	X-axis Length: 1000 mm, Diameter: 8 mm Y-axis Length: 1000 mm, Diameter: 8 mm Z-axis Length: 365 mm, Diameter: 8 mm
2	Aluminum Plates	Thickness: 10 mm
3	SBR12UU Linear Blocks	Fixed mode of sliding block: Locking type Rail shaft diameter: 12 mm used for Z axis
4	SBR12 Linear Rails	Length: 300 mm Width: 32 mm Shaft diameter: 12 mm
7	Stepper Motor Driver	Type: TB6600 Operating voltage: 9–40 V DC Output Current: 0.7-4.0 A Pulse input frequency: up to 20 kHz 5 V levels input signal 200–6400 pulse per revolution Logic signal current: 8–15 mA Output current selectable in 8-steps via DIP switches Suitable for 2 and 4 phase motors
15	NEMA 23 57 mm Stepper Motor	Voltage Rating: 3.2 V Current Rating: 2.8 A Step Angle: 1.8 deg. Steps Per Revolution: 200 No. of Phases: 4 Motor Length: 78.74 mm No. of Leads: 4 Inductance Per Phase: 3.6 mH
16	Wood Trimmer Router	Rated power input: 650 W Rated Voltage: 220-240 V Rated Frequency: 50/60 Hz No Load speed: 3000 rev/min Collect chuck Diameter: 6 mm

3.2. Machining precision and tolerance

The precision of the CNC milling machine was evident in its consistent dimensional accuracy when creating varied test components. This inspection was done using an accurate digital caliper. The measured average variation from the desired dimensions was well contained within a margin of ±0.02 mm. Furthermore, the CNC milling machine was tested for tolerance capabilities by making components defined by complicated features and rigorous dimensional tolerances. Comparative measurements done against reference dimensions proved the machine's adherence to stipulated tolerances, with variances found well within permissible boundaries. This substantiates the machine's consistent ability to meet high tolerance criteria and enables the production of accurate and precise components as presented in Tables 4 and 5.

Table 4. Drilling test on the z-axis

Drilling test	1st reading (mm)	2nd reading (mm)	3rd reading (mm)
1	0.98	1.02	1.00
2	1.98	2.02	2.00

Table 5. Precision test on x-axis

Pocket test (mm)	1st reading (mm)	2nd reading (mm)	3rd reading (mm)
10.00	9.98	10.02	10.00
20.00	20.00	20.00	20.00
25.00	24.98	25.02	25.00
40.00	40.00	40.00	40.00
50.00	50.00	50.02	50.00

3.3. Material-specific observations

3.3.1. Wood

Few things to consider in machining wood are the grain orientation, grain pattern, wood density and moisture content. These considerations determine the choice of machining parameters such as feed rate, tool type, and cutting depth. Wrong selection of these parameters can result in splattering, tearing out, and a rough surface finish. This can make postprocessing difficult or even impossible [23]. The choice of sealant, whether polyurethane, varnish, or oil, extends the wood's longevity and accentuates its natural beauty. A sample milling operation showing the cutting process and final product is presented in Figures 4 and 5.

Figure 4. Z-axis router holder milling operation

Figure 5. Cut-out wood of the x-axis router holder

3.3.2. Plastic

When machining plastics, managing heat generation is critical. Unlike metals, plastics have lower heat resistance, and excessive heat can lead to melting, warping, and rough surface finishes. Observations suggest that optimizing cutting parameters such as feed rates, spindle speeds, and depth of cuts can help manage heat buildup and produce clean, precise cuts without compromising the integrity of the material. Clamping and fixturing play a crucial role when machining plastics [24], [25]. Observations show that adapting cutting strategies to the specific plastic type enhances machining precision and reduces the risk of issues like melting or chipping [21]. The cutting of parts for a robotic arm is presented in Figures 6 and 7 to demonstrate the performance of acrylic in the milling process. Samples of drilling test, pocket test with smiley cut on wood and acrylic are presented in Figures 8 to 11, respectively.

Figure 6. The cutting progress of the robotic arm parts

Figure 7. The assembled robotic arm

Figure 8. The drilling test

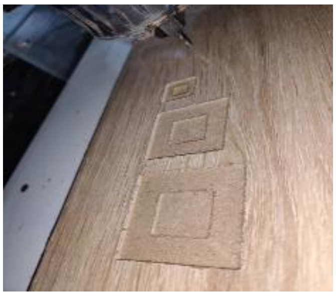

Figure 9. Pocket test

Figure 10. Smiley shape cut test on wood

Figure 11. Smiley shape cut test on acrylic

3.3.3. Comparative analysis of wood and acrylic

CNC milling machines can be used for machining wood and plastic, but understanding the differences is crucial for achieving optimal results [14], [23]. Wood machining involves adjusting tools to accommodate variations in grain patterns, density, and moisture content, while heat control is essential to prevent burning or warping. Chip evacuation is also vital for achieving a smooth surface finish. Techniques like sanding are necessary for projects requiring aesthetics.

Conversely, plastic machining requires specialized tools, such as single-flute end mills or spiral "O" flute cutters, to avoid issues such as melting and chipping. Heat management is critical due to plastics' lower heat resistance compared to metals. The comparative performance and parameters are presented in Table 6.

Table 6. Comparative performance and parameters for wood and plastic

Property	Wood	Plastic
Rotation frequency (n (rpm))	10000	10000
Advance Speed (F (mm/ s))	0.15	0.15
Cutting Speed (V_c(m/ min))	508	205
Depth of cut (a (mm))	2	3

4. CONCLUSIONS

The process of designing the CNC milling machine has been an exceptional achievement that embodies the synthesis of creativity, engineering expertise, and relentless problem-solving. Through the collective efforts of our team, we developed a design that effortlessly merges mechanical accuracy with intelligent control, resulting in the construction of a sturdy and highly efficient milling tool.

From its inception, the CNC milling machine was created to strike a harmonious balance between economic efficiency and structural integrity. The design iterations and precise simulations have transformed this goal into a cutting-edge machine that connects with contemporary industrial demands. The developed machine is positioned to make a real impact across varied industries, ranging from rapid prototyping to precision manufacturing. Our journey does not finish here; it provides the framework for continual advancements, continuous refinement, and an unwavering pursuit of excellence as we continue to stretch the boundaries of our design's potential. The machine has demonstrated high performance cutting on wood and plastic materials.

Continuous improvement is an intrinsic aspect of the design process, as no design is devoid of imperfections. Consequently, a consistent cycle of creative design iterations becomes imperative. There is, however, room for improvement in the design and development of the 3-axis milling machine. Future works to enhance the CNC milling machine’s performance and versatility include introducing a fourth axis for more flexible manufacturing, adoption of automation and AI/ML for the control of production and tool change, development of a portable version, and reconfiguring for other manufacturing processes, such as laser cutting.

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Godwin Thompson	✓	✓	✓	✓		✓	✓	✓	✓					✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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