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Design and Control of 3-Axis CNC Milling Machine

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Abstract

Automation and precision are two main aspects of manufacturing; computer numerical control (CNC) milling machines are important machinery that must be in a workshop. First, a new CAD model was designed in Solidworks software with the required specifications. Afterwards, the materials were chosen to build a fully functioning CNC machine prototype. The second step was to set up the GRBL controller on an Arduino UNO. Then, the UGS platform was used as a G-code reader and as a user interface to access the GRBL controller. The third step was to build the prototype from the chosen materials. Finally, the last step was to wire the stepper motor drivers together with the power supply and the Arduino. As a result, the prototype was built and the machine achieved an accuracy of 0.01 mm.

Keywords
CNC, Milling Machine, Arduino, GRBL, Solidworks, UGS Platform

1. Introduction
National economic strength and productivity rely heavily on industrial manufacturing, which is being transformed by technologies such as big data, cloud computing, artificial intelligence, and IoT. Countries such as U.S.A., Germany, and China have implemented strategies, such as Industry 4.0, to integrate advanced technologies for smarter, sustainable manufacturing. Milling, a critical subtractive process known for its high Material Removal Rate (MRR)

and excellent surface finish, plays a key role in this evolution. CNC milling machines, widely used in aerospace, automotive, and mold manufacturing, utilize CAD and CAM software to manufacture complex parts with high precision in addition to minimizing reliance on the operator skill. Traditional ISO6983 programming for CNC machines is being replaced by STEP-NC (ISO14649), which integrates design and manufacturing data for improved performance. Variations in machine controllers, algorithms, and kinematics influence the efficiency and accuracy of CNC milling systems, underscoring the importance of innovation in manufacturing processes.

1.1 Objectives

This paper aims to manufacture a CNC milling machine. First, the machine is designed using SolidWorks CAD software. Second, the DC stepper motors are controlled by GRBL, which is an open-source CNC controller. Then the GRBL is uploaded on an Arduino UNO to control it with the UGS platform as a user interface. After which, a CAD design file is exported to the Inventor CAM software to generate a G-Code to simulate the CNC machine's control and motion. Finally, the product accuracy was tested by using a vernier caliper.

2. Literature Review

A crucial step in designing and manufacturing of a CNC milling machine is to increase the productivity and the quality of a workpiece in order to have an accurate and efficient program for machining products as stated by Kukreja et al. (2020). The CAM software frequently offers inefficient toolpaths and needs many user inputs and trials, which is time inefficient. Therefore, developing a toolpath planning algorithm to efficiently generate a program to manufacture a part on a CNC milling machine was essential. Chiu et.al (2020) use the particle swarm optimization (PSO) technique, with a hybrid objective function and an adaptive-network-based fuzzy inference system (ANFIS) predictor, to present an intelligent machining system (IMS). The suggested IMS offers the right machining parameters, such as speed, surface smoothness, and accuracy, to meet the customers' needs. Also, the IMS can offer a comparative analysis of machining performance. Petrakov et.al (2022) used a mathematical model for the interaction between the cutter and workpiece in the cutting zone, to create CNC machine control programs for contour milling during machining contours with different curvatures. It was found that the productivity increased by 70%.

In a study conducted by Anggorro et al. (2022), it was shown that the best cutting parameters for producing an insole with a CNC milling machine were chosen using an orthogonal array. A combination of cutting parameters was obtained using the Taguchi design of experiments technique. The response surface methodology (RSM) was employed to produce the ideal Ra value by using a regression model of the second order. On the other hand, another study, conducted by Kelekci et al. (2023), highlighted the problem of the deflection of the toolpath from the main toolpath planning created by the NC files. This study showed a new method that creates a trajectory planning and feed rate scheduling algorithm for point-to-point control of linear and circular paths in the NC-File, using G01 and G02/G03. Given that the suggested approach avoids feed rate variations at creates the tool path without deviating from the junction points and NC-File. Regarding the formability of the part formed concerning the various operating parameters and materials, Kannarasu et al. (2023) attempted to address the many ambiguities that emerge in the Incremental Sheet Forming (ISF) process. The forming and the formability of metals and polymers were compared with a specifically designed tool and fixture system. It was shown that the thickness distribution effect was more uniform when polymers were taken into consideration.

In another study, Huang et al. (2024) tackled the control from another perspective, enhancing the prediction model of some essential structural parts during the design process. The lumped parameter method and the model reduction theory are used to create the state-space equations, by transforming the electromechanical coupling parameter equation of the servo system to a state-space equation. The findings indicate that the system response efficiency error is 14.8%, the position accuracy and delay characteristics error is less than 10%, and the real size error is within 28 mm of the prediction model's predicted size, with a minimum prediction error of 7 mm. Li et al. (2024) tackled a clustering algorithm-based technique for forecasting the machining stability of CAD NC cavity milling to increase the machining efficiency and stability of rough surfaces. According to the experimental findings, there is no chatter during the entire processing process, the track line's length is decreased by 16.7%, and processing time is decreased by 17%. To increase processing efficiency, Liao et al. (2024) suggested a novel approach using the point cloud data by utilizing the octree and four-point denoising techniques. According to the experimental results, the layer slicing approach reduces the computation time to 35 seconds and has a minimum error on the roughing path generation of about 10%, whereas the residual height method has a finishing path error rate of 10.17% and a computation time of just 11.82 seconds, it exhibits a great degree of accuracy and trajectory smoothness.

3. Methods

3.1 Mechanical Design

This section will discuss our approach to implementing the 3-axis CNC milling machine as shown in Figure 1.

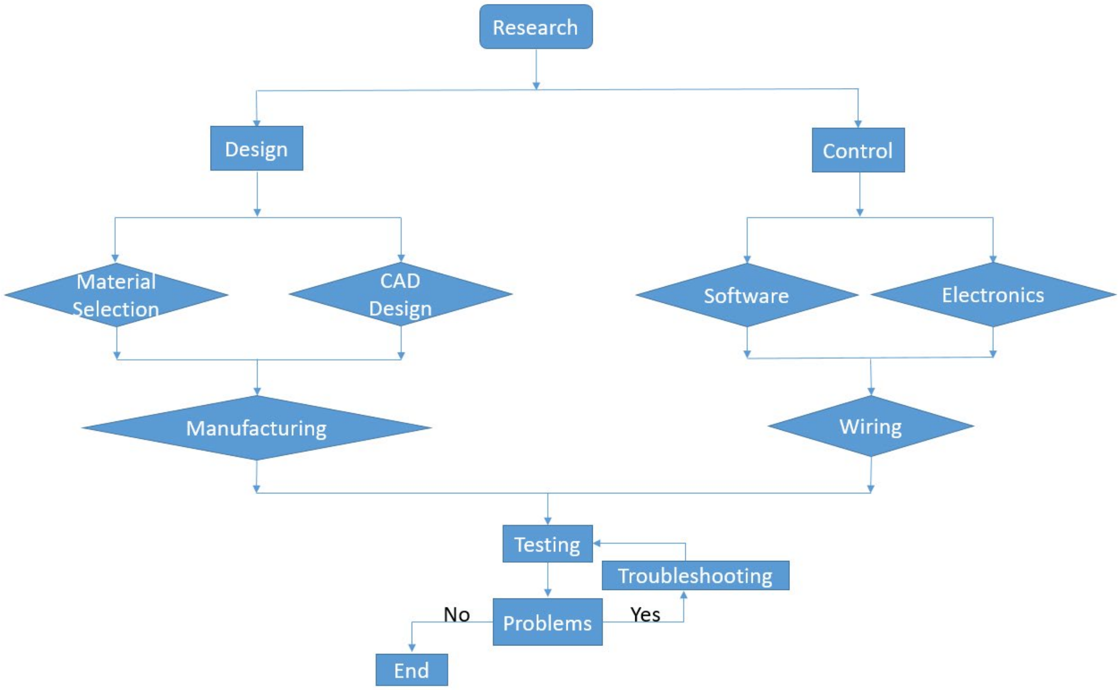

Figure 1. Flow chart

The first step in implementing the CNC machine was the design process using CAD software, specifically SolidWorks. The design process begins with the creation of the base, Y-axis, X-axis, and Z-axis. After that, the control box, which houses the electronics and the cooling system, was designed. The second step is material selection. Galvanized iron was chosen in the construction of the base between the X-axis platform and the Z-axis platform, for its durability and high tensile strength. Aluminum profiles were selected as the second material due to their high durability, strength, and lightweight properties. These profiles were utilized in the platforms of the axes to reduce the bending stress on the lead screw.

The third step was determining the mechanism by which the machine would operate. A lead screw and a nut mechanism was selected. To achieve the targeted accuracy of 0.01mm, the lead screw was designed with four starts, giving the lead a value of four times the pitch. With a pitch of 2mm, the lead was calculated to be 8mm. Stepper motors with a 1.8° step angle were chosen to meet the accuracy requirement, as calculated using the equation $P \times (1.8/360) = 2 \times (1.8/360) = 0.01$ mm. For the motors, which form the core of the machine, the design incorporated four NEMA 23 stepper motors. Three motors with a holding torque of up to 12.6 kg.cm were included; two of them were fixed on the Y-axis, and one was fixed on the X-axis, as these axes move linearly. Another stepper motor with 18.9 kg.cm holding torque was mounted on the Z-axis to counteract gravity, the weight of the spindle, and the Z-axis platform, which has a mass of 9kg.First, the base was designed from two 3mm sheet metals. The first sheet metal, measuring 1100 × 1000 mm, was cut from the corners and deflected to achieve a base thickness of 150 mm. The second sheet metal, measuring 800 × 700 mm, was used as the cover for the base.

Then, two holes were drilled in each corner to create height adjusters. Next, four 600 mm L-shaped construction rods were slotted at the ends for the height adjusters. The four rods were then fixed to the base using eight M8 screws and nuts. To increase the weight of the machine without resorting to expensive cast iron, the base was filled with concrete, a material used in building construction that consists of water, sand, small rocks and cement. In addition to that, four L-shaped rods, two measuring 800 mm and two measuring 700 mm, were added. After the parallelism of the machine's construction was calibrated using the eight tolerance slots, the construction structure was sprayed with zinc spray to prevent the iron from rusting.

The machine bed, made from six 2060 aluminum profiles cut into 500 mm lengths and bonded together with solid silicone, was fixed. The solid silicon was designed to prevent water or oil from passing through. Next, the Y-axis was assembled by fixing two Nema 23 stepper motors mounting brackets onto the top of the construction structure, one on the right and one on the left of the longer side. After that, two bearing holders were manufactured using two 50 × 50 × 5 mm sheet metals, bent perpendicular to each other. Two ball bearings, with an 8 mm inner diameter and a 22 mm outer diameter, were fixed to the bearing holders using steel epoxy. The steel epoxy was used to join the Y-axis platform. After that, the X-axis mechanism was designed. The process began by fixing the standoff Nema 23 stepper motor mounting plate to the top holes of the Y-axis platform's aluminum profile using two thread-form screws. Next, two 1000 mm linear bearing rails were mounted on top of the Y-axis platform. Two 400 mm 2060 aluminum profiles were then cut and joined together by fixing two linear bearings to the bottom of the aluminum profiles. The linear bearings were slid into the linear rails to complete the assembly.

After that, the Nema 23 stepper motor was mounted onto the standoff. The lead screw was then installed by attaching a coupler to the Nema 23 stepper motor and connecting the lead screw to the coupler. Finally, a lead screw nut holder was mounted on top of the X-axis platform, and the lead screw was screwed into the nut. The final step in the design process was the design of the Z-axis. Two 500 mm 2060 aluminum profiles were cut and joined by mounting the Nema 23 stepper motors to the holes of the aluminum profiles using two thread-form screws. The Nema 23 stepper motor was then mounted onto the standoff with four M4 screws. Two linear rails were mounted on top of the aluminum profiles using M5 screws. Following this, two linear bearings were attached to the nut holder using M6 screws, and the nut holder was slid onto the linear rails while simultaneously screwing the lead screw into the nut. The nut holder was specifically designed to serve as the connection between the X-axis and Z-axis. It was constructed as a single piece from a 5mm galvanized iron sheet as shown in Figure. 2.

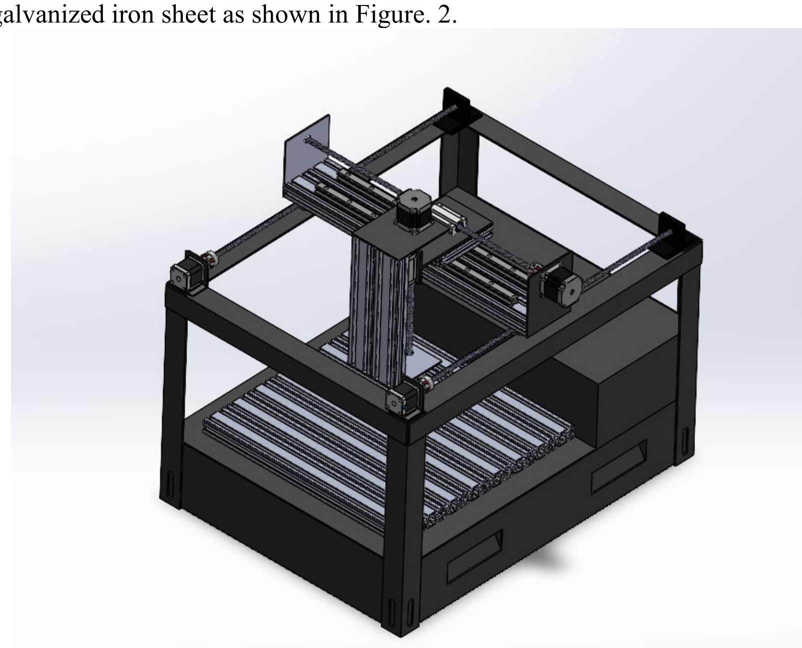

Figure 2. Full Design of CNC Milling Machine

3.2 Electric Design

The electronic components used in this project were as follows: an Arduino UNO, microcontroller, serving as the brain that controls the motors, sensors, and software. Four TB6600 stepper motor drivers were utilized to control the steps and resolution of the stepper motors. The resolution was set to 3200 pulses/rev for the X and Y axes, while the Z-axis resolution was 6400 pulses/rev. Two cooling fans, 24-volt brushless models, were employed for cooling. Three limit switches were used to define the machine's origin. Finally, a power supply was included to convert 220V AC from the wall outlet into a 24V, 16-ampere power source. The electric circuit was designed to start by connecting the four drivers to the Arduino UNO. Regarding the X-axis, two PINs from each driver; PUL+ and DIR+, were connected to the Arduino's digital PINs 2 and 5. Regarding the Y and Z axes, the first two drivers were connected to PINs 3, 6 and PINs 4, 7, respectively. Then the next step was to connect the drivers to the stepper motors. Next, the +ve and GND of the driver will be connected to the +ve and -ve terminals of the power supply. At the end, the Normally Open (NO) PIN was connected to the 5V PIN of the Arduino, the Normally Closed (NC) PIN was connected to the ground of the Arduino. While, the Common (COM) PIN for the X, Y and Z-axes were connected to the Arduino PINs 9, 10, and 12, respectively. Finally, the two cooling fans were connected in parallel directly to the power supply as shown in Figure. 3.

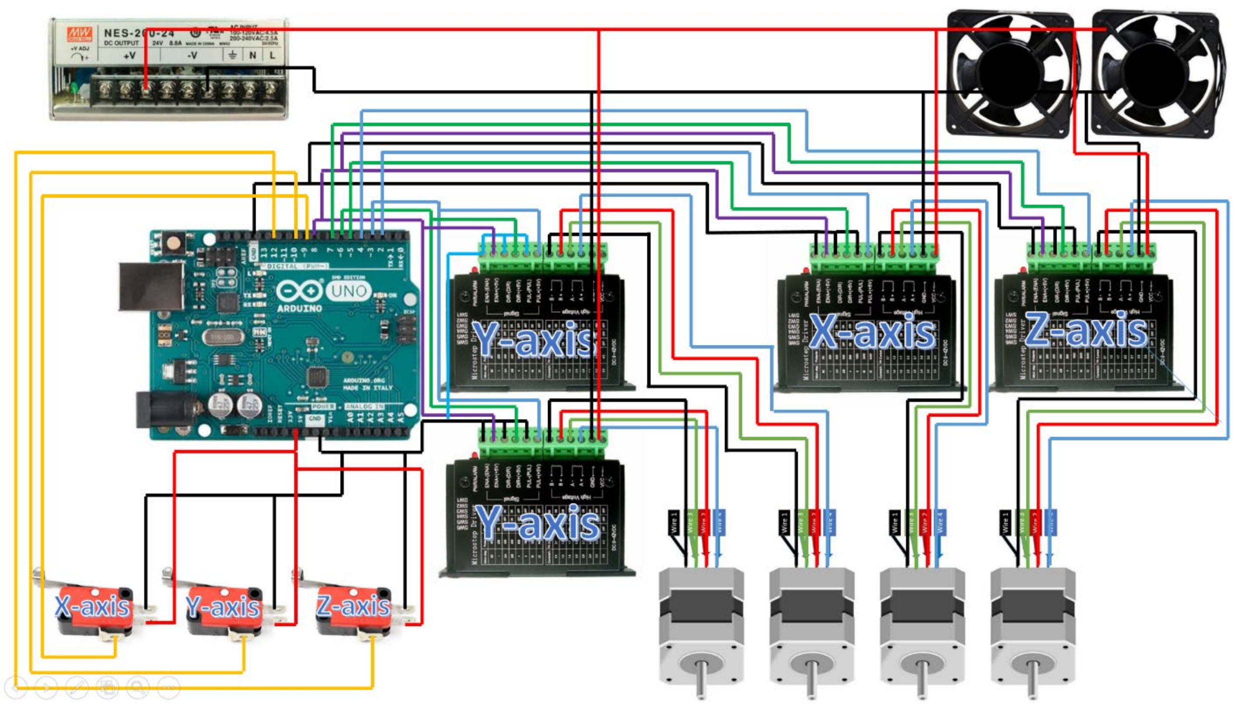

Figure 3. Electric Circuit Design

3.3 Software Controller

The used controller was GRBL, which is an open-source CNC machine controller. That was accessed using the UGS platform which is a G-code reader. The first step to use it is to connect with the GRBL on the Arduino using the connect button. Next, check that the stepper motors are moving in the desired direction instead of reversing it in the wiring. Then, check that the limit switches are connected correctly by manually pressing them and checking the color in the UGS. After which, the G-code is uploaded and appears on the screen with the visualizer of the UGS.

4. Results and Discussion

4.1 Mechanical Structure Manufacturing

The base of the machine consisted of an 1100 ×1000 × 3 mm sheet metal cut by a laser cutting machine. The faces of the machine in addition to the L-shaped rods were cut into rectangles by a sawing machine in order to hold the CNC machine. The spaces were sealed by making right-angled triangles from the inside and welded using arc welding method. Holes were drilled using twist drill tool. After that, a small rectangle was slotted from the end of each face of the L-shaped rods to make a height adjuster with a sawing machine. Then, at each hole, a welded nut had been put by arc welding. Then, the four construction rods were screwed by two M8 screws at each corner to fix them. The base of the machine was stabilized, using concrete. Also, the base was sprayed with a zinc spray to prevent the iron from rusting.

Regarding the building of the Y-axis, two stepper motor mounting brackets were mounted on the horizontal L-shaped construction rods. The mounting brackets were welded by arc welding to the horizontal construction L-shaped rods.

The two stepper motors were fixed to the mounting brackets by four M4 screws. A bearing holder for the bearings of the lead screw was manufactured for assembling the Y-axis. The bearing holder consisted of two 80 × 80 × 5mm sheet metal that were perpendicular to each other. Then, four square sheets of metal were cut from a big sheet of metal by a sawing machine; two of them were drilled by a cup bit with a hand drill to make a hole of 22mm for the bearings. One of the drilled and the non-drilled square sheets were perpendicularly adjusted and welded together by arc welding. The same process holds for the other two square sheets. At last, they were both sprayed with black spray and stuck to the other end of the construction of the machine with metal Epoxy.

The next step was attaching a coupler to the shaft of the stepper motor by a M3 screw. Then, two 800 mm lead screws were passed through the bearings in order to screw the lead screw nut in them. Two lead screw nut housings were screwed to two 1000 mm 2060 aluminum profiles stuck together by four M4 screws each. After that, a set of two wheels was stuck under the near-bearing holder nut housing to minimize the torque that would happen from the Z-axis. Regarding the building of the X-axis, a stepper motor mounting plate was cut to half its thickness by a sawing machine. Then, it was held by the vise from its end and was bent with a hammer to make 90 degrees. After which, it was screwed to the top of the aluminum profile which is the Y-axis platform by two M4 screws. The stepper motor was fixed to the mounting plate by four M4 screws, and the coupler was fixed to the stepper motor shaft by a M3 screw. Two 200 × 150 × 5 mm sheet metals were cut by a sawing machine. The two sheet metals were adjusted perpendicularly to each other by the short side of the sheet which will be for the X-axis to the long face of the sheet which will be for the Z-axis. Then, an L-shaped rod was spot-welded by an arc welding machine to the face of the Z-axis sheet. The X-axis sheet was adjusted to the same L-shaped rod and spot-welded to ensure the perpendicularity of both sheets. Two linear rails were fixed to the Aluminum profile by M5 screws.

At last, a bearing holder was manufactured from a 100 mm aluminum profile and drilled by a 22 mm drill cup with a hand drill. Then, this bearing holder was fixed at the other end of the Y-axis platform aluminum profile. Regarding the building of the Z-axis, a 1000 mm 2060 aluminum profile was cut into half by a sawing machine. Then, a stepper motor mounting plate was fixed by two thread-form screws at the top holes of the aluminum profile. After that, the stepper motor was fixed to the mounting plate by four M4 screws. After which, a coupler was fixed to the shaft of the stepper motor by a M3 screw. Next, two linear rails were fixed to the aluminum profile by M5 screws. The Z-axis platform was fed in the linear bearings that were fixed onto the manufactured link between the X and Z axes. A lead screw was screwed into the nut that was fixed on the manufactured link, and the lead screw was fixed to the coupler with an M3 screw. Finally, it was sprayed in black and the aluminum profile was drilled and the holder was fixed to the aluminum profile by two M6 screws and nuts. The full assembly of CNC milling machine is shown below in Figure 4.

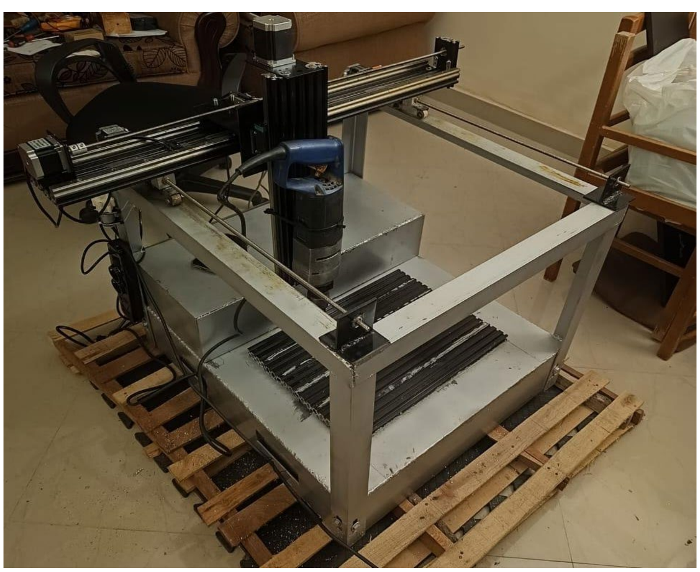

Figure 4. Full Assembly of CNC Milling Machine

4.2 Electric Wiring

The control box was build; four sheet metals were cut using a laser cutting machine. Then, they were welded together using arc welding technique. All the electric components; the Arduino UNO, the four TB6600 stepper motor drivers, the power supply, and the three wire connectors were all screwed by thread-shaped screws to a wooden plate. A laser-cut 3mm MDF wooden sheet was placed at the front of the control box that has a place for the cooling fans and on/off buttons. The next step was to manufacture fix the limit switches, for the Y-axis a part was for the limit switch to be mounted on it. This part consisted of a 100 × 100 × 3mm sheet metal that was cut with a sawing machine. Then, this sheet metal was drilled into two holes by a hand drill with a 4mm drill bit for the limit switch. After that, another two holes were drilled by a hand drill with a 4mm drill bit to be fixed to the Y-axis motor. At last, the sheet metal was cut to its half thickness at the end to be bent on the vise, and then the part was mounted to the mounting bracket and to the stepper motor by 2 M4 screws, and the limit switch was fixed to the manufactured part by two M4 screws and nuts. For the X-axis limit switch, two holes were drilled by a hand drill with a 3mm drill bit in the Y-axis platform. Then, the X-axis limit switch was fixed to be triggered by the linear bearing. At last, for the Z-axis limit switch, two holes were drilled by a hand drill with a 3mm drill bit. Then, the Z-axis limit switch was fixed to be triggered by the linear bearing. Regarding the stepper motors, the wires were too short; they were extended by CAT6 cables, Then, all the limit switches were connected to CAT6 cables, and each was wrapped with spiral wrap. Then, the power supply was connected to the wire connector, and all the electric components were connected. The electric Components Wiring is shown below in Figure 5.

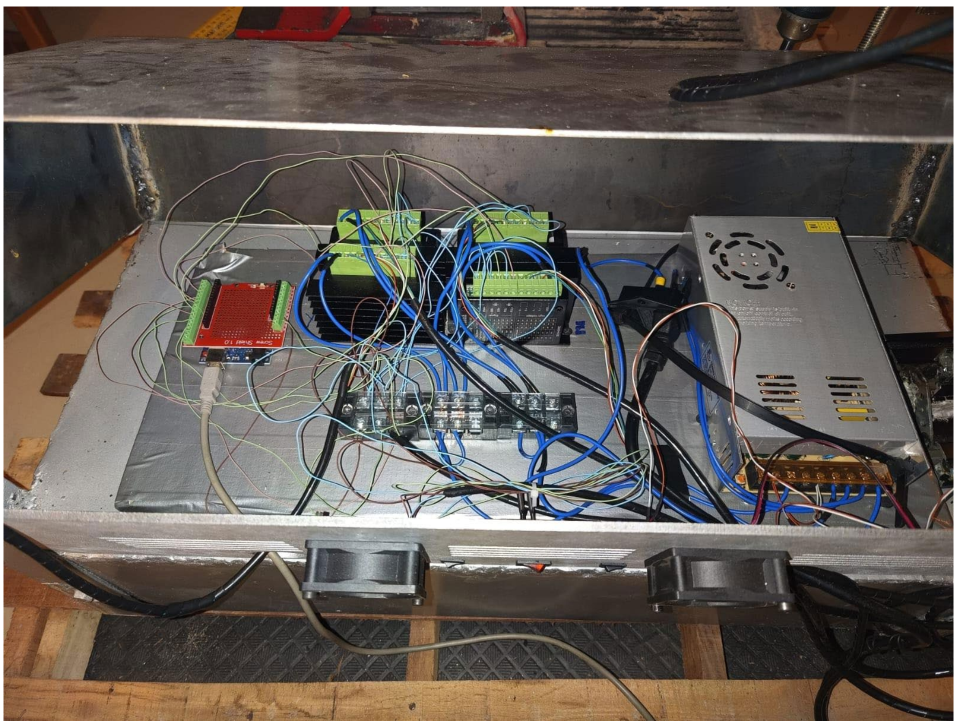

Figure 5. Electric Components Wiring

4.3 Software Controller

A workpiece was designed and manufactured to test the controller and CNC machine capabilities. This part has slots and cutting lines. The G-code was written manually not with CAM software, and the material used was 3mm MDF wood. The calibration of the machine was conducted to adjust the machine zero. After that, the distance from the cutting tool to the workpiece is calibrated. The workpiece machine zero was (50, -50, 0).

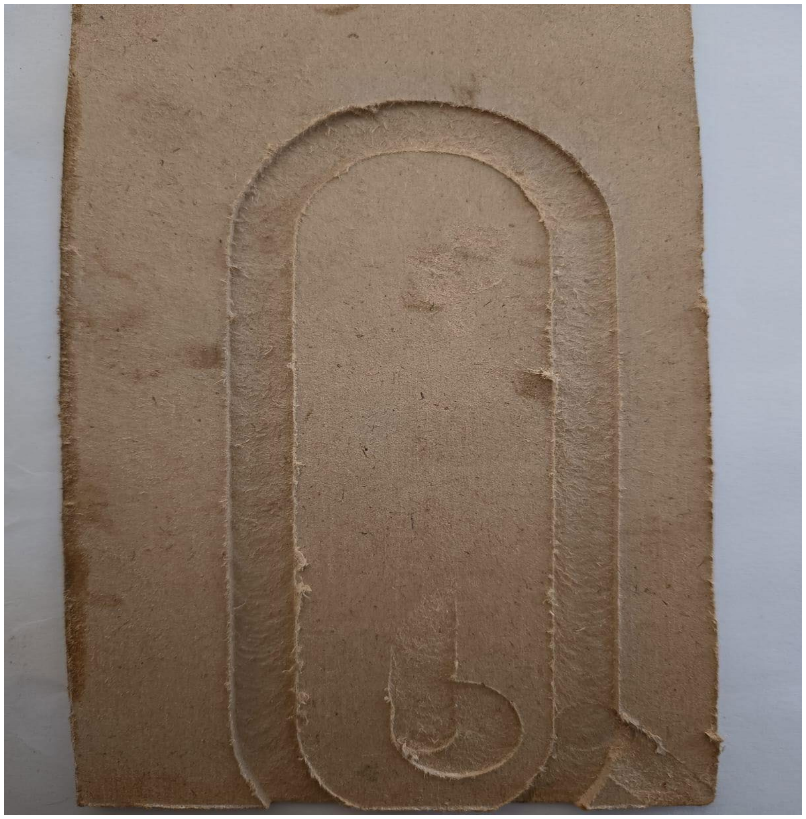

Figure 6. Final G-Code Product

4.5 Proposed Improvements

The machine base structure needs to be 100 mm lower to work on hard materials like iron. Also, the X-axis and Z-axis platforms can be machined from iron instead of aluminum profile to increase the rigidity of the machine. Finally, servo motors can be used instead of stepper motors for sending feedback.

5. Conclusion

In conclusion, it was found that high stability was obtained using concrete instead of cast iron. Also, the machine manufactured a workpiece using a G-code; the accuracy was 0.01 mm.

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Biographies

Abdelrahman A. Elsayed is a highly motivated senior robotics ad automation student at the German International University. He finished his bachelor thesis which is talking about the design and control of CNC milling machine, which included using GRBL CNC controller, design using solid works, and manufacturing a full CNC milling machine prototype by himself. Worked on deferent projects like building a 6-DOF Industrial robot arm, a RC car that can move in multiple direction including crab walk, and made a water pumping system prototype for solving the lake of water in some places. As an enthusiastic engineer I like to know how things work and try to replicate it, and to build projects as I like the research and developing.

R. Shenouda is an assistant professor in the field of robotics and automation, renewable energy and manufacturing at the department of engineering at the German International university (GIU), Egypt. He started as a teaching assistant in 2014. He received his M.Sc. degree in 2017 from the GUC. During his masters, he worked on cooling of solar panels. He is currently working on developing new techniques to mitigate dust on solar panels and his interests are renewable energy especially solar energy.

Seif Salah is currently pursuing his M.Sc. degree in Design and Manufacturing Engineering at the German University in Cairo (GUC), Egypt, also I have been a teaching assistant at a German international university since May 2022. In this role, also involved in teaching and supervising students through their academic journey in engineering. Seif's research interests target to optimize cross-sectional shape of extruded aluminum profile from semi-hollow die. The scope of his research is to integrate design and manufacturing in addition to achieving both quality and productivity.1