Konya Mühendislik Bilimleri Dergisi, c. 11, s. 4, 986-1005, 2023
Konya Journal of Engineering Sciences, v. 11, n. 4, 986-1005, 2023
ISSN: 2667-8055 (Electronic)
DOI: 10.36306/konjes.1272454

MINIMIZING ERRORS IN PCB MILLING PROCESSES THROUGH A 3-AXIS PCB ROUTER

[1,*]Emrehan YAVSAN, [2]Burak SELVI, [3]Tarik UNLER, [4]Ilhan ILHAN

[1] Tekirdağ Namık Kemal University, Electronics and Automation Department, Tekirdag, TÜRKİYE
[2,4] Necmettin Erbakan University, Engineering Faculty, Mechatronics Department, Konya, TÜRKİYE
[3] Necmettin Erbakan University, Aeronautics and Astronautics Faculty, Avionics Department, Konya, TÜRKİYE
[1]eyavsan@nku.edu.tr, [2]buraksselvi@gmail.com, [3]tunler@erbakan.edu.tr, [4]ilhan@erbakan.edu.tr

Highlights

- Homogeneous milling achieved with multi-point referencing
- Precise and stable PCB milling with Z-axis homogeneity
- Low dimensions and metal body to reduce vibrations
- Mechanical CNC method for prototyping without environmental harm

***Corresponding Author:** Emrehan YAVSAN, eyavsan@nku.edu.tr

Konya Mühendislik Bilimleri Dergisi, c. 11, s. 4, 986-1005, 2023
Konya Journal of Engineering Sciences, v. 11, n. 4, 986-1005, 2023
ISSN: 2667-8055 (Electronic)
DOI: 10.36306/konjes.1272454

MINIMIZING ERRORS IN PCB MILLING PROCESSES THROUGH A 3-AXIS PCB ROUTER

[1,*]Emrehan YAVSAN, [2]Burak SELVI, [3]Tarik UNLER, [4]Ilhan ILHAN

[1] *Tekirdağ Namık Kemal University, Electronics and Automation Department, Tekirdag, TÜRKİYE*
[2,4] *Necmettin Erbakan University, Engineering Faculty, Mechatronics Department, Konya, TÜRKİYE*
[3] *Necmettin Erbakan University, Aeronautics and Astronautics Faculty, Avionics Department, Konya, TÜRKİYE*
[1]eyavsan@nku.edu.tr, [2]buraksselvi@gmail.com, [3]tunler@erbakan.edu.tr, [4]ilhan@erbakan.edu.tr

(Received: 04.04.2023; Accepted in Revised Form: 15.08.2023)

ABSTRACT: Printed circuit boards (PCBs) can be produced by chemical or mechanical methods. Continuous copper paths are difficult to print in the chemical method and breaks may occur in copper paths. In addition, this method is harmful to human health and the environment, as various chemicals are used. In the mechanical method, PCB is processed with computer-controlled numerical workbenches (CNC). Although prototyping can be done quickly and without harming the environment with these benches, the desired results may not be obtained. Reasons for unsuccessful machining in CNC machines; manufacturing and assembly errors in the production of benches, the use of low quality mechanical and electronic components, and the reference of a single point especially for the Z-axis of the part connected to the benches. In this paper, a precise and stable PCB Router is presented to make fast, cost-effective and successful PCB machining. In order to minimize the vibration and oscillations of the PCB Router caused by manufacturing and assembly errors, the dimensions of the router were kept low and metal material was preferred for the router body. Precision is ensured by quality motor drivers and stepper motors. The PCB Router is controlled by an original control board. This card is equipped with a multi-point referencing feature for the Z-axis. Thus, homogeneous machining in the Z-axis for the entire surface of the PCB can be realized by performing referencing operations on the PCB connected to the workbench as many points as the user enters. With the developed router, PCBs with rectangular and circular patterns were engraved at cutting depths of 0.030 mm and 0.050 mm with 0.20 mm and 0.30 mm diameter milling tools with a 30-degree tip angle, respectively. Moreover, a 16-terminal integrated circuit element was successfully engraved at a cutting depth of 0.040 mm with a 0.34 mm diameter V-tip with a 30-degree tip angle. Homogeneous milling was achieved utilizing the proposed multi-point referencing feature. Each milling operation was completed in approximately 30 min - 45 min.

Keywords: *Printed circuit board, Computer-aided design, Computer-aided manufacturing, CNC, 3-Axis Milling*

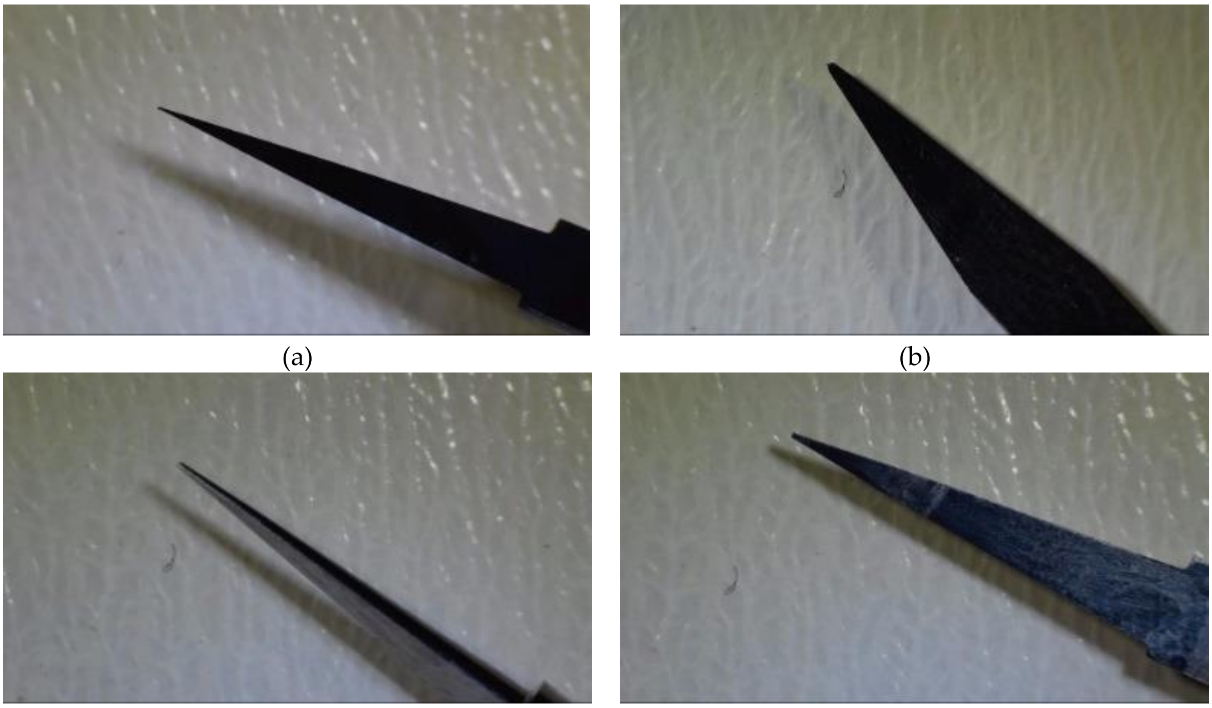
1. INTRODUCTION

There are various methods for the production of printed circuit boards (PCB) [1]. These methods can be grouped under two headings. The first method; It is based on etching the copper with various chemicals, and the second method is based on engraving the copper with Computer Aided Numerical Control (CNC) benches [2]. It is difficult to print continuous copper paths with the first method [3]. Besides, as the various chemicals are used, they have negative effects on human health and the environment. In the second method, production is made with PCB CNC Router devices without harming nature and humans [4], [5]. Rapid prototyping can be done with these benches, also called PCB Routers. PCB Router machines work on a 3-axis (XYZ) [6], [7]. In these benches, besides the drive motors that provide movement in 3 axes, there is 1 Spindle motor that enables the engraving of copper from the PCB plate and 1 cutting tip/milling tool connected to this motor. Each motor is driven by a motor driver and these drivers are controlled by a control card [8].

Madekar, K. J. et al. [9] produced a mini CNC machine with a developer board with an ATMEGA 328 controller. In this way, they tried to reduce the cost. However, the output of a processed PCB sheet was not included in their work. In addition, their workbenches are not suitable for PCB processing, as

***Corresponding Author:** Emrehan YAVSAN, eyavsan@nku.edu.tr

they use wooden materials on the chassis or the body of their workbenches like Yildirim et al. [10]. Shilpa et al. [11] also introduced a 3-axis CNC PCB machine with low cost motivation. Although they presented a more rigid body than Madekar, K. J. et al., a processed PCB image was not included in their work. Mahesh Raut et al. [12] presented a prototype-level desktop PCB machining bench. The machine they offer has rudimentary mechanics and is therefore inadequate for machining PCBs. Apart from these studies, Vegard Størkersen [13] carried out a hybrid study by combining mechanical and chemical methods. In his work, he etches/corrodes the PCB with a chemical, not mechanically removing. In none of the studies presented within the scope of the literature review, dynamic zeroing in the Z axis or multi-reference process was not mentioned. However, this feature is very critical for machining PCBs by mechanical method. Otherwise, the cutting tip breaks in Figure 1 and, accordingly, the unsuccessful machining in Figure 5 are obtained.



(a) (b)

(c) (d)

Figure 1. The cutting tips used for machining PCBs on a CNC machine without multi-point referencing. (a) V-tip before the milling, (b), (c) and (d) images of the broken V-tips after the milling under the microscope from various angles

Although solutions such as laser processing in Figure 2, using a vacuum table in Figure 3 and increasing the quality of the table surface to which the PCB will be attached in Figure 4 were tried to prevent tip breakage in Figure 1 and unsuccessful PCB processing, positive results could not be obtained.

(a) (b)

Figure 2. Commercial CNC machines used for laser processing of PCBs

The workbench in Figure 2a is a costly solution and has burnt on the PCB. It is difficult to configure the characteristics of the laser for different PCB machining. On the workbench in Figure 2b, there are serious reflections from the PCB surface. This not only hinders the processing of the PCB, but also damages the laser machine.

Figure 3. Vacuumed table production

In Figure 3, a vacuum table is machined to prevent swelling of the PCB when the PCB is attached to the table and to connect the PCB plate to the bench more easily. Although the vacuum table pulled the PCB homogeneously, problems were encountered due to the heterogeneous distribution in the Z axis. On top of that, the surface quality improvement solution in Figure 4 was tried, but this solution did not yield any results. Again, there are height differences in the Z axis. These differences pose a problem in removing the thin copper layer (1 oz) from the PCB surface.

Figure 5 shows PCB circuits designed in various geometries. Figure 1a and Figure 1b show the geometries that are tried to be printed by chemical means, and the Figure 5c, Figure 5d and the Figure 5e show the geometries processed on an industrial 3-axis CNC Router [16]. As can be seen from the image, there are breaks in the copper roads in these Figures.

Copper thicknesses on PCB plates can vary between 0.5 – 2 oz (0.035 mm – 0.070 mm) [14], [15]. The homogeneous etching of this copper at every point of the PCB plate is the key to successful engraving.

However, this cannot be achieved in most PCB Routers. In order to achieve homogeneous engraving or successful machining, engravings of the same depth must be made all over the PCB connected to the router table. Otherwise, the cutting tips break, the copper paths of the electronic circuit break or the PCB cannot be engraved to the desired thickness. In addition, most PCB Routers remain idle or at best are used for rough machining such as wood, plastic or metal, out of purpose.

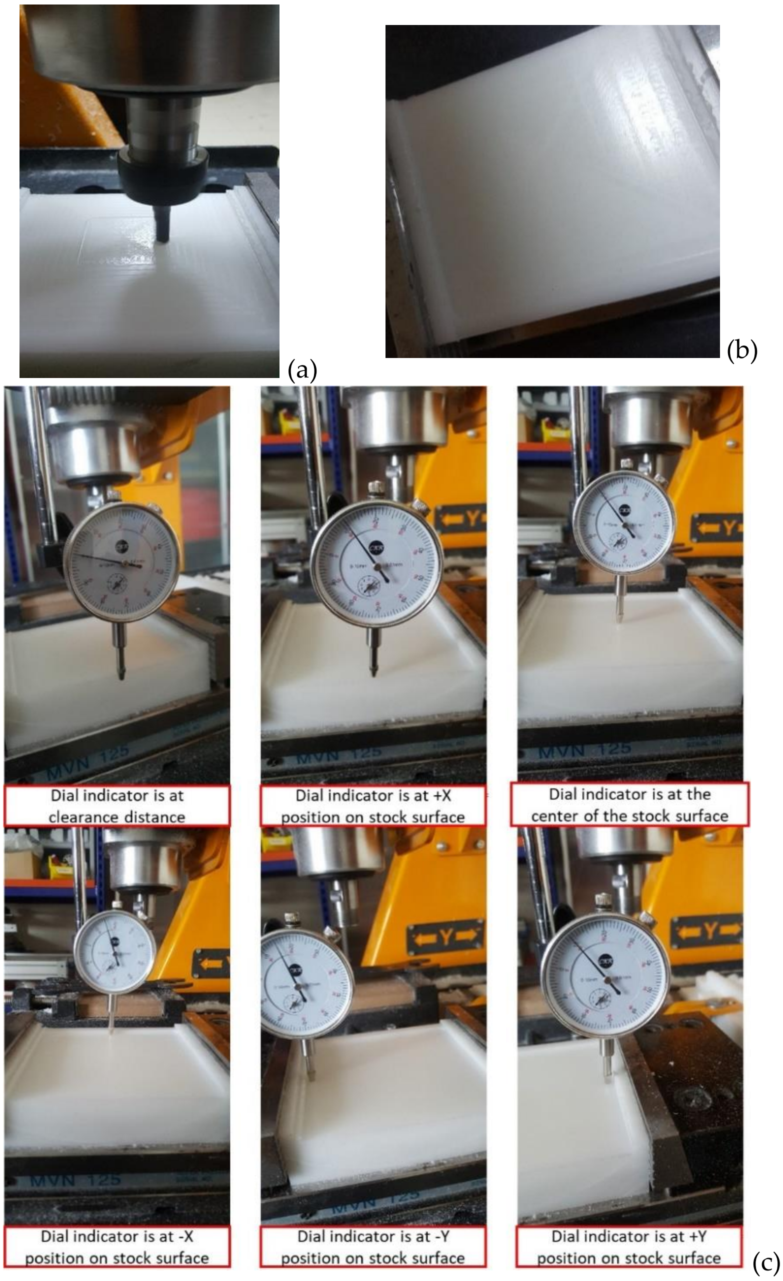


Figure 4. Increasing the surface quality and obtaining a homogeneous height on the surface by machining the surface to which the PCB will be attached with an end mill with low depth and low lateral shifts. (a) Table surface machined with a flat end mill, (b) Table surface obtained after machining, and (c) Checking the table surface after machining with a dial indicator

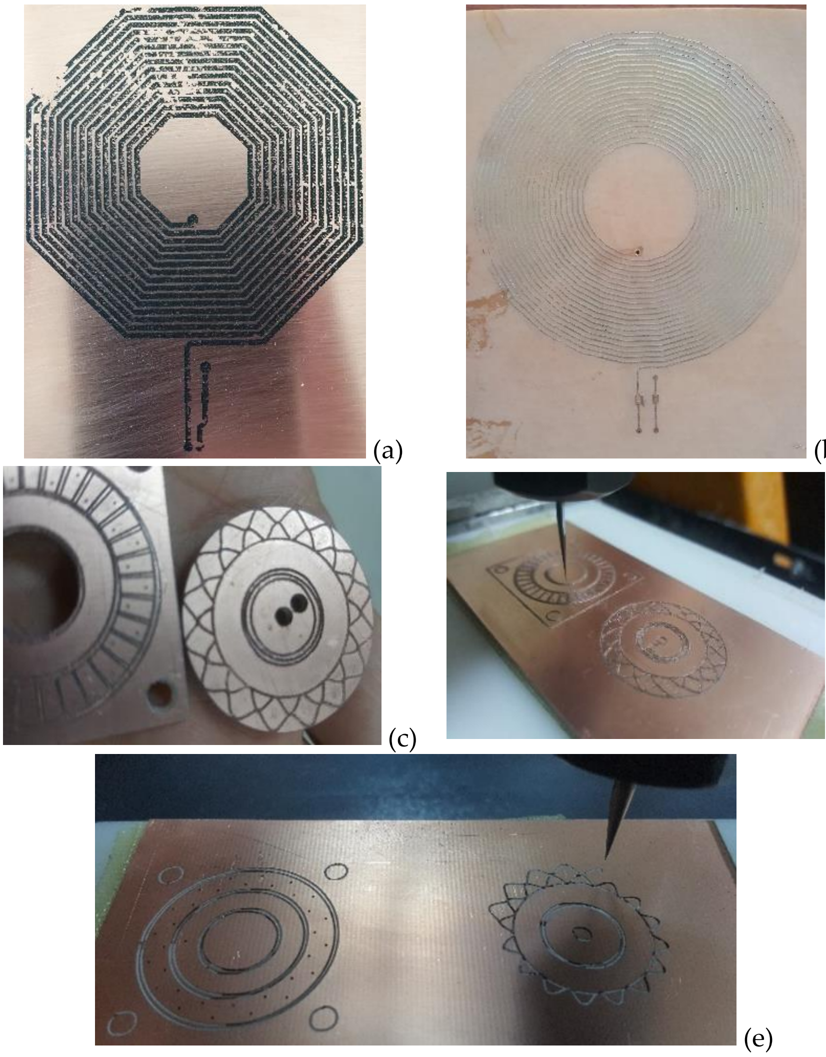


Figure 5. The geometries processed on the PCB surface by chemical and machining methods. (a) and (b) geometries printed by chemical methods, (c), (d) and (e) milling with a single point zeroing/referencing with a 3-axis commercial router

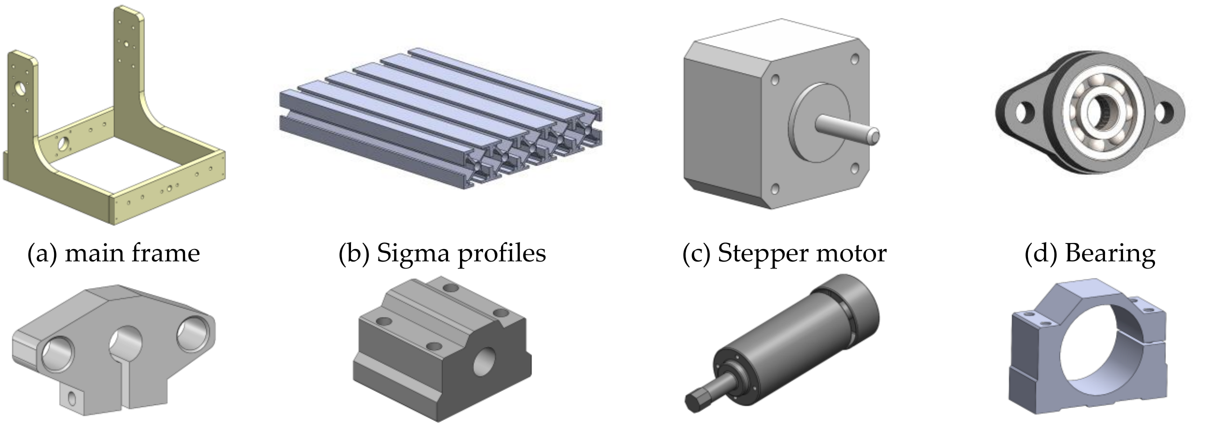
In this research, it is desired to carry out successful PCB processing in order to avoid the unsuccessful engravings in Figure 5. For this, it is aimed to prevent possible imbalances with a small router, to protect the accuracy and sensitivity in these movements with step motors for the axis movements of the router, and to perform successful processing by performing a multi-point zeroing process instead of a single point, unlike most existing PCB Routers.

One of the key points of the study is the multi-point zeroing solution. Because in most routers, the PCB connected to the bench is referencing from a single point. This situation leads to tip breakage due to the insertion of the cutting tip insert too deep at different points of the PCB, as in Figure 5c, Figure 5d and Figure 5e, or Failure processing of copper tracks due to inability to reach the desired depth. In this study, a solution to this problem was sought by zeroing at multiple points before starting the PCB engraving process.

2. MATERIAL AND METHODS

2.1. Design and Modeling

Computer aided design programs were used to model the PCB Router. In Figure 6, the preliminary model designs for the various components of the machine are given respectively.

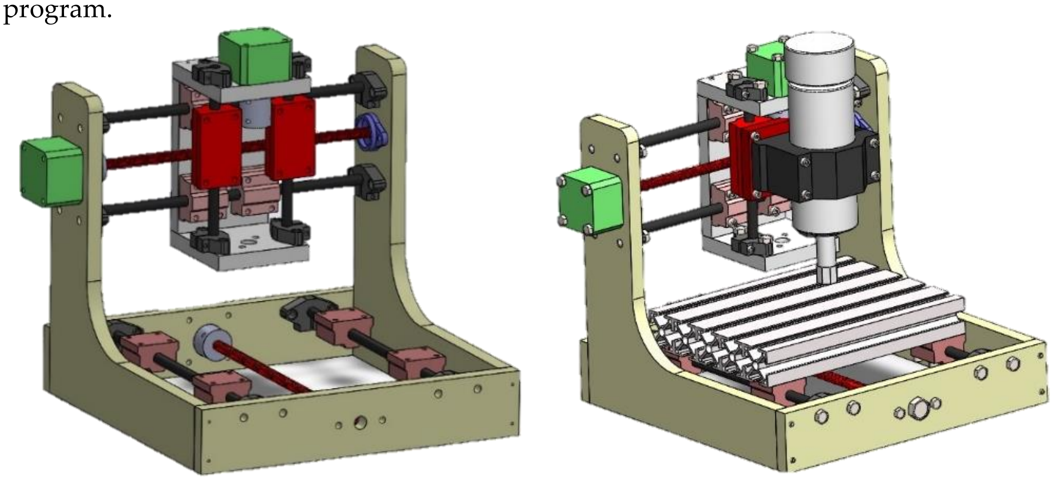


(a) main frame (b) Sigma profiles (c) Stepper motor (d) Bearing

(e) Holder (f) Linear bearing (g) Brushless spin motor (h) Holder for motors

Figure 6. Preliminary models of various PCB Router components made through the computer aided design program

Using the components in Figure 6, the PCB Router was assembled in Figure 7 on the computer aided design program.



(a) (b)

Figure 7. PCB Router preliminary design. (a) Preliminary design including body, shafts, holders, bearings and couplings, (b) Preliminary design to which spindle motor and sigma profile table are added.

The model and assembly drawings presented at this stage constitute the first stage of the study. After this first stage, the following parts were modeled and produced for the chassis of the router using the models in Figure 6 and Figure 7.

The assembly image of the parts was created by using the computer aided design program of the designed body models. At this stage, all the fasteners used in the assembly image were taken from the library of the relevant design program. The compatibility of the designed parts with each other was checked at the first stage, and the parts that did not fit into the assembly were modeled with alternative dimensions and replaced with other parts. The router body assembly, in which a virtual environment is created using the parts in Figure 8, is given in Figure 9.

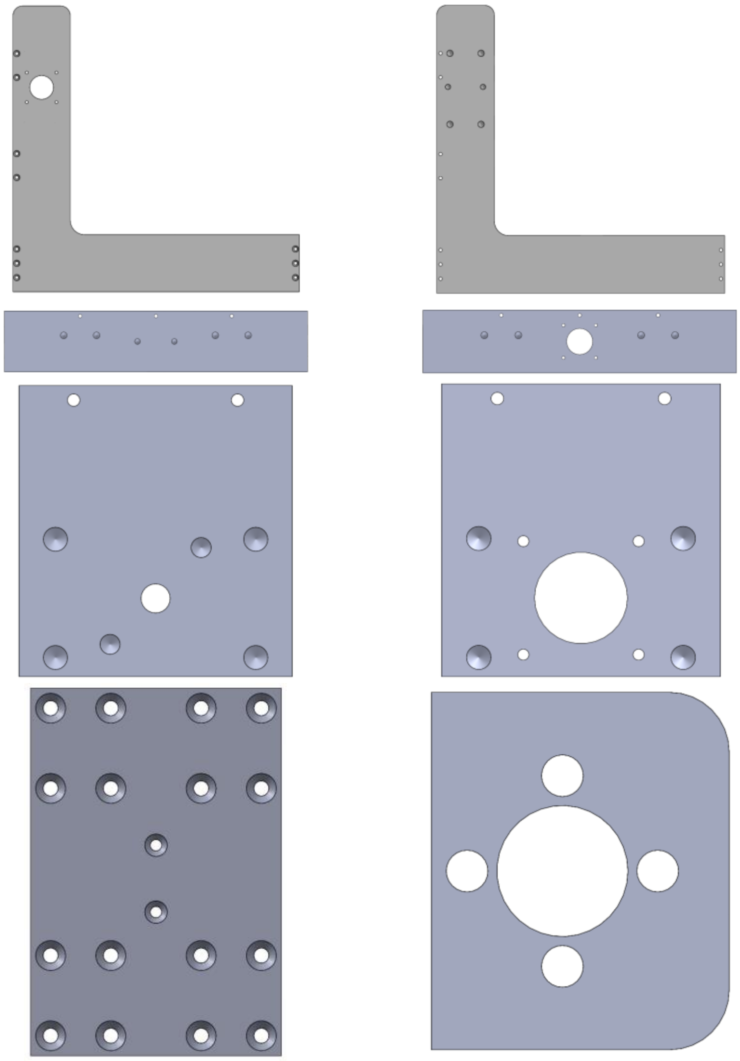


Figure 8. Parts designed for the router frame in the second step

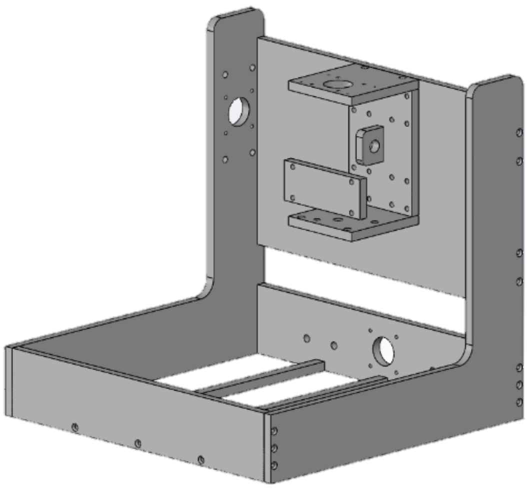


Figure 9. Mounted view of the designed frame parts

2.2. Production and Assembly

After the solid modeling of the body parts was completed, the production of these parts was started with various methods. Since there is too much burr on the edges and corners of the parts while aluminum plate is produced by laser cutting method, it has been decided to use machining methods instead of laser cutting method. After the parts were produced with the machining method, the assembly phase was started. The components of the machine body, whose production has been completed and whose mounting holes have been drilled, are given in Figure 10.

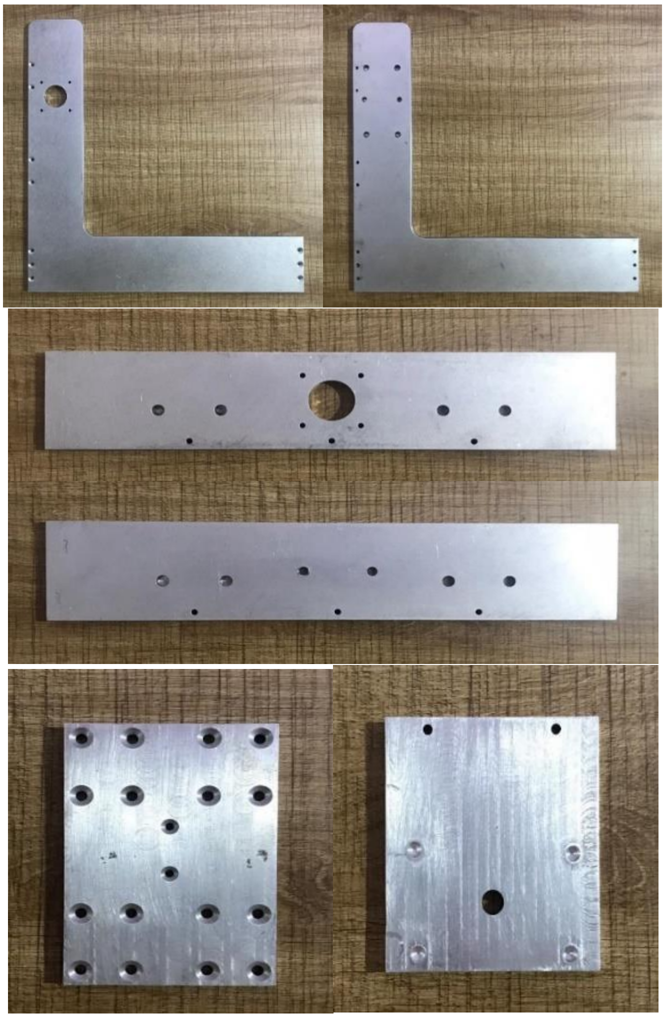


Figure 10. Parts produced for the router body

With the assembly of the mechanical parts of the PCB Router and the axis motors, the assembly steps in Figure 11 were followed, and the assembly of electronic components in the bench mechanics was started after the bench mechanics in Figure 12 were created.

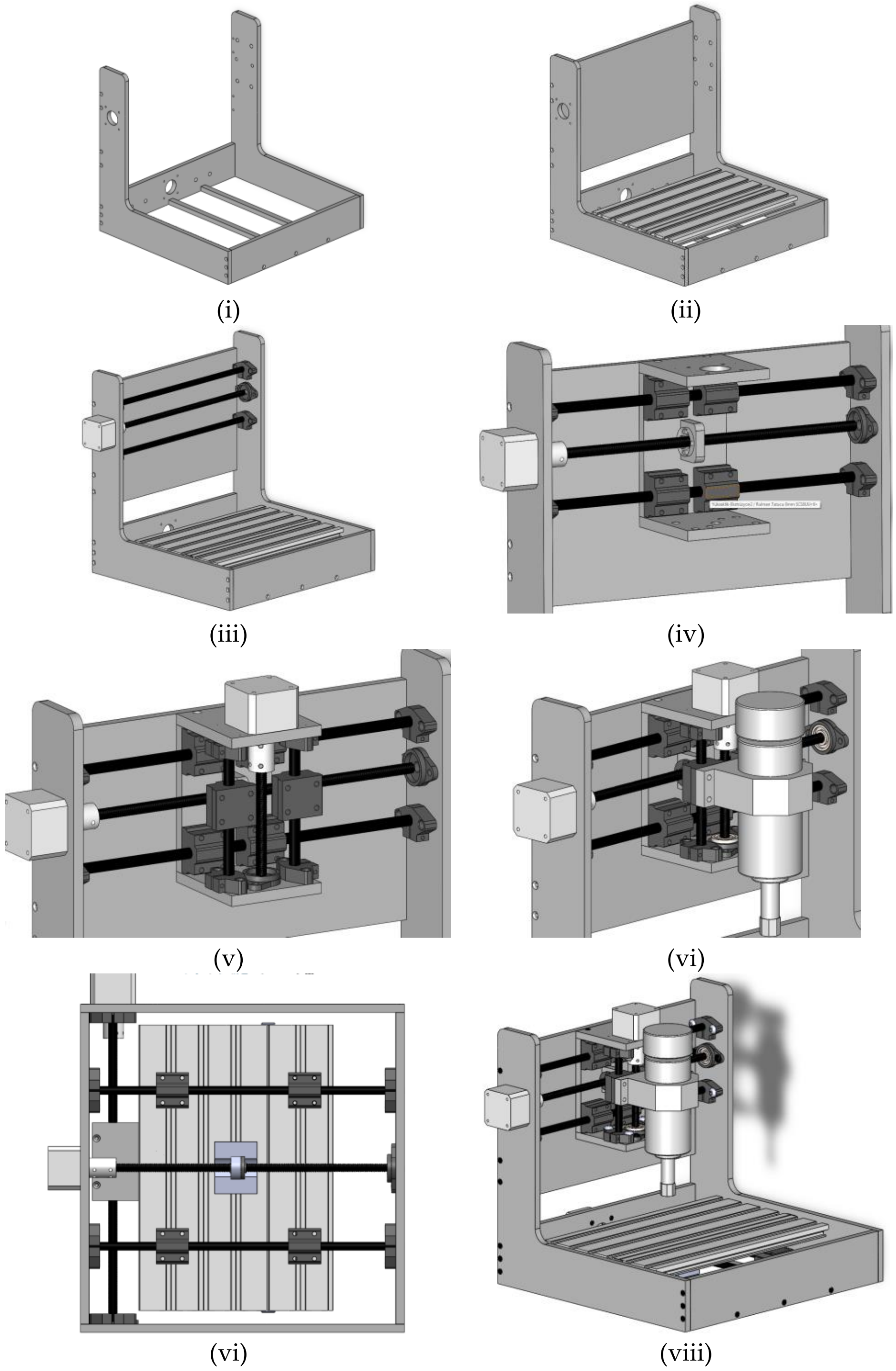


Figure 11. Machine mechanics via assembly steps

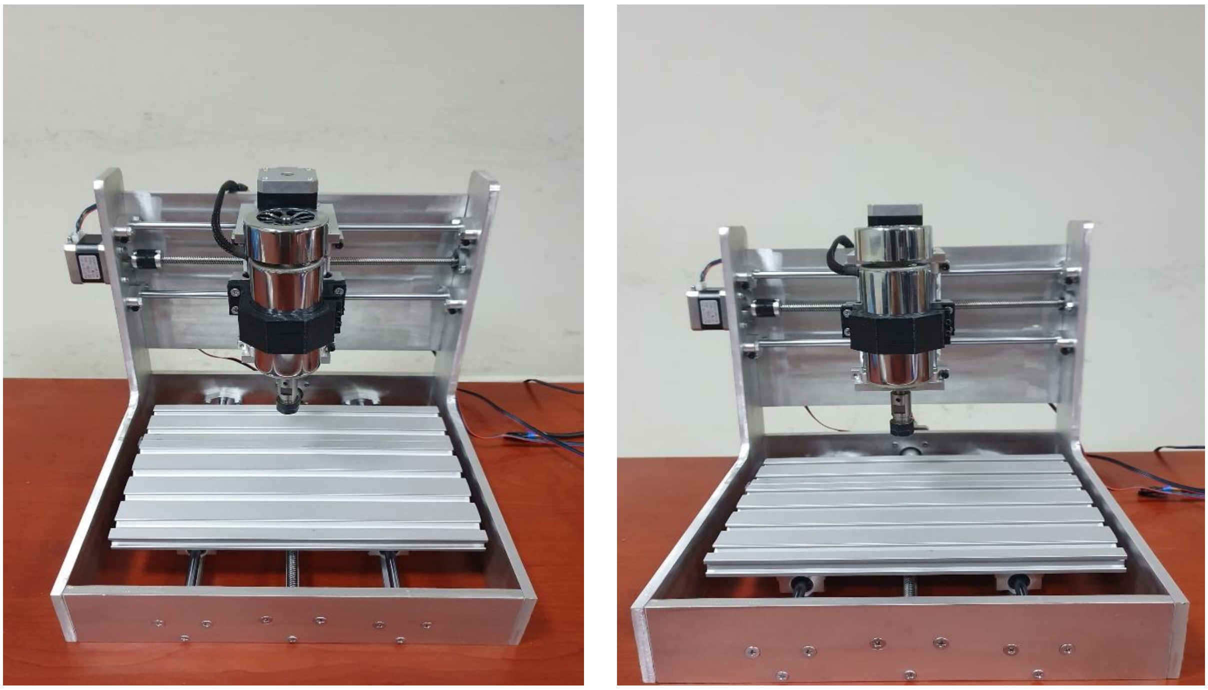


Figure 12. PCB Router after production and assembly stages

The processing area of the PCB machine is given in the technical drawings in Figure 13.

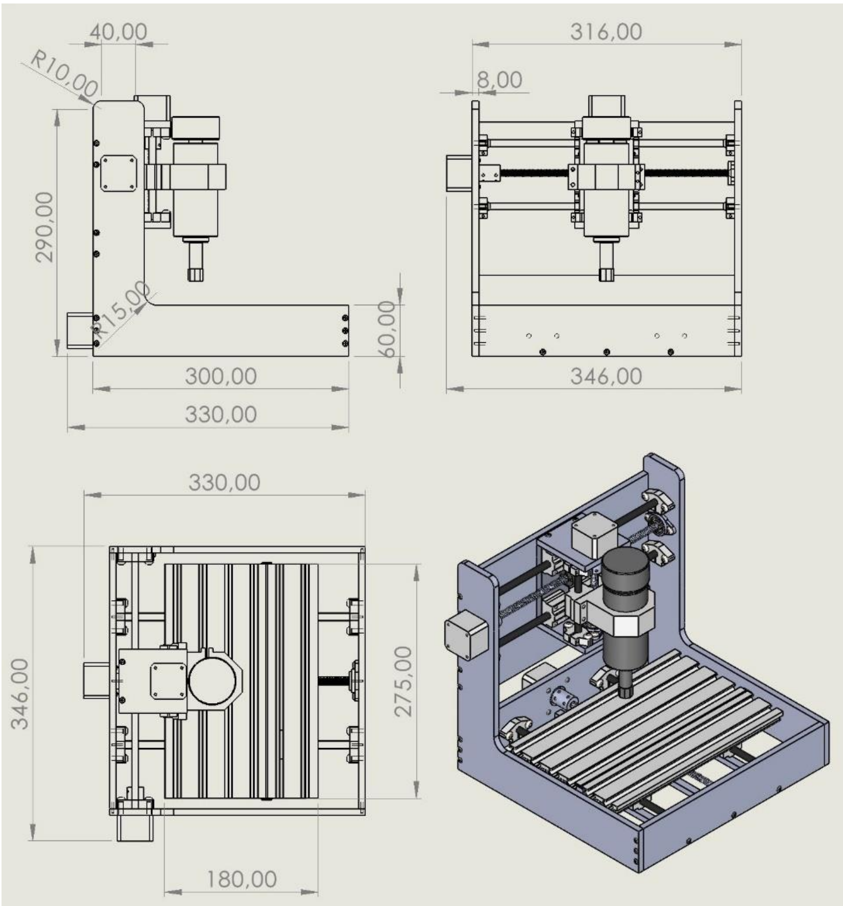


Figure 13. Technical drawings of the PCB machine and its processing area

2.3. Electronic components of the PCB router

Basic components of router electronics; control card and motor drivers. Power supplies are sub-components. Other essential components of machine electronics are motor drives. These drivers, which will work in harmony with the control card, can be practically connected to the control card with various expansion cards. For bench electronics; the application diagram of the control card, motor drivers, power supplies and motors is given in Figure 14.

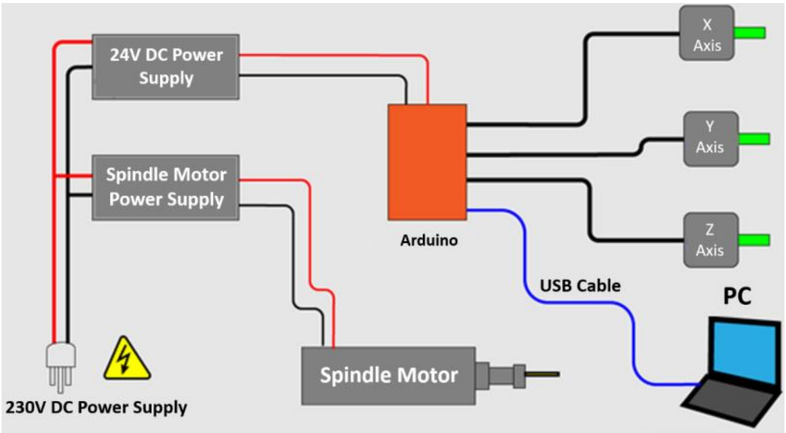


Figure 14. The basic components diagram of the PCB Router electronics

The original development board in Figure 15 was used as the control board [17]. Mach3 control cards are used in most of the 3-axis CNC machines in the market [18]. The reason for using an original control card in this project; is to bring the multiple reset feature to the PCB Router. Because the desired results could not be obtained in the multi-point reference applications we made on Mach3 and other non-original cards.

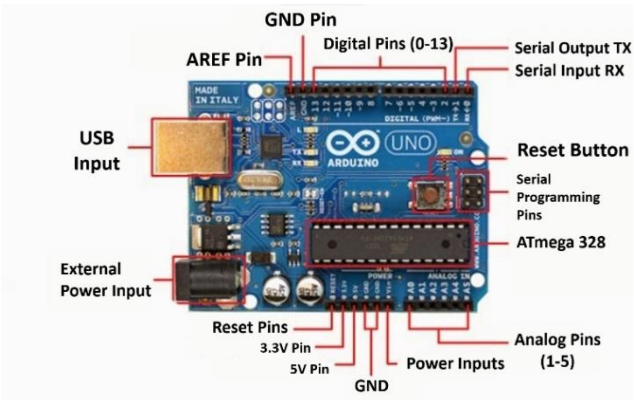
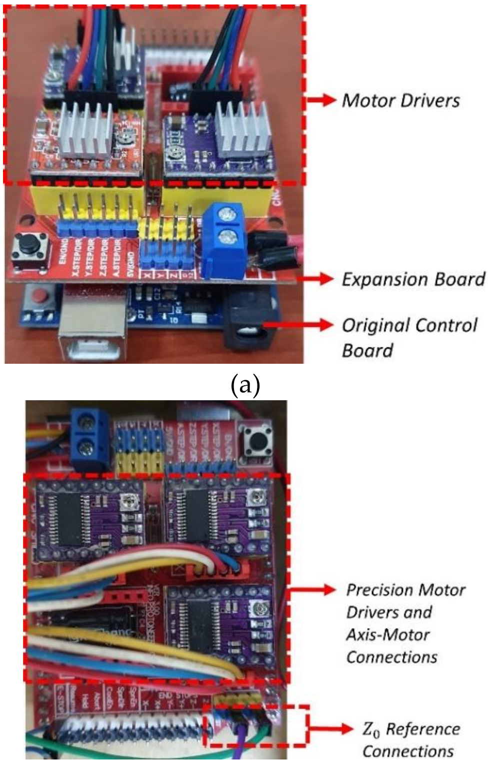


Figure 15. The original control card to be used in the control of axis movements [17]

Figure 16 shows the control unit with integrated axis motor drives. The drivers of the control unit, which are disassembled in Figure 16a, were updated with more sensitive ones and mounted on the control card with the same expansion card, and motor-driver connections were made.



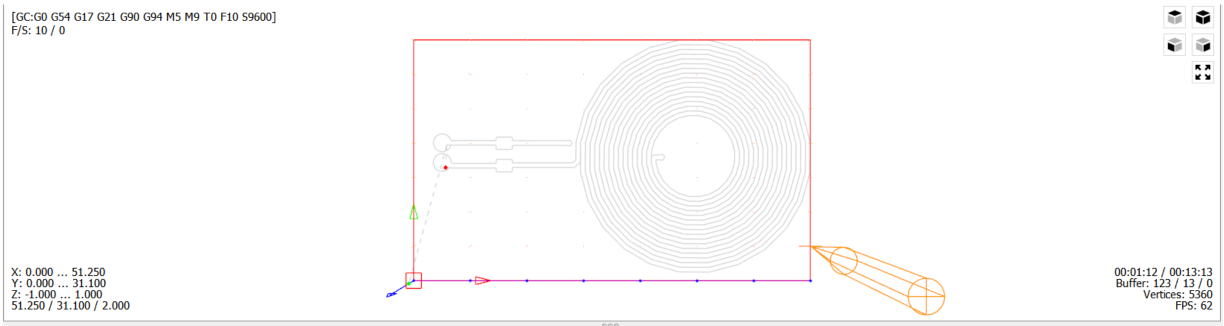
(a)
(b)
Figure 16. Electronic control unit

2.4. Multipoint Referencing

One of the most common problems in PCB milling in routers is that the entire surface of the copper plate on which the engraving will be made cannot be homogeneously. This problem may occur due to various reasons such as the material to be processed is not connected to the workbench in properly, swelling occurs in the connected part, or the material surface is uneven. In the present study, the multi-point referencing or zeroing feature has been added to the router workbench, which was developed to overcome this problem. With the multi-point referencing feature, before starting the engraving process, the distance between the engraving tip and the copper plate is measured, and reference values are taken from the points desired by the user. A height mapping is made on the basis of these references.

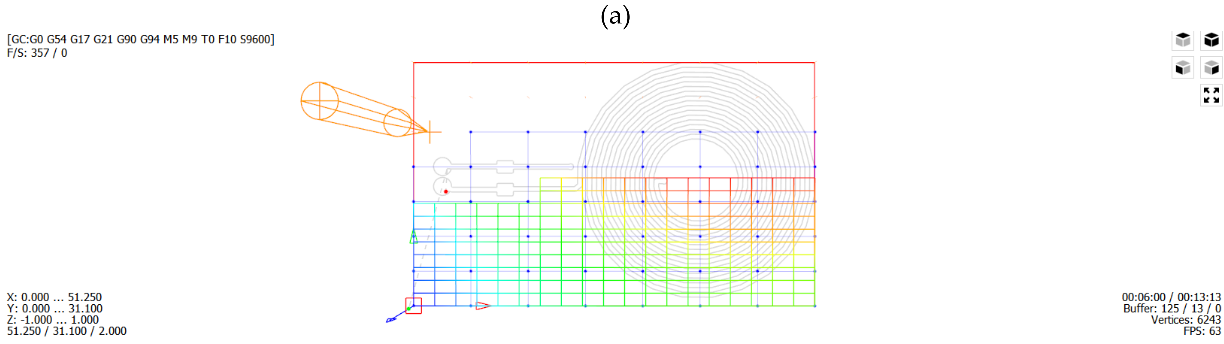
The reference value (Z_0) for the Z axis may not be the same at every point of the plate. When multi-point referencing is performed, the router engraves each region of the PCB plate not at the same depth, but according to the reference values it receives from the relevant points determined by the user. Thus, since the depths of the copper paths on the PCB are equal, short circuits as a result of less engraving between the paths or disconnections as a result of excessive engraving are prevented. At the same time, cutting tips breakage is largely prevented.

In Figure 17, height mapping images related to the multi-point zeroing process performed within the scope of this study are given. In Figure 17a, the PCB surface to be engraved was determined and this PCB surface was divided into an 8x8 (row x column) matrix. Figure 17b shows the process of sequentially referencing from a total of 64 points of the 8x8 matrix. Figure 17c shows the height map of the PCB surface referenced from 64 points in total. Here, regions with a lower height compared to other points with a blue hue, and regions with a relatively higher height with a red hue are indicated. As can be seen from Figure 17c, height differences are noticeable in a certain PCB area. The points that make up these differences are the multiple reference (Z_0) points on the surface of the same PCB during the processing of the PCB. While processing the PCB, milling is carried out by taking these points into consideration.



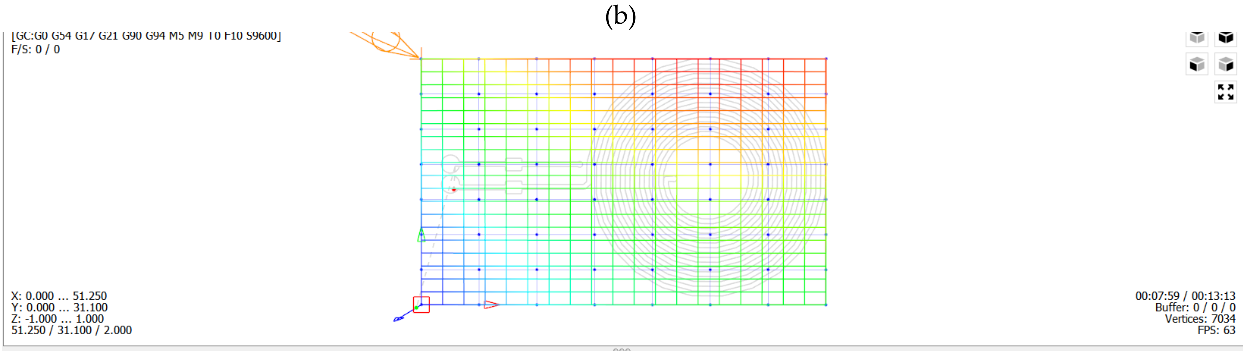
nan	nan	nan	nan	nan	nan	nan	nan
nan	nan	nan	nan	nan	nan	nan	nan
nan	nan	nan	nan	nan	nan	nan	nan
nan	nan	nan	nan	nan	nan	nan	nan
nan	nan	nan	nan	nan	nan	nan	nan
nan	nan	nan	nan	nan	nan	nan	nan
nan	nan	nan	nan	nan	nan	nan	nan
0.002	0.037	0.064	0.084	0.099	0.108	0.112	0.113

(a)



nan	nan	nan	nan	nan	nan	nan	nan
nan	nan	nan	nan	nan	nan	nan	nan
nan	0.132	0.163	0.185	0.200	0.207	0.204	0.190
0.058	0.103	0.134	0.161	0.179	0.193	0.195	0.188
0.049	0.087	0.114	0.138	0.153	0.163	0.165	0.156
0.023	0.059	0.087	0.112	0.132	0.147	0.154	0.152
0.020	0.049	0.071	0.093	0.108	0.119	0.125	0.120
0.002	0.037	0.064	0.084	0.099	0.108	0.112	0.113

(b)



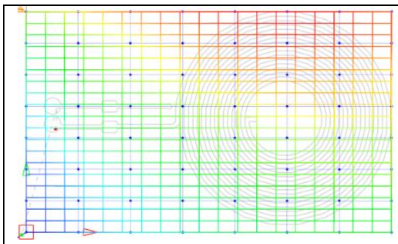
0.152	0.185	0.211	0.231	0.242	0.246	0.240	0.224
0.106	0.148	0.179	0.205	0.223	0.231	0.231	0.220
0.091	0.132	0.163	0.185	0.200	0.207	0.204	0.190
0.058	0.103	0.134	0.161	0.179	0.193	0.195	0.188
0.049	0.087	0.114	0.138	0.153	0.163	0.165	0.156
0.023	0.059	0.087	0.112	0.132	0.147	0.154	0.152
0.020	0.049	0.071	0.093	0.108	0.119	0.125	0.120
0.002	0.037	0.064	0.084	0.099	0.108	0.112	0.113

(c)

Figure 17. Multi-point referencing interface

Table 1 gives the height differences on the surface of the PCB connected to the router table with dimensions of approximately 51x31 mm. If multiple referencing is not performed, these heterogeneous height distributions cause tip fractures and breaks in the continuous copper paths as shown in Figure 5. However, with the method used in this study, the height differences given in Table 1 can be tolerated. Homogeneity can be improved by increasing the number of reference points, but this will increase the processing time. In addition, possible vibrations in the router and the milling tool quality have an impact on the PCB processing. These limitations will be addressed in future work. In the PCB image in Table 1, the height of the point in the red square is 0.002 mm

Table 1. Heterogeneous height distribution on the PCB surface

PCB Surface	Reference Point Heights (mm)							
	0.152	0.185	0.211	0.231	0.242	0.246	0.240	0.224
	0.106	0.148	0.179	0.205	0.223	0.231	0.231	0.220
	0.091	0.132	0.163	0.185	0.200	0.207	0.204	0.190
	0.058	0.103	0.134	0.161	0.179	0.193	0.195	0.188
	0.049	0.087	0.114	0.138	0.153	0.163	0.165	0.156
	0.023	0.059	0.087	0.112	0.132	0.147	0.154	0.152
	0.020	0.049	0.071	0.093	0.108	0.119	0.125	0.120
	0.002	0.037	0.064	0.084	0.099	0.108	0.112	0.113

3. RESULTS

3.1. Testing and Analysis

For the multi-ponit referencing, the probes are connected to the PCB plate and the engraving tool/cutting tip as seen in Figure 18. When the cutting tip touches the PCB plate, the probes are short-circuited and the circuit used for referencing is completed. A signal is given from the relevant pin of the control card to the probe connected to the cutting tip. This signal is grounded through the other probe connected to the plate surface when the cutting tip touches the plate surface. This process is also called as short circuit test within the scope of the study. The short-circuit test is repeated at various points on the PCB surface as many as the number entered by the user, and the Z-axis of the Router is zeroing as a result of each test. Thanks to this zeroing process, the same depth of processing can be achieved for the entire surface of the PCB.

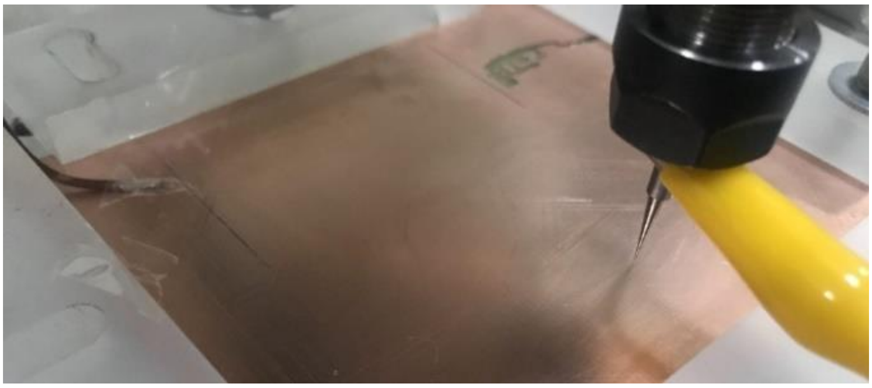
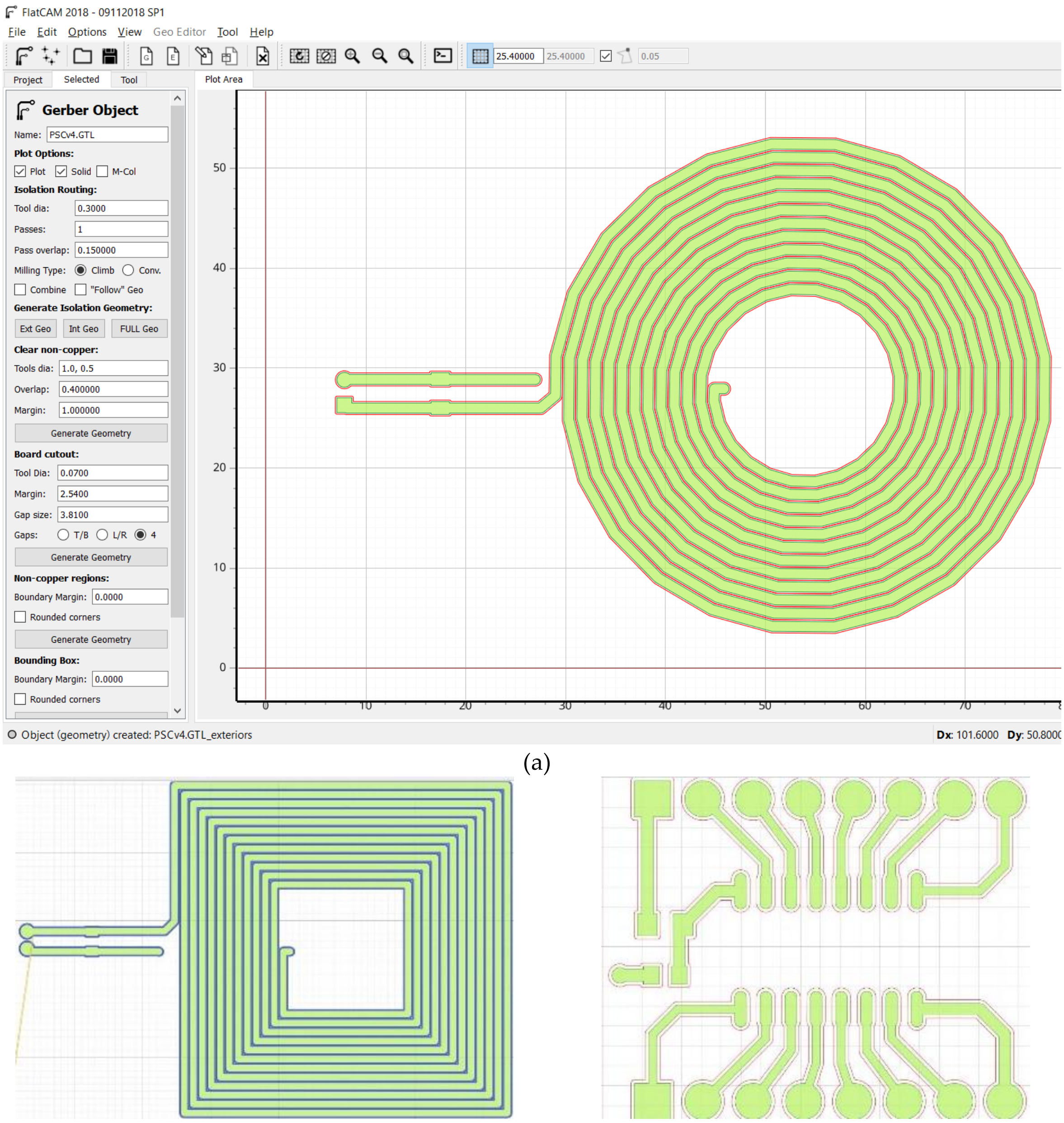


Figure 18. Connections to plate surface and insert for multi-point reference

After providing the PCB Router with multi-point referencing capability, various geometries and electronic integrated circuit in Figure 19 were successfully processed. Images of the processing process are given in Figure 20.

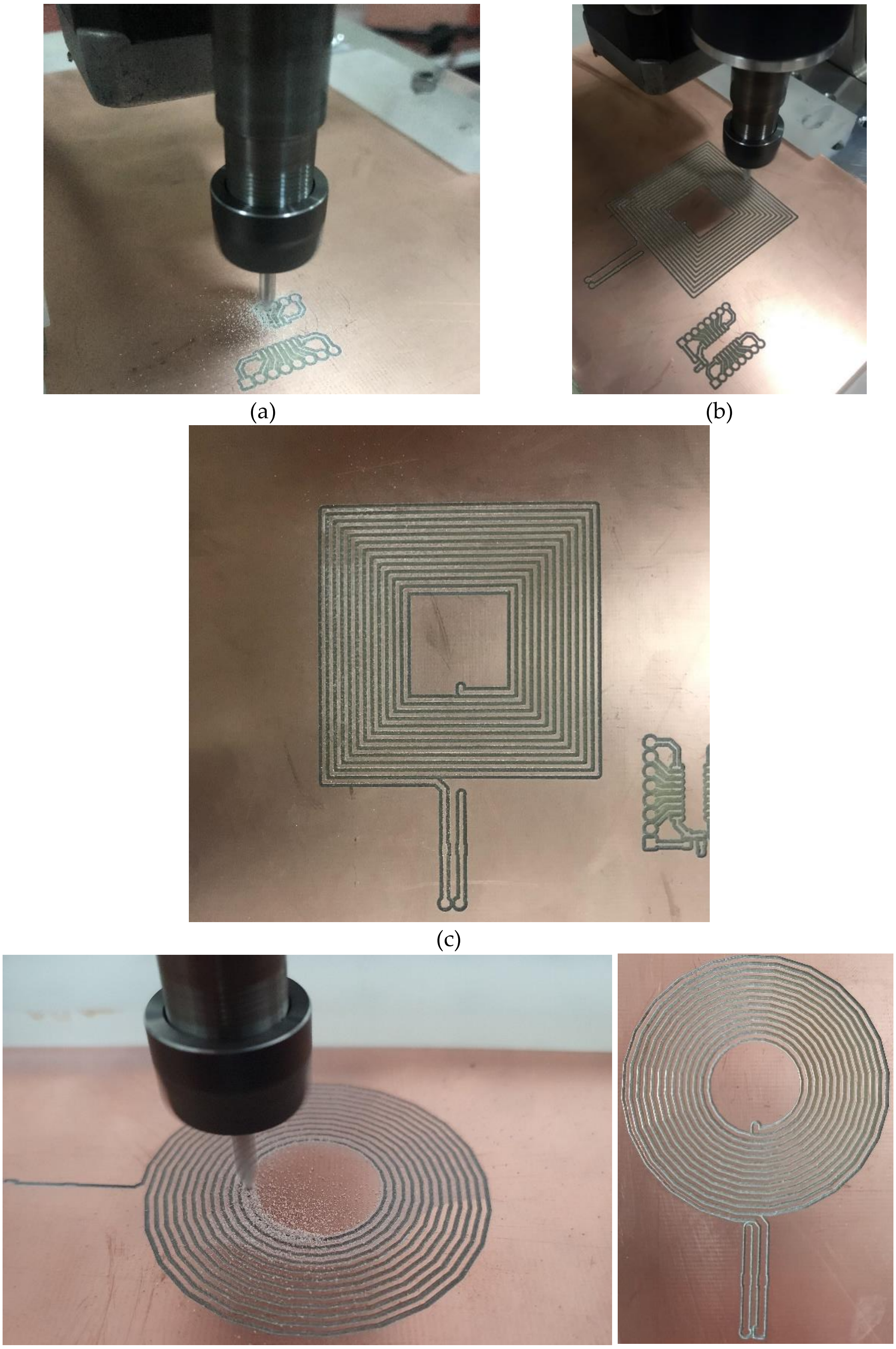


(a)

(b) (c)

Figure 19. Circuits to be extracted G-Code with the electronic circuit production program. (a) circular, (b) square geometries and (c) electronic integrated circuit to be used as SMD-DIP converter.

In Figure 20, the circuits with the g-codes are engraved on the PCB and processed mechanically. As a result of the process, both circuits were checked for breaks and short circuits in the copper paths. No disconnection or short circuit was found during the controls. Especially the successful processing of different geometries forms the basis of his future studies. In this way, the PCB Router has been successfully tested.



(a) (b) (c) (d)

Figure 19. PCB engraving process and the outputs obtained at the end of the engraving. (a) Package converter, (b) and (c) planar square and (d) circle geometries.

To numerically verify the homogeneous distribution on the PCB surface, the thickness of the copper tracks was measured with a digital caliper on the PCB in Figure 19c. Similar measurements were taken from various regions of the PCB. The measurements are shown in Figure 20.

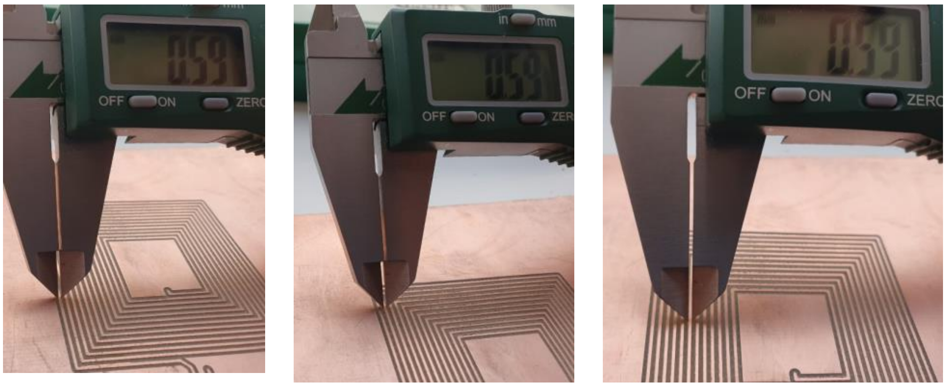


Figure 20. Testing for homogeneous distribution

For the test phase, first of all, the relevant electronic circuits were designed from the electronic circuit design programs and the gerber outputs were taken. After these gerber outputs were transferred to the CAM programs used to generate the g-code, the necessary production parameters/limitations were entered into the related program and the g-codes were obtained.

As can be seen from the output images in Figure 19, successful PCB milling proceses were carried out. There is no breakage or any short circuit on the copper paths for the PCBs in Figure 19. These PCBs were processed with the parameters in Table 2. The values of the processing parameters in Table 2 were determined by the experience gained from the experimental applications and the information obtained from the expert opinions.

Table 2. Key parameters of various PCB milling with the developed router machine

No	PCB	Tools (V shape)	Passes / Pass overlap	Feed / Plunge / Rapid Movement Speed (mm/min)	Depth Cut	Height Map Matrix Dimensions [rows x columns]
1	SMD-DIP Chip	Dia: 0.34 mm, Tip angle: 30^0	1 / 0.15 mm	%80 / %40 / %80	-0.040 mm	2 x 2
2	Quadratic PCB	Dia: 0.20 mm, Tip angle: 30^0	1 / 0.15 mm	%80 / %40 / %80	-0.030 mm	8 x 8
3	Circular PCB	Dia: 0.30 mm Tip angle: 30^0	1 / 0.15 mm	%80 / %40 / %80	-0.050 mm	8 x 8

The key machining parameters of the PCB engravings and the values selected for these parameters are given in Table 2. It was observed that less burrs remained in PCB-1 and PCB-3 compared to PCB-2. This may be due to manual referencing at the beginning or the depth cut. PCB-3 production took 33.20 minutes. PCB-2 was completed in approximately 47 minutes. Since the surface area of the PCB-1 is smaller than the others, the time record was not kept. In the future, PCB processing with different and various cutting tips is considered. Because the cutting tip is one of the most important factors affecting the engraving quality. Another important factor is the zeroing on the Z-axis. Also in the future, manual zeroing for the starting point is also planned to be automatically provided before the height map is generated.

In this study, a PCB router was developed with a cost effective solution. The developed PCB machine was cost analyzed by comparing it with various routers in the market. Table 3 is presented for cost analysis.

Table 3. The cost analysis list

PCB Machines	Type	Cost (€)
WEGSTR PCB [19], [20]	Commercial	3874.89
VOLTERA V-ONE [21]	Commercial	4797.29
CUBE 3D XR PRO [22]	Commercial	4299.00
PCB ROUTER DESKTOP [23]	Commercial	1556.64
R-CNC [24]	Hobbyist/personal use	601.36
PCB-CNC [25]	Hobbyist/personal use	513.10
Our PCB Machine	Laboratory	471.92

4. CONCLUSIONS

In this study, a 3-axis precision router has been developed for successful PCB processing. Electronic circuits in various geometries are processed with this machine. The PCB workbench works by taking reference from multiple points. Thus, engravings can be made at homogeneous depths in the Z axis across the entire PCB surface. Thanks to the multiple referencing, tip breakage and copper path breaks are largely prevented. Although breakage can still be observed at 10-degree V-ends, the breakage rate is much lower at wider angle V-ends, and in this study, successful PCB machining was performed with 80% feed and 40% plunge speed ratios between 0.035 mm - 0.07 mm depths without breakage. In addition to the feed rates, to determine the cutting tip and the engraving depth are the key factors in PCB machining.

Declaration of Ethical Standards

Not applicable.

Credit Authorship Contribution Statement

E.Y.: Conceptualization, Investigation, Methodology, Software, Writing – review, Original draft & editing, Funding acquisition, Supervision, Validation, Design and Manufacturing. B.S.: Conceptualization, Investigation, Methodology, Software, Writing - review, Software, Original draft & editing, Design and Manufacturing. T.U.: Conceptualization, Investigation, Methodology, Software, Writing – review, Design and Manufacturing. I.I.: Conceptualization, Investigation, Methodology, Software, Writing – review.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding / Acknowledgements

This study was supported by Scientific Research Projects Unit with project number 221219011.

Data Availability

Not applicable.

REFERENCES

[1] H. Shamkhalichenar, C. J. Bueche, and J. W. Choi, "Printed Circuit Board (PCB) Technology for

Electrochemical Sensors and Sensing Platforms," *Biosensors*, vol. 10, no. 11, 2020, doi: 10.3390/bios10110159.
[2] Y. Dong, C. Bao, and W. S. Kim, "Sustainable Additive Manufacturing of Printed Circuit Boards," *Joule*, vol. 2, no. 4, pp. 579–582, 2018, doi: 10.1016/j.joule.2018.03.015.
[3] Y. Huang, J.-S. Zhang, X.-Y. Chen, W.-Y. Ho, and W. Li, "Comparison of Cutting Performance of Router with CrAlSiN and DLC Hard Coatings," *Int. J. Mater. Mech. Manuf.*, vol. 7, no. 3, pp. 124–127, 2019, doi: 10.18178/ijmmm.2019.7.3.444.
[4] U. Shinde, R. Somalwar, N. A. Kale, A. J. Nandeshwar, and A. V. Mendhe, "Short Paper on Cnc Based Pcb Milling Machine Considering Human Safety," *J. Res. Eng. Appl. Sci.*, vol. 5, no. 3, pp. 104–107, 2020, doi: 10.46565/jreas.2020.v05i03.005.
[5] H. Kaygisiz and K. Çetinkaya, "CNC Milling Training Set Design and Application," *SDU Int. J. Technol. Sci.*, vol. 2, no. 3, pp. 53–71, 2010.
[6] M. Demir, M. Kuncan, and H. Ertunç, "3 Eksenli Mini Cnc Freze Tezgâhı Tasarımı Ve İmalatı," in *Otomatik Kontrol Ulusal Toplantısı, TOK2013*, 2013, pp. 26–28.
[7] N. Camuscu and E. Aslan, "Comparison of the Performances of Coated Sintered Carbide and Coated Cermet Cutting Tools in End Milling of X210CR12 Cold Work Tool Steel with Different Hardnesses," 2005.
[8] F. Gümüş, "Bilgisayarla Bütünleşik İmalat Sistemi Tasarımı," pp. 53–69, 2017.
[9] K. J. Madekar, K. R. Nanaware, P. R. Phadtare, and V. S. Mane, "Automatic mini CNC machine for PCB drawing and drilling," *Int. Res. J. Eng. Technol.*, pp. 3–7, 2016, [Online]. Available: www.irjet.net
[10] F. Yıldırım, O. Doğan, L. Elen and B. Çiçek, "Transfer of Project Development Training to Vocational High School Students To Three Axis Mini Cnc Router Design: An Applied Study", Uluslararası Eğitim Bilim ve Teknoloji Dergisi,vol. 3 no.3, Dec., pp. 125-134, 2017.
[11] V. J. Shilpa, "Design and Implementation of Three-Axis Cost Efficient CNC PCB Milling Machine," *2018 Int. Conf. Recent Trends Electr. Control Commun.*, pp. 106–109, 2018.
[12] M. Raut, G. Shete, S. Vipul, and S. Ashok, "Automatic mini cnc machine for pcb drawing using arduino," *Ijciras*, vol. 2, no. August, pp. 51–58, 2019.
[13] V. Størkersen, "Configuring electrochemical 3D printer for PCB production," UiT, 2022.
[14] PCB Universe, "Technical Tips for PCB's," 2022. https://www.pcbuniverse.com/pcbu-tech-tips.php?a=4
[15] JLCPCB, "PCB Manufacturing & Assembly Capabilities," 2023. https://jlcpcb.com/capabilities/Capabilities
[16] E. Yavsan, "Development of Innovative and High-Performance Capacitive Rotary Encoder," Necmettin Erbakan University, 2020.
[17] Arduino, "Arduino UNO Overview," 2022. https://docs.arduino.cc/hardware/uno-rev3
[18] Mach Support, "Mach3 Mill Install Config," 2022. https://www.machsupport.com/Mach3Mill_Install_Config.pdf
[19] ProSMT "3 Eksenli CNC Freze Makinesi WEGSTR PCB Devre Kazıma Makinesi", prosmt.com, Available:*https://www.prosmt.com/urunler/wegstr-3-eksenli-cnc-freze-makinesi, [A*ccessed :Feb. 12, 2023].
[20] Wegstr, " CNC Wegstr ", *wegstr.com.* [Online]. Available: *https://wegstr.com/CNC-Wegstr-(English),* [Accessed: Jul 7, 2023].
[21] Voltera," V-One", *www.voltera.io.* Available: *https://www.voltera.io/v-one.* [Online]. [Accessed Jul. 7, 2023].
[22] Derinmotion, "CUBE 3D RF Pro PCB Prototipleme Makinesi", *derinmotion.com.* [Online]. Available: *https://derinmotion.com/urunler/cube-3d-rf-pro* , [Accessed: Jul. 7, 2023].
[23] Meonotomasyon, " Pcb Ahşap Masaüstü Cnc Router", *meonotomasyon.com.* [Online]. Available: *https://www.meonotomasyon.com/urun/pcb-ahsap-masaustu-cnc-router*, [Accessed Jul. 7, 2023].
[24] MakerFR, " R-CNC", *makerfr.com,* Available:*https://www.makerfr.com/en/cnc/r-cnc/,* [Accessed Jul.

7,2023].
[25] Github, " DIY Printed small PCB CNC for fast Prototyping ", *github.com.* [Online]. Available: *https://github.com/Shortcircuitboards/PCB-CNC,* [Accessed Jul. 7, 2023].