A PCB Manufacturing Machine with Protection Features for Milling RF/Microwave Printed Circuit Boards

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Abstract*: A printed circuit board (PCB) with a non-flat surface is very common in radio frequency applications. For this reason, we have designed and produced a PCB milling machine capable of milling a PCB with a non-uniform flatness. Method: By embedding the suggested machine with a G-code reconstruction software, the milling device is programmed to implement the following tasks: Step 1, the machine executes the probing procedure to generate the PCB's Heightmap; Step 2, the machine transforms the input probing signal to a surface map which is a 2-dimensional grid, Step 3, When the machine is running, the height of the drill tip is adjusted according to the PCB surface flatness condition, and the machine before the actual milling operation. As a result, the proposed machine is capable of milling elastic and unlevelled PCBs at high speed with height differences ranging up to 150mm and an ability to halt when the plane angle varies severely. The proposed machine has been used to fabricate microwave print circuits. A close agreement has been obtained between the measured and simulated S-parameters. Although the machine works properly and is equipped with all basic safety functions, it only costs around US$1500 while the market price of a related German product is about US$70000. Conclusion: A machine able to mill microwave PCBs with an uneven surface and equipped with safety function has been successfully built at the Vietnamese - German University a cost of US$1500, which is far less than the market price of similar ones.

Keywords*: AutoLeveller, G-code, LinuxCNC, Mach3, Microwave Application, PCB milling machine.

I. INTRODUCTION

PCB fabrication service has been one of the mandatory sources of incomes for electronics stores throughout Vietnam. The competition in this business is very intense in terms of both quality and quantity. The quality of a PCB making machine is not easy to determine until the measured performance of a milled PCB is actually measured at microwave frequencies. For microwave or millimeter-wave applications, the quality has to be ensured in 3 dimensions because even a 10 micron deviation in any dimension can result in a huge difference in the measured S-parameters. A small variation in a milled antenna geometry can lead to noticeable difference in the measured radiation pattern during the quality assurance process.

This quality issue can be traced back to the height calibration mechanism which is supposed to be available in any PCB milling machine. Up until now, not many machines in the market is equipped with a subsystem capable of calibrating the milling heights. In the hobbyists's community, an open source freeware "AutoLeveller" is one of the solution dedicated to height adjustment purposes. This software is an add-on for the existing platforms like Opencncpilot. What AutoLeveler does is interfering with the G-code [3] instruction by changing the height value of the spindle with respect to the measured value during the probing process. The software itself is also a set of instructions at the beginning of the G code which determines which points on the PCB surface is to be probed by the. A height gradient map for the entire surface is generated after executing the probing section. This map illustrates the height changing in value during the milling operation.

To utilize "AutoLeveller", executing the probing section from G-code during the starting phase is mandatory. However, not many PCB machine firmware is compatible with AutoLeveller, and only a few products carries LinuxCNC or Mach3 firmware.

Among the published papers about PCB milling machines [4-8] in recent years, not many focus on the issue of microwave circuit construction. This research delivers a completely new PCB fabrication system equipped with an ability to produce a high-quality microwave PCB with an uneven flatness. The system is equipped with a safety function to minimize any damage on the PCB. This module algorithm could be executed at real-time to cope with extreme height variations. Both the software and the PCB milling machine used for this project were designed and made by students and professors of Vietnamese-German University.

II. METHOD OF SOLUTION

A. Hardware

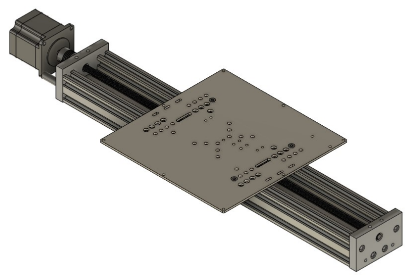
First of all, the hardware architecture was designed as illustrated in Figs. 1a and 1b to propel the spindle in free space in a controlled manner supported by the surface roughness mapping system. The system's body build was generated using 8 V-slot and 3 C-beam made from stainless steel. The bottom of the frame constructed by two 30x 60x 800 mm profiles and two 30x 60x 500 profiles mounting with four L-shaped supports in a way to form a rectangular foundation. The rails, X-axis and Y-axis, of the frame used two 500-mm C-beam profiles. For the Z-axis rail, a 250-mm C-beam profile was used. The X-Axis C-beam profile is parallel to the bottom of the frame, in addition to the Y-axis and Z-axis, while the C-beam profile crosses at the top of the frame.

The system's movement axes divided into two parts: a) The self-reliant moving Y-axis that acts as the base axis (in Fig. 1a) and b) the X/Z axis that is attached together with the function to control the spindle. Three stepper motors attached to a microcontroller circuit helped to control the three-dimensional travel.

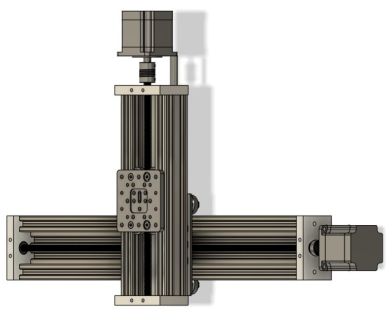
The spindle along with the driller was positioned by the Cartesian guiding system. The Z-frame was attached to the X-frame. This allows these two frames to travel along the Y-axis. With respect to the PCB specification, the spindle mounted on the Z-frame was allowed to move horizontally.

The stepper motors used for the system were the NEMA 23 (size 57) with 1.8 degrees per step (200 steps per revolution) [2]. The NEMA 23 has two phases, each of which draw 2.8A and contribute a holding torque of 1.26Nm.

The spindle used for the system has minimum runout defect, high speed (approximately 10,000 to 50,000 RPM). The spindle works at the no-load resolution of 50000 RMPs for the input of 2.2kW. For the operating voltage at 100 volts, the torque can reach 5000G/CM. The spindle spinning rate can be controlled by configuring input voltage through the Speed Governor, which is a frequency manipulator implemented in the motor control board.



a)



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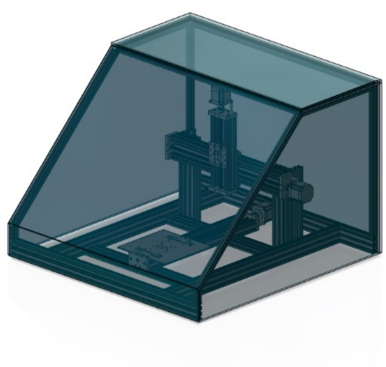


c)

Fig. 1. a) The Y-axis; b) The X and Z axis in combination; c) The overall structure of the PCB milling machine

B. The software

An Arduino Uno was used as the main controller for the system. Attached to the Arduino Uno were the CNC shield v3 and three DRV 8825 motor drivers with the main purpose of manipulating the stepper motor. Before installing the firmware, a GRBL must be loaded into the system. GRBL is a firmware for arduino boards (uno,nano,Duemillanove) designed to control stepper motors and spindles/lasers. GRBL uses gcode as an input and generates signals via the arduino pins. GRBL was used to control the stepper motors and spindles/lasers. The system uses g-code as the main language for the input and output signals via Arduino pins. The input signal was transmitted from a computer connected through the USB cable. Then the g-code is translated into the micro-stepping driver control signals. Next, the signals were sent to the stepper motors as a current control signal, which is built-in H bridges for 2 coils with an overcurrent protection mechanism [4].

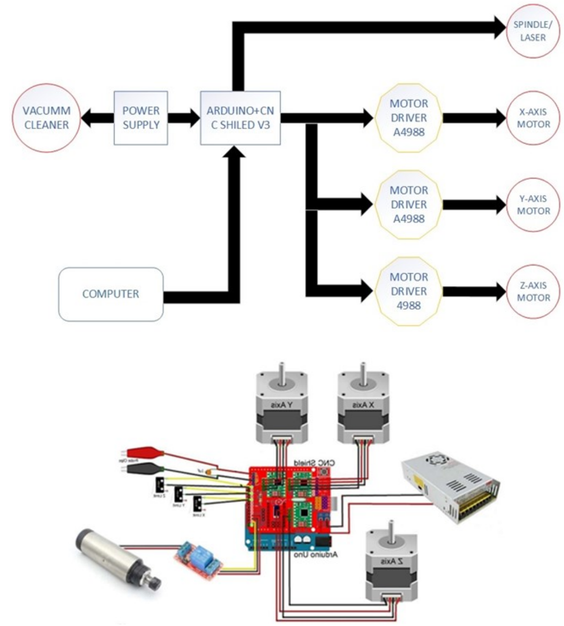


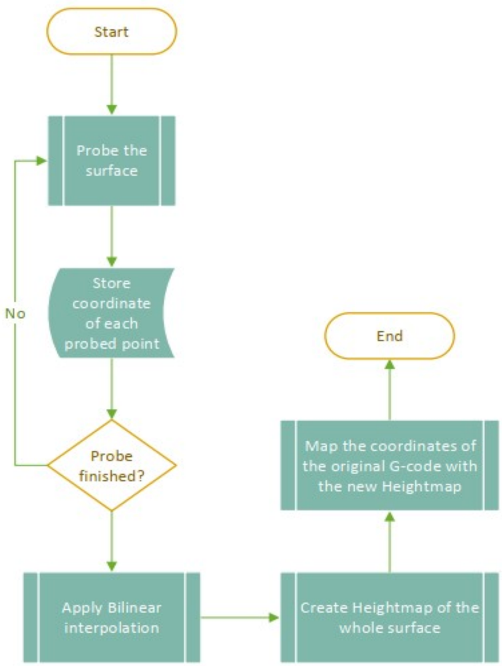
Fig. 2.The firmware of the PCB milling machine.

C. The Operation of Milling

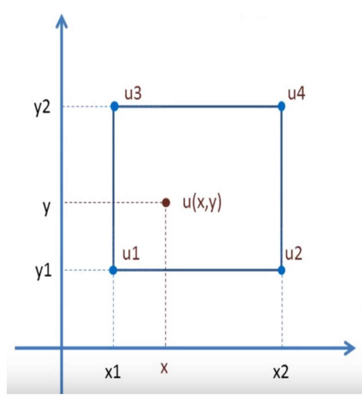
The controlling software of the firmware was constructed to establish a serial connection between the Arduino and the computer. After the G-code file has been loaded by the users, it was displayed on the GUI. If the users need to probe and generate a heightmap, the board's region will have to be defined.

The software has a function called HeightMap which is to be inserted a segment of probing data into the original g-code. As Figs. 3a and 3b have shown, this function was created to probe, measure, and calculate the surface height variation for each X and Y position over the entire surface before going through the milling process. The surface heights are measured and calibrated in a grid fashion and interpolated by bilinear interpolation. The printed circuit was assumed to be either three dimensional or not 100% flat.

When the operation of probing started, two soft but flexible needles were specially used to probe the defined PCB's surface. During the probing operation, one needle is attached to the surface and the other is connected to the milling drill. Then the software will command the Z-axis to slowly push the drill down, and hitting multiple specified points on the surface of the PCB board. The software will record the XY coordinates and the heights of the touchpoint. After capturing all the data, the software will calculate the average and the appropriate position of each point on the heightmap to make sure it was ready for the next operation.



a)



b)

Fig. 3.Surface probing function "HeightMap": a) Flow diagram; and b) Using u1, u2, u3, and u4 values, bilinear interpolation can be applied to determine u.

D. The laser re-calibration safety system

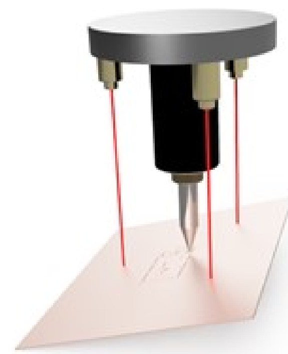


Fig. 4. The Laser Safety System in CAD design.

This module is intended to add a layer of protection to the machine while operating. When the angle of the milling plane tilt over 1 degree from original, the module sends an emergency stop signal to the main system, then the system disconnects the power supply to the spindle and stops all stepper motor movements.

Three laser distance sensors are attached to a Spindle holder in an equilateral formation Fig 5 such that the central point of these sensors aligns with the tip of the milling bit.

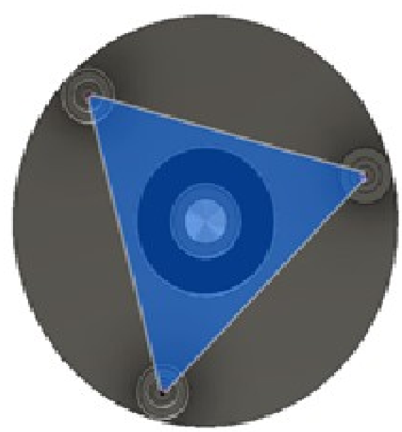


Fig. 5. Top section view of Laser Safety System

The center point coordinate $\overline{Z}$ can be calculated as a median of the received distance measurements according to the following equation. Therefore, the angle difference can be extracted through the corollary of this center point coordinate and the previous plane function.

$$\overline{Z} = \frac{(d_1 + d_2 + d_3)}{3} - \Delta h$$

$\overline{Z}$: desired height to calibrate the drill tip.

d_1, d_2, d_3: Distance received from laser sensors.

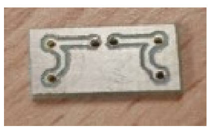
Δh : Debounce distance to the height.

The framework is outfitted with a protection system, which naturally interrupts the milling operator when the height adjustment crossed the edge of 0.1 mm distinct. Nevertheless, the firmware can be improved to sustain the machine operation in another plane as opposed to delaying the entire progress.

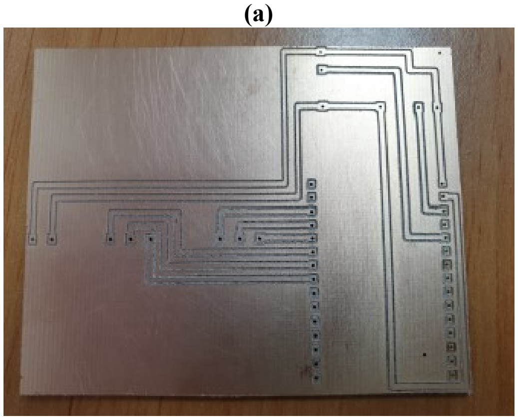
III. RESULTS AND DISCUSSION

The proposed PCB milling machine has been successfully tested with expected outcomes. As shown in Fig. 6, two microwave circuits operating at 2.4 GHz have be built with the proposed machine. The example circuits as shown in Fig. 6 contain curves and crossing points superficially intended for testing the accuracy of the proposed processing machine. The device has effectively stopped the milling procedure upon emergency and continued as requested when there was an adjustment in surface point during the milling process.

The PCB milling machine has not only successfully passed the stress test but also produced an expected PCB with high accuracy, smoothness and precise trace geometry according to the design specification



(a)



(b)

Fig. 6.a) Small RF/microwave PCB with coplanar waveguide, and b) Large and software RF/microwave PCB with a number of coplanar waveguides.

An experiment on the RF/microwave applications has been done by using a network analyzer in Telecommunication & Digital Routing Lab at Vietnamese-German University. The test subject was a coplanar waveguide as shown in Fig. 7. The tested frequency was between 100 MHz and 10 GHz. The S-parameters have been measured and simulated in CST. Fig. 8 shows a comparison between the measured S-parameters and the simulated S-parameters. As shown in Fig.8, the insertion loss (i.e. S21) and the return loss (i.e. S11) of this coplanar waveguide have closely agreed with the simulated values at frequencies below 3 GHz. At frequencies higher than 3 GHz, the measured gain (i.e. the measured S21) was still consistent with what was predicted by simulation. However, the measured reflection at frequencies higher than 3 GHz was void of any higher order mode resonance. The CST simulations were conducted in time-domain, which has factored in all the high order modes. We believe that the higher order mode resonanaces as predicted by CST simulation have been totally filtered off by the SMA connectors.

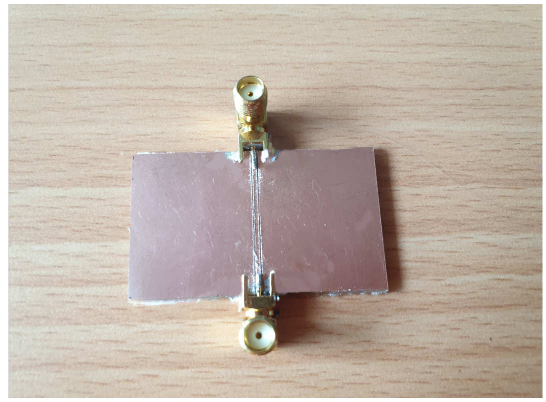


Fig. 7. A fabricated end-fire antenna [9].

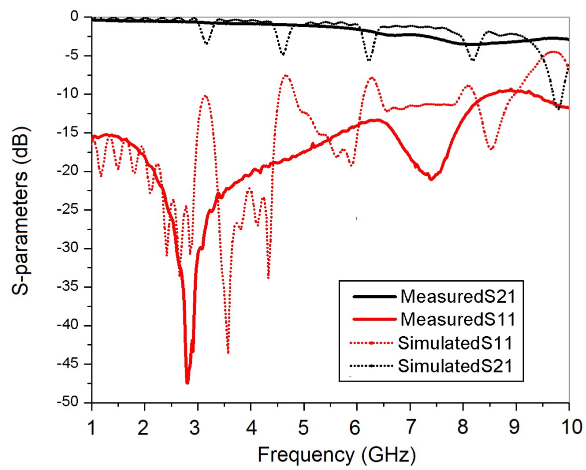


Fig. 8. The measured and simulated S-parameters as a function of frequency.

Separately, we have also fabricated a novel endfire antenna using the proposed machine (See Fig. 9). This endfire antenna has been previously published by research group specialized in wireless power transfer [9], which is currently one of the ongoing research projects in Vietnamese German University. The measured S11 of the fabricated end-fire antenna has fluctuated between -5 dB and -30 dB, which is totally reasonable in comparison with the published results. The operating frequency of this antenna was predicted by simulation to be anywhere between 6 GHz to 12 GHz, which was consistent with our measurement as shown in Fig. 10. According to Fig. 11, the measured S11 at 8 GHz was around -21 dB, which was expected by CST simulation.

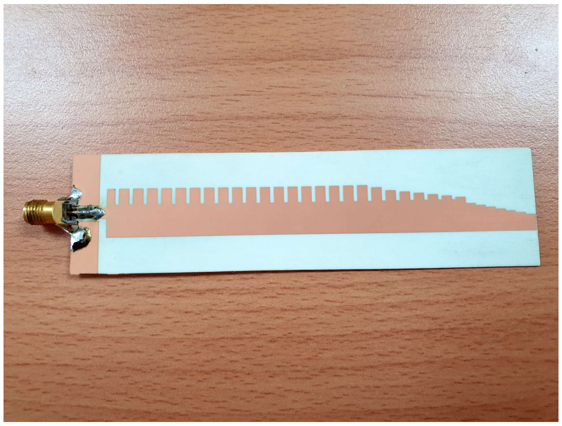


Figure 9. A fabricated endfire antenna [9].

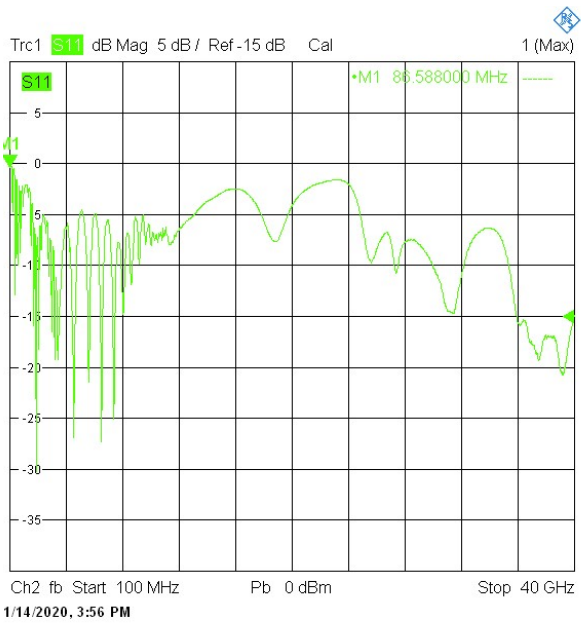


Figure 10. The measured S11 parameters of the endfire antenna as shown in Figure 6 [9]

The measured results as accumulated so far demonstrate the fact that the proposed PCB milling machine can be reliably used for production of high quality PCB's operating at microwave frequencies.

For the first time, the result of this investigation demonstrated the reasonably close agreement between the measurement and the simulation results at microwave frequencies. At this stage, the proposed machine is reliable enough to produce microwave PCB's, ranging from transmission lines to antennas. More research will be required before the proposed PCB milling machine can be safely used for production of circuits operating at millimeter-wave frequencies.

IV. CONCLUSION

In this work, a PCB milling machine capable of milling microwave PCB's has been successfully constructed. It is capable of milling unlevelled PCB at high speed. Users can calibrate the machine while operating by a laser proximity sensor. All of the PCB basic functions were included in the device.

The machine has been designed to mill a PCB based on the given g-code, with the ability to compute and stop the milling bit anytime when it crosses the height threshold using a set of laser sensors.

We have fabricated a number of microwave circuits with measured results highly consistent with the prediction by simulation. The microwave circuits fabricated includes an end-fire antenna [9] and a coplanar waveguide.

The measured insertion loss of the fabricated coplanar waveguides was in general consistent with the results of CST simulation. The measured reflection of the fabricated coplanar waveguide was consistent with the simulation results up to 3 GHz. The CST simulation predicted a series of high order mode resonances at frequencies higher than 3 GHz, which was not found in measurement.

At frequencies from 5 GHz to 12 GHz, the measured S11 of the fabricated end-fire antenna has fluctuated between -5 dB and -30 dB, which is totally reasonable in comparison with the published results.

Whilst the proposed PCB milling machine has much room for further improvement, the results of our measurements and simulations suggest that the proposed machine can be reliably used for production of microwave printed circuits.

REFERENCES:

1. L. L. E. N. America, "LPKF protomat s63 the all-rounder for rapid PCB prototyping," LPKF, 2017. [Online]. Available: www.lpkfusa.com
2. C. INC, "Stepper servo motor," NEMA23-AMT112S, 2018. [Online]. Available: https://www.cui.com/product/resource/digikeypdf/nema23-amt112s.pdf
3. C. Cookbook, "G-code and m-code reference list for milling," CNCCookbook, 2019. [Online]. Available: https://www.cnccookbook.com/g-code-m-code-reference-list-cnc-mills/
4. Kubra Fathima; V. Jean Shilpa; S. H. Mahmood; Machupalli lahari, "Design and Implementation of Three-Axis Cost-Efficient CNC PCB Milling Machine", 2018 International Conference on Recent Trends in Electrical, Control, and Communication (RTECC), 2008
5. Rohit Choudhary; Sambhav; Sunny David Titus; P Akshaya; Jose Alex Mathew; N Balaji, "CNC PCB milling and wood engraving machine", 2017 International Conference On Smart Technologies For Smart Nation (SmartTechCon), 2017
6. Ariana Tulus Purnomo; Farkhad Ihsan Hariadi; Arif Sasongko, "Development of interface and coordination for control module CNC PCB milling machine", 2015 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS), 2015
7. J. Martheyn Berbesi; K. Saumeth; F. Pinilla, "Parallel control firmware for CNC milling machine based in Arduino", 2017 12th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), 2017
8. Muhammad Hidayatullah; Farkhad Ihsan Hariadi; Arif Sasongko, "Development of interface and coordination module of FPGA-based controller for CNC PCB milling and drilling machine", 2017 International Symposium on Electronics and Smart Devices (ISESD), 2017
9. Abhishek Kandwal, Qingfeng Zhang, Xiao-Lan Tang, Louis Wy Liu and Ge Zhang, "Low-Profile Spoof Surface Plasmon Polaritons Traveling-Wave Antenna for Near-Endfire Radiation", IEEE Antennas and Wireless Propagation Letters, Volume: 17, Issue: 2, Feb. 2018.