1. Aleksandra PROSTAK[1], 2. Remigiusz USZOK[2], 3. Łukasz KOLIMAS[3]

Warsaw University of Technology (1), Warsaw University of Technology (2), Institute of Electrical Power Engineering, Warsaw University of Technology(3)

doi:10.15199/48.2023.12.38

Development of an office-friendly CNC mill

***Abstract**. In this paper we describe the development of a small, office-friendly CNC machine. We compare popular CNC archetypes and their ability to be operated in a non-workshop environment. We have made an enclosed machine that is safe both for the operator and people nearby and clean to use, with outer walls fully integrated into the frame for improved rigidity. We made some unique design decisions for increasing the working area without sacrificing stiffness in a small form factor CNC.*

***Streszczenie.** W tym artykule został opisany proces tworzenia małego plotera przystosowanego do pracy w biurze. Zostały porównane popularne konstrukcje maszyn frezujących oraz ich możliwości pracy poza warsztatem. Skonstruowaliśmy maszynę czystą i bezpieczną dla osób znajdujących się w jej pobliżu, dzięki w pełni wbudowanej w ramę obudowie, która jednocześnie dodaje sztywność do naszej maszyny. W trakcie projektowanie zastosowaliśmy parę niestandardowych rozwiązań mających na celu zwiększenie pola roboczego, nie wpływając na sztywność konstrukcji. (**Opracowanie przyjaznej frezarki CNC**)*

Keywords: mill, CNC, machining, router
Słowa kluczowe: frezarka, CNC, frezowanie, ploter

Introduction

Recently, 3D printers significantly have simplified the prototyping of a range of products. Their ease of use and the ability to produce any desired shape make them extremely popular. However, they can only print out of thermoplastics or resins and depending on the type of printer they may also have some additional limitations, such as an uneven finish and, especially for FDM printers, a relative lack of precision. This is why CNC milling machines still have their place in rapid prototyping [1].

They can mill a multitude of materials including all types of steel, carbon fiber and high-performance composites (e.g. PEEK). Moreover, materials adapted to milling are usually much cheaper than the ones made for 3D printing, such as ABS (or ASA) filament and ABS sheets.

Nevertheless, while you can operate a 3D printer in an office environment or even at home, it may be hard to operate a CNC mill. Most small CNC mills are not enclosed, which may cause dust and debris to scatter on the floor and may even pose a safety hazard for people passing nearby. Debris can sometimes be thrown out of the mill, which means everyone around needs to wear eye protection. Furthermore, when materials are not properly affixed to the table, they might be shot out of the machine at high speed, which may cause serious injuries. Also, many CNC machines are not designed to optimize space. That is why we decided to build a CNC milling machine optimized for use in the office environment instead of the workshop.

Comparison of 3 axis CNC machines design

On a market, there is a lot of different CNC designs. The biggest different between them is the size of the working area which describes the range of the movement of the spindle. In other words, it is the size of the cube in which the spindle can operate. Below we are describing the two most popular types of industrial 3 axis CNC mill constructions.

The first one, sometimes called a CNC router (Fig.1), is designed for cutting large sheets (usually exceeding 2m^2). This type of construction is most often open, and sheets are affixed to the machine by a pressure table. The main advantage of this design is a large working area, especially in XY plane. There is the possibility of enclosing the construction by adding an external case, which is not usually done because of construction problems.

The second one, usually just called a CNC mill (Fig.2), is optimized for milling smaller parts, usually out of metal mounted in a vice. It usually has a heavy built-in encloser that adds a lot of stiffness to the machine.

Fig.1 Example of CNC router produced by Stepcraft [2]

In contrast to the CNC router, the CNC mills usually move the table in a y axis instead of moving the spindle. It is another solution to reduce bending and vibrations. This in combination with a more powerful spindle makes them much faster and more precise than the first type. However, the thicker frame and especially the moving table does take a lot of space, so the CNC mill will have a lot smaller working area then the CNC router of the same size. It means it may be impossible to machine some larger parts.

Fig.2 Example of CNC mill produced by Bantam [3]

It may seem intuitive that scaling down one of construction type described above is an easy way to make an office friendly machine, especially the second type since it is already enclosed. Unfortunately, there are some problems with this approach.

CNC mills already have a relatively small working area. Making them even smaller may seriously impede the usability of the machine, as the working area would be so small as to make the machine virtually useless for some manufacturers. In contrast to the CNC mill, the CNC router has a much better ratio of working area to machine size. However, there are also some problems with this design as they are very hard to enclose because of the moving side columns holding the x axis. It was possible to build an enclosure which would protect people and stop the dust from scattering, but we could not see a way to incorporate it into the machine frame, which would add to the desired stiffness. Moreover, in this type of machine most tasks, like mounting materials and cleaning, are done from the shorter side of the machine, because of the moving side columns. For comfortable use, access from one of the longer sides or from the back is required because of the length of the machine. Adding an external encloser complicates things even more.

Right now, most companies on the market that produce small CNC mills scale down one version of the archetypes describes above, such as Stepcraft, Shapeoko or Bantam Tools. That is why we have decided to design and build a CNC mill using more unique approach, focused on usability in an office environment.

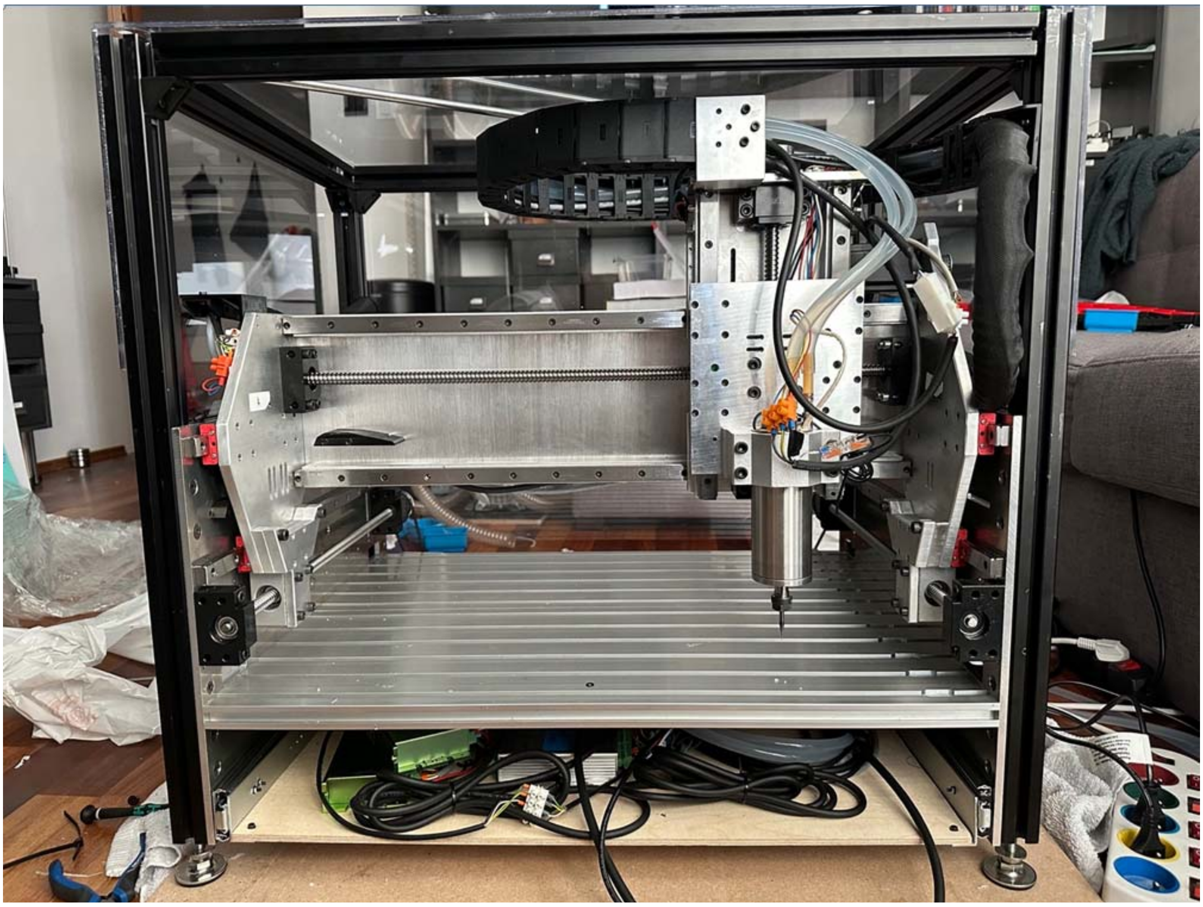

Fig. 3. Photo of CNC machine

Description of our construction

In the picture above (Fig. 2), you can see the CNC mill which we designed. The frame of our mill is made of aluminum [4], that we have machined out of 6 and 10 mm 7075 sheets and 20x20 mm full aluminum profiles. In addition, we made upper frame and strengthened side walls using 30x30 mm construction aluminum profiles. For linear movement we use linear rail, carts, and ball screws. Our machine is assembled

using only bolted connections. We are mostly using M3 to M6 screws ISO 4762 class 12.9.

We decided to make our construction out of aluminum instead of steel to reduce the weight of the machine. Our CNC mill weights 47 kilograms which makes it comparatively easy to move, only requiring two people with no additional equipment. The dimensions are 510x700x620 mm overall and the working area is 310x390x85 mm.

To reduce the size of our machine we decided to forgo a moving table and move the machine spindle in all three axes. Another issue, which was crucial for us, was ease of access. Because of that, we wanted our machine to require only one accessible side for setting up material. This one accessible side should preferably be the longer one, to not have to reach a long distance to access the other side of the machine, while possibly handling heavy pieces of material. That is why in our design the moving axis (x axis) is longer than the stationary (y axis) (Fig.4). This is the opposite of what is usually done in CNC routers. Our approach may sacrifice stiffness for increased accessibility. To reduce that effect, we raised the y axis rails and mounted them on the extremely stiff side walls, also adding two additional y axis rails to make a total of four.

Working area

One of the main drawbacks of using a compact CNC milling machine for rapid prototyping is the small working area, which makes it impossible to make larger parts that may sometimes be needed. Moreover, in our opinion it is cumbersome to make some multipart designs, since you may need multiple programs for one assembly and must run them one after another, which increases wasted materials and operator time needed for setting up the process and changing milling tools.

Fig. 4 Photo generated by Autodesk Inventor with coordinate system [5]

That is why we devoted a lot of time to maximizing the available working area without increasing the overall machine size. Our focus was on the x and y plane since we were trying to make mill optimized for cutting sheets.

The efficiency of using our mill's volume is measured using two ratios:

- 2D ratio – x and y working plane area to largest horizontal machine intersection area
- 3D ratio – working area volume to the volume of the smallest cube our machine can fit into.

On the market we have found enclosed machines of similar size with 2D ratio ranging between 0.11 to 0.27 and for 3D ratio ranging between 0.02 to 0.05. However, the machines incorporating their enclosures into their machines frame have ratios smaller than 0.11 One machine available on the market has a ratio of 0.27 and has a 61 kg external enclosure which does not add any stiffness to their 28 kg machine. Our CNC mill has a 2D ratio of 0.33 and 3D ratio of 0.04 It has fully incorporated enclosure in machine frame.

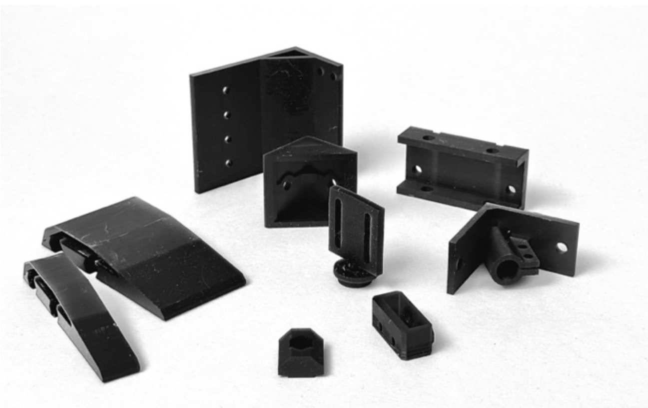

Fig. 5 Printed parts

3D printed parts

Despite the stiffness requirement of our CNC machine, we printed a lot of parts using a resin 3D printer. It has greatly speeded up creating our machine and reduced costs. In Figure 5 are presented all the components that we printed and used. None of them had any significant strength requirements. They are used for triggering limit switches, holding nuts in place, holding cable and mounting cable chain.

Stress analysis

Every part of our CNC mill was drawn in Autodesk Inventor, and then added to our general assembly. This enables us to run many stresses analysis which guide our design choices.

To show the importance of incorporating the enclosure in the machine's frame we included a stress analysis of our CNC machine with and without enclosure.

In Figures 6 and 7, the colour bar represents von mises stress to allow the reader to see stress distribution. However, we used displacement to measure the rigidity of the frame. In the compression we applied 400N of force to the end of the spindle.

In Figure 6, we can see the stress analysis of our assembly with steel reinforced enclosure walls. The displacement measured at the end of the spindle is 0.044 mm.

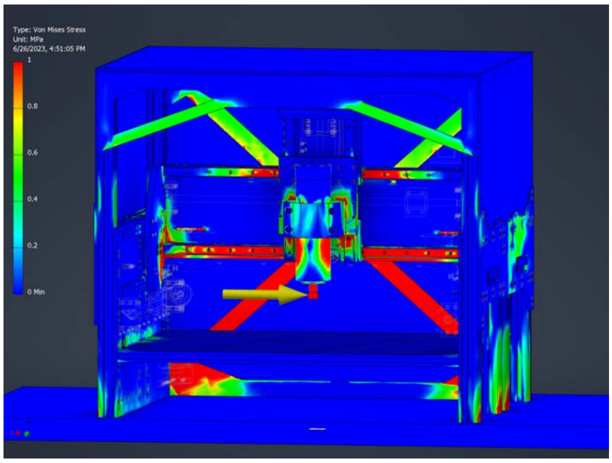

Fig. 6 Stress analysis with enclosure

In Figure 7, we can see stress analysis of our assembly without the enclosure. The displacement measured at the end of the spindle changes to 0.062 mm which is 41% more.

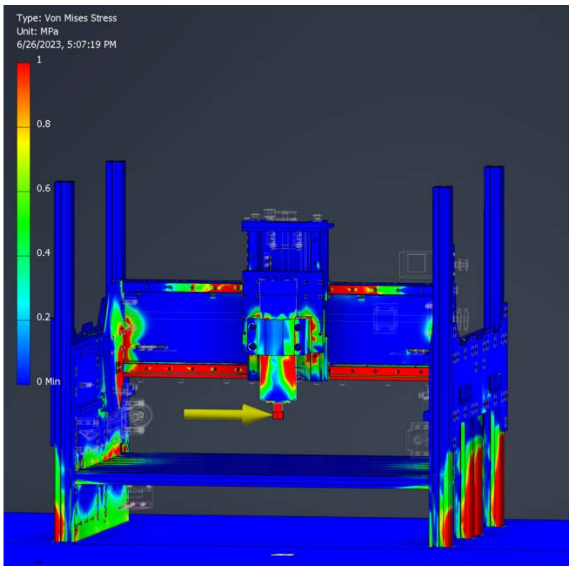

Fig. 7 Stress analysis without enclosure

Electric components

To make our machine compact and moveable, we put all electric and control elements underneath the machine's table, which introduced a height requirement. Our machine allows for a multitude of spindles to be mounted. For precise finishing, we are using 300 W 60 000 rpm water cooled spindles. The high rotation speed allows us to use very small milling tools (less that 1 mm diameter) effectively. To power our spindle, we used a Delta ME 300 inverter. We chose this inverter, because it enables us to use SVC (Sensorless Vector Control) for our spindle and fulfill dimensions requirements. For linear movement we used four Nema 17 0.8Nm, with 2:1 belt drive and 4 mm ball screws giving us 2mm movement for revolution. On y axis we used two such drives, also doubling the number of ball screws and limit switches. To control the motor drive, we used closed loop 2 phase drivers. We used a 4 axis microcontroller, because of additional y axis engine.

Fig. 4 Photo of electronics compartments

For machine safety, we used 3 limit switches in NC mode, one for each axis with 6 adjustable triggering bumpers. At front of the machine, we installed an emergency button. Our enclosure is made of 6 mm polycarbonate sheets [6].

Precision

During our tests we have been measuring dimensional tolerance of parts machined using our mill. It does depend on a multitude of factors including chosen milling tool, its condition and speed of milling. However, we found that it stays below 0.08 after the finishing pass.

Conclusion

In conclusion, we believe our CNC mill, because of our unique design choices, is well suited to operate in an office environment or even at home.

However, there are some things we would like to improve were we to decide to build a second version of the machine.

Even though by making a mill out of aluminium instead of steel, we achieved a lighter construction, we no longer believe that it is worth the added costs. Thinner sheets made of laser cut steel would decrease costs while possibly increasing working area.

All sheets in our CNC were machined by ourselves with high precision. Using water jet instead may have reduce costs and speed up the process. We now believe that the lower precision of the water jet compared to CNC mill would not impact the construction significantly.

Another thing that could have been improved is screw accessibility. During building our CNC, we had to disassemble significant parts of the construction multiple times to be able to access some screws.

The last thing we would consider is an additional protection for ball screw and rails to shield them from debris which we are planning to add.

***Authors**:*
Aleksandra Prostak, student at Warsaw University of Technology, 00-662 Warsaw, Poland, ola.prostak19@gmail.com
Remigiusz Uszok, student at Warsaw University of Technology, 00-662 Warsaw, Poland, remigiusz.uszok@gmail.com
Łukasz Kolimas, Institute of Electrical Power Engineering, Warsaw University of Technology, 00-662 Warsaw, Poland, lukasz.kolimas@pw.edu.pl

REFERENCES

[1] Rob Thomson, Manufacturing processes for design professional, Thames&Hudson, 2018, 182-189, 346
[2] Picture from catalog The D-series, Stepcraft
[3] Picture from BanTam website
[4] Rob Thomson, The Materials sourcebook for design professionals, Thames&Hudson, 2021, 42-53
[5] Alexander Bordino, Autodesk Inventor 2023 Cookbook, Packt, 2022
[6] Rob Thomson, The Materials sourcebook for design professionals, Thames&Hudson, 2021, 144-151