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Designing and Building a CNC Router Using Stepper Motors

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Abstract

A CNC (computer numerical controlled) milling machine is a computer guided machine tool, used for creating sophisticated parts requested by modern technology. A milling machine can be very complex and can have up to 9 axes, being able to support translational or or rotational movements and therefore it can create very complex parts with an improved surface finish.

A CNC milling machine that uses stepper motors is easier to be produced, being accessible even for home built applications. The stepper motors have the great advantage of not needing a feedback from the process while providing high precision and repeatability.

Key words: *CNC, router, milling machine, stepper motor*

Introduction

The stepper motor technology has various applications, being used for motion inside the computer peripherals (floppy disks, printers, plotters), the ATMs, the copiers, for process control systems (automation) but also for realizing simple and reliable CNC machines.

In this paper we will only focus on the 3 axes vertical CNC machines (routers) actuated by stepper motors. They are versatile machines that can be used for milling or drilling in different materials (wood, plastic, metals, and foam), 3D printers, as laser or plasma cutters, as foam cutters or sticker cutters, for photogravure and engraving, for producing electronics circuit boards (PCBs) and others. A router can also be easily upgraded to a lathe, if on the worktable is fitted a device that turns the machined piece (fig. 1) [1].

Cinematic Chain (Transmission) Design

The elements involved into the kinematics of a common CNC router are: the stepper motors; the coupling gears or transmission belts; the ”lead screw” (or threaded rod); the end bearings; the actuating nut; the guiding shaft; the bushings (or linear bearings).

The Cartesian coordinate system is composed of 3 axes (X, Y and Z) each perpendicular to the other two. So, for covering the 3D space we need translation movement by each of the three Cartesian axes. We will need three identical individual assemblies, one for each axis, which will be fitted together in order to form the router. Each one of these assemblies is consisted of one stepper motor (fig. 2 - item 1) connected through coupling gears or transmission belts and pulleys (fig. 2 - items 2) to the threaded shaft (fig. 2 - item 3).

Fig. 1. Milling router with a lathe device [1]

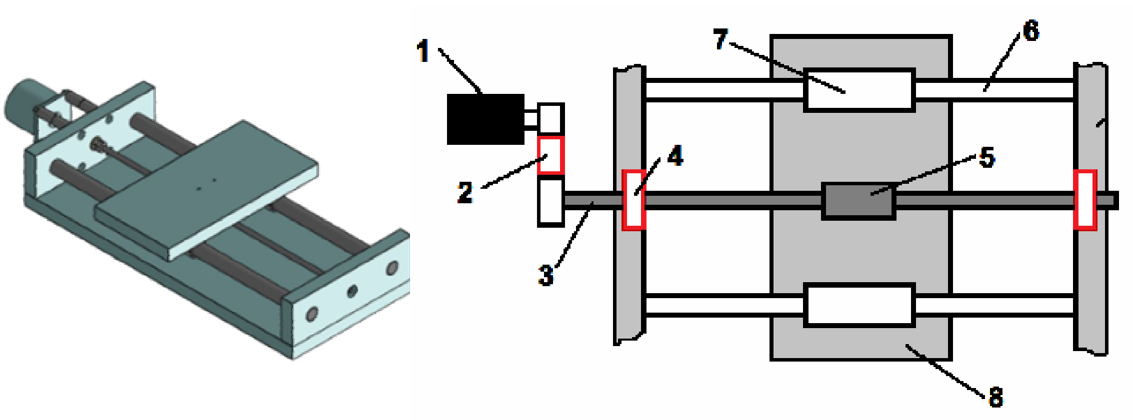

Fig. 2. The cinematic chain of a CNC router [2]

The coupling ratio is not important, because any software dedicated for such applications will calculate on its own the number of pulses transmitted to the stepper for different ratios. The adjustments and configurations will be made just before the first use of the machine. The more expensive alternative to the stepper motors are the servomotors: DC motors provided with encoders that send to the computer the feedback about the rotational movement of the servos.

When the stepper motor rotates the screw, the actuating nut (fig. 2 - item 5) [2] which is fixed on the holding plate (fig. 2 - item 8) transforms the rotating movement into linear movement, so the nut is the one who will move the holding plate to the desired position. The holding plate is usually coupled to the guiding shafts (fig. 2 - items 6) by two bushings (fig. 2 - items 7). The guiding shafts will absorb all the efforts and will not allow the holding plate to rotate.

The ideal “lead screw” (or ”threaded rod”) is a ball screw (fig. 3) [2], which is a mechanical device for translating rotational motion to linear motion with little friction and high precision, while being able to withstand high thrust loads. A threaded shaft provides a spiral raceway for balls inside the nut. The only disadvantage of this type of screw is its high price, which for a home built application may be too restrictive. This type of screw is also used for the industrial CNC machines.

Fig. 3. Ball screw [2]

There are other cheaper alternatives to the ball screw, which are represented by the trapezoidal or triangular threaded screws. The trapezoidal screw is the better choice, because it will provide higher precision, a smaller backlash and a longer operational life. The triangular thread screw's only advantage is the low price and the possibility to be found in any construction materials store. There is an ingenious way to eliminate the backlash, by using a back-nut tightened against the lead nut so that the backlash is reduced and the nuts will still rotate easily. The so tightened nuts must be immobilized by welding them together or by other mechanical system (they may have double thread or may be coupled by a pin).

The backlash may also be compensated by the utilized software (if it allows it), which will do the calculations and will add extra steps when the direction is changed.

The stepper motor's shaft and the lead screw can be coupled by different ways (fig. 4): by using an elastic or rigid adapter, by using coupling gears or transmission belts and gears. The choice is not important for the router's kinematics. The designer of a router must consider the durability of the choice and the materials used for putting into practice. The choice will also depend to the budged.

Fig. 4. Elastic coupler and transmission belt-gear system [3]

The lead screw will have to permanently rotate during the router's operation, so the end bearings (fig. 5) are absolutely necessary. The threaded shaft needs to be machined to each end so the bearings will fit tightly. The bearings can also be provided with housings for an easier mounting. The bearings will be mounted into the assembly's side plates.

Each axis assembly will connect to another through bushings mounted on the holding plate which will slide on two shafts. There are other ways like linear guide rails or bearings running on shafts. The bushing-shaft assembly is the most common because of the affordable price and high reliability. The linear guide rails are more precise, but also more costly than the other methods. The bearing-shaft method is the cheapest, and probably most reliable, but it provides the lowest precision. If the designer chooses to use guiding shafts, he should be very careful when he selects the shaft's diameter so it will not flex under the stress it is subdued to. The bushing can be manufactured out of bronze, cast-iron or other composite materials like raylon or strong polyamides. The improved alternative to bushings is the linier bearings which will provide smaller friction and longer life, of course at a higher price (fig. 6). They also have the advantage of not needing periodical lubrication.

Fig. 5. Bearing in fixing housing [3]

Fig. 6. Linear bearing, grinded and hardened shafts and linear guide rails [4]

Mechanical Structure Design

When you decide you want to make your own CNC Router the first thing you will need to do is to decide on a design. There are basically two types of designs to choose from (fig. 7):

1) Stationary gantry, mobile bed;
2) Mobile gantry, stationary bed.

1) *Stationary gantry, mobile bed*

The mobile bed is usually used on smaller machines like engravers and it is less encoutered between the hobby CNC routers.

The major disadvantage of this type of design is that as the length of the axis increases the mobile bed design becomes less efficient, because the size of the object that could be machined is relatively small as the bed itself is relatively small (the bed needs to be light so the guides will not flex under load). If the distance between the bushings is small, the construction is not rigid; if the distance is larger, the usable stroke decreases.

2) *Mobile gantry, stationary bed*

The mobile gantry design is used for probably 95% of the hobby CNC routers. This design type is similar to the mobile bed except the whole gantry moves along the axis. This is advantageous because the overall size is virtually limitless.

The disadvantage is that it can be problematical to design a gantry that is light enough that is light enough to cause just a slight shaft flex, but still being rigid. With a mobile gantry, you must take into consideration the weight of the gantry itself and the size, in regard to the shaft's diameter.

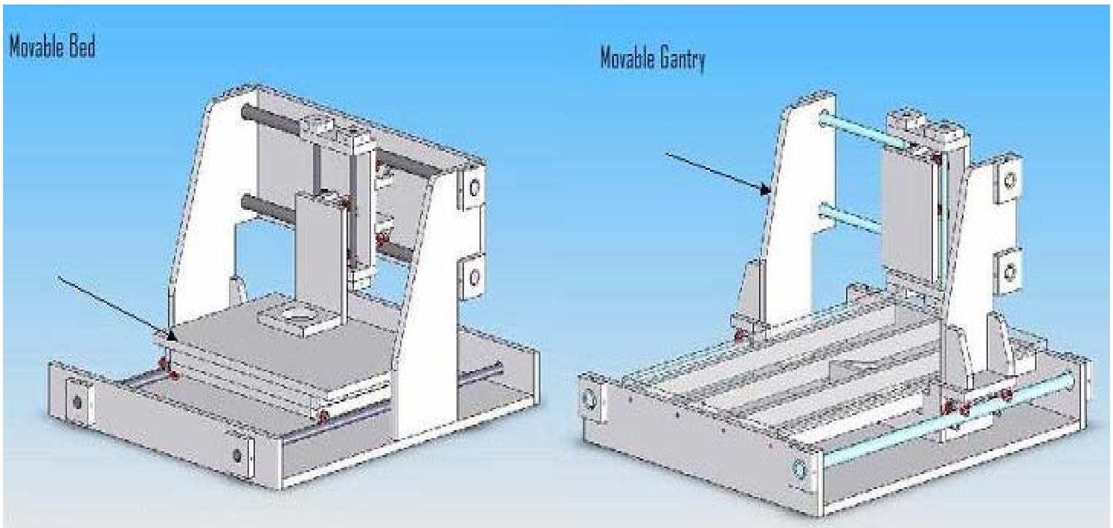

Fig. 7. Different types of CNC router designs [4]

The main advantage of this design is that even if the gantry is robust, the guiding shafts will not flex under load, because the gantry is stationary and does not have to be light. The type of machine is also easier to build and for a smaller machining area this design provides increased rigidity.

Hobby CNC routers are constructed by all types of materials from wood, MDF, plastic to aluminum, steel, and others. The choise of the material from which the machine is built should be based on 3 criteria: budget, tools for machining it and materials available. The tools the builder has access to, may also define the type of material used. If he doesn't have access to a milling machine or to metalworking equipments, then it may be hard to build the design correctly out of metal. There are solutions that limit the machining operations for buiding a router, by purchasing holders for the guiding shafts, housings for bearings and bushings. All sorts of products are available that ease the work for realizing a CNC router, but aslo rise the costs. A popular method for the ones with limited tools is to build a basic CNC router and then use it to build an improved one by using stronger materials. All sorts of aluminum or alloy profiles are also available on the market for building a hobby router, that have the advantages of being light, strong and easy to be joined together.

Another important consideration when designing or building a CNC router is the precision of the machine, because, if a lower precision is required, you shouldn't spend a lot of money for achieving a high precision that is not necessary.

The worktable should allow in one or another way the constraint of the machined part. There is more than one way to achieve that:

- by practicing T-shaped grooves into the table in which T-shaped nuts can be inserted for fixing the part;
- by practicing connected holes into the worktable and constrain the pieces by the use of vacuum, that sucks down the machined pieces;
- by performing threaded holes into the worktable at regular distances in which screws can be introduced for fixing the piece;
- by using a magnetic worktable if the router is used for machining steel pieces.

Designing the Electrical Section

The main electrical components of a CNC router are (fig. 8): a DC power supply, the stepper motors, a driver circuit board for the stepper motors, an emergency stop button, limit and homing switches, a spindle and optional a MPG (manual pulse generator) for manually positioning the tool (jogging).

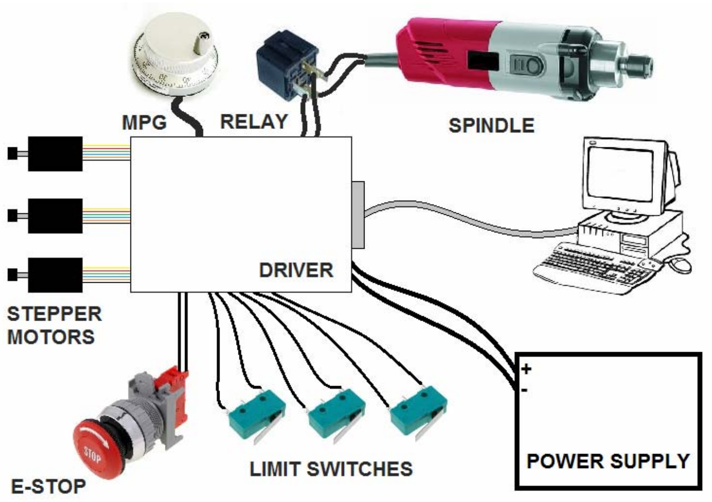

Fig. 8. Main electrical components of a CNC router

The driver for the stepper motors is a controller that converts the impulses received from the computer into commanding signals for the stepper's windings (into the right order). The power supply is connected to the driver which powers the stepper windings. The stepper must be correctly wired to the driver in order to function and if it is wrongly wired it will just buzz, vibrate and not rotate.

Most of the drivers are connected to the computer by the parallel port. Each stepper motor needs two signals: one for the frequency and one for the direction.

There are many configurations for the drivers, varying from the simplest constructions that use binary operations integrated circuits, up to the most sophisticated that can limit the current through the windings and allow half-stepping and micro-stepping driving. Limiting the current is important, because by doing so the voltage can be increased so that the stepper motor will gain power. If the limit current is exceeded the motor will overheat or may burn out.

Most of the drivers available on the market gives the possibility of connecting an E-stop button and switches for homing and limits to its board. These switches warn the computer about the working space physical limits so the control software will stop the machine before a collision takes place. The homing is important for the software to know the position of the tool in the working space.

It is advised that the wires are inserted through flexible cable, so they will not bend over and break during operation. It is also recommended to use flexible cables instead of rigid ones.

The spindle is usually represented by an affordable hand-held mill that is mounted onto the Z axis assembly. These tools have a revolution speed of up to 40.000 rpm, are reliable, can work for long periods of time without overheating and will probably satisfy the requests for a hobby application. A relay can be connected to the computer so the software will be able to start and stop the spindle. For the most pretentious users there is the alternative of using DC brushless motors which do not need periodical maintenance or the more powerful three-phase AC motors along with a frequency converter for adjustable rotating speed.

For receiving a feedback, encoders can also be mounted on the lead screw, but they are not really necessary, being useful only if the stepper motor is losing steps (because the mechanical parts are stuck).

The Control Software

There are many software applications that control CNC milling machines (Mach3, K-Cam, Camsoft, Kay), as well as other CNC machines (lathes, plasma cutters and others).

Mach3 is probably the most used application for hobby CNC machines. ArtSoft, the company which develops the Mach3 software provides a freeware version that only embraces g-code programs of maximum 1000 lines.

G-code programming knowledge is not absolutely necessary for the operator, because the parts can be build using 3D CAD software. After that CAM software can be used for generating the g-code program that can be loaded into the control software.

The control software must be configured before the first use of the machine. The software needs some information for the machine to function:

- which pins are being used for each motor's step and direction commands and for the spindle's control;
- which pins are being used for the limit and homing switches, e-stop button and optional for the mpg, spindle's rotational speed sensor or for the encoders;
- the axes must be calibrated so the software will know the how many steps are needed for the tool to travel a distance unit (mm or inch).

The Designing and the Practical Achievement

The machine built was designed with the Solid Works CAD 3D software package. In this way they managed to foresee some problems that could appear during operation.

I chose the mobile gantry and stationary bed design and for guiding I chose the shaft-bushings solution. The worktable is 820×620 mm wide, and the working space is 700 (Y) × 500 (X) × 200 (Z) mm (fig. 9).

The bronze bushings are built-in polyamide holders that are being mounted onto the holding plates. The guiding shafts are grinded and hardened by induction and their diameter is 20mm for the Y axis and 16mm for the X and Z axes. The lead screws are made from threaded rods: M16 for the Y axis and M12 for the X and Z axes and they are machined at their ends for the bearings to be fitted on (type 6000 bearing for the Y axis and type 628 for the X and Z axes). The rigid structure is made up by polyamide and the machining operations were made on a CNC vertical machining centre with the support of UZTEL Ploiesti.

The stepper motors are engaging the X and Y axes screws by transmission belts and the Z axis screw by gears. The motors are actuated by the driver build around the L297 specialized integrated circuit, which allows current limiting and half-step driving. The power source is represented by a PC power supply which provides a voltage of 12Vdc and a maximum current intensity of 10A (which is enough because the current needed for the motors is 4A). The cables and electrical couplers are specialized, the flexible cables being introduced through cable carriers. On each axis two switches are mounted for determining the end stroke.
I also added a light source (ultra bright LED), push buttons for manual jogging and an E-stop button. The utilized spindle is an Einhell mini carving tool which attains 35.000 rpm, but which is only powerful enough for machining soft materials (wood, MDF, plastic, styrofoam).

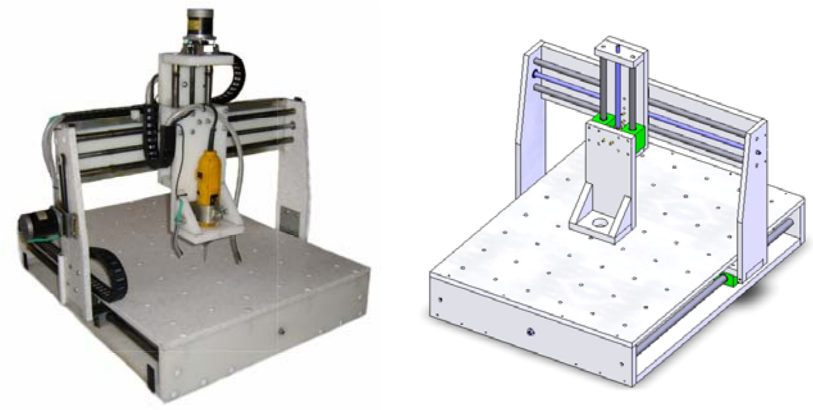

Fig. 9. CNC router

Conclusions

On the Internet there are lots of sites that provide instructions and plans for producing a diy (”do it yourself”) CNC machine and there are also many online shops where anyone can find all the parts needed for manufacturing such a machine or even kits that only need assembling.

The complexity and reliability of the machine mostly depends of the construction budget. If the budget is big enough, the result can be close to an industrial machine that can be used for years without major repairs and with precision of up to 0.001 mm.

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Proiectarea şi execuţia unui router CNC ce utilizează motoare pas cu pas

Rezumat

MUCN (maşina-unealtă cu comandă numerică) reprezintă o maşină de lucru programată numeric prin intermediul unui echipament de comandă numerică, utilizată pentru execuţia pieselor având forme geometrice complexe şi care reclamă asigurarea unei precizii şi repetabilităţi ridicate.

Lucrarea propune ca alternativă pentru MUCN clasice realizarea unui router CNC care utilizează elemente tipizate ce pot fi asamblate pentru obţinerea diferitelor mişcări ale sculei aşchietoare şi ale semifabricatului. Lucrarea prezintă principalele elemente tipizate existente pe piaţă, modul de asamblare a acestora pentru a realiza în final un router CNC cu trei axe, destinat prelucrărilor prin frezare. Soluţia propusă este simplă, având avantajul flexibilităţii şi preciziei ridicate, la care se adaugă avantaje economice ridicate.