CNC Machine Building Through Open Sources Projects and Programs

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Abstract

This research presents a theoretical and practical approach on the construction of a low-cost CNC machine, using as a base model found on the internet. Having his knowledge of movement that in the past was movement only one axis at a time, and in current controls movement on three simultaneous axes. The use of an Arduino micro controller will be the key part of the machine's operation, since it behaves like a PLC, starting from basic to advanced programming. The use of the project will end in its academic use and the dissemination of the technology used.

Keywords: CNC. Low cost. Opensource. Three axes. Arduino.

1. Introduction

The main responsible for the development is the FAA (American Air Force) and the aerospace industries. The precursor to this area is John Parsons and his partner Frank Stulen, where they were FAA contractors in 1940 and experimented with the use of coordinated data for cutting an airfoil. In March 1949, Parsons hired the Massachusetts Institute of Technology (MIT) laboratory to carry out studies on the systems, the creation of a prototype. (GROOVER, 2011).

In 1950 certain technical details were defined, such as the use of magnetic tapes to store the data, the reason was that the use of the punched card was not achieving the desired performance and details of the control system for the machine tools. And a patent was applied for in May 1952, however by the study done no machine has the Parsons-Stulen configuration. The prototype went into operation in March 1952, and some companies in the aviation sector requested test parts to gain knowledge of the machine's operating characteristics. Some advantages were demonstrated, which included good cutting precision and repeatability, reduced machining time, and the ability to machine complex geometries. (LAMB, 2015).

The machines had a different configuration than today, they had the need for human intervention so that they could function correctly, so the exchange of the punched card for magnetic tapes, and in the future for diskettes and centralized data. (AZEVEDO, 2008).

The companies reacted cautiously in relation to the innovation, because without knowing how they would proceed in their facilities, for fear of the technology having a negative return with the teams to maintain the equipment. Thus, the FAA sponsored two tasks: First, the study of information in the industry and then the economic viability of the project. Thus, spreading the technology within the industries and taking its team of professionals to the laboratories to have demonstrations of the use of the machine and the economic study showed where the application would be more viable.

According to Azevedo (2008), the need for more complex systems, the alternative was to standardize operations and create a standard programming language, the G code, In the 50s CNC's began to obey direct orders from computers, as early as the mid-1970s, CAD / CAM systems started in the industries, thus replacing manual drawings.

CNC (Computer Numerical Control) controls have the ability to control the X, Y, Z axes simultaneously, allowing production time to decrease considerably, machine repeatability to be greater and the use of more complex projects to be executed with greater accuracy, where technology was made cheaper by the use of a micro controller from the year 2000, making it possible to be used in microenterprise and hobby media, and in 2009 Simen Svale Skogsrud released the first version of the GRBL (Integration of inverse kinematics), which is a controller for Cartesian axes X, Y and Z, which can be installed on a simple Arduino.

2. Theoretical reference

According to Santos and Sales (2004), the machining process is characterized by the transformation of the raw material into a defined geometry through the removal of material by shear in the form of chips. Among the manufacturing processes, machining stands out for the variety of methods that can be used and for its significant presence in the production chain of manufactured goods. Different technologies can be used to remove material in the machining process. In conventional machining, material removal occurs by the action of a cutting tool with defined geometry. This category includes several well-known manufacturing processes such as drilling, turning, milling, sawing, among others (SOUZA and ULBRICH, 2013; SANTOS and SALES, 2004).

In the milling process, the cutting tool rotates around its axis and meets the part, which performs the forward movements. A great feature is the versatility in the production of different geometries, besides guaranteeing high rates of material removal. In this process, the tool rotates while the piece, attached to the table, is responsible for the longitudinal and transverse feed movements. In some situations, the part may remain static while the cutting tool performs all the movements. (MACHADO et al., 2015).

According to Stoeterau (2004), milling operations can be classified into three basic types according to the movement of the tool: top or front milling, milling in three dimensions.

End milling, it is used one by a multi-edged cutter, which are wrapped around its axis, in addition to being a precise and very dynamic equipment for moving in several directions at the same time, speeding up the production and the cutting process and also being able to be applied in numerous variations within the industry.

It is the result of combined actions of the cutting tool's edges that are at right angles to the face of the part to be machined. The face after machining it is flat without having any relation with the teeth of the tool, among the processes mentioned above it has greater productivity, if it should be chosen as far as possible.

Being able to be used in horizontal and vertical cuts, we can emphasize that there are several models of cutter currently it is up to the identification of the work to be performed for the choice of the ideal tool, knowing that it has a diversity in formats that can be them: spherical, straight, with radius, chamfer. And their rods being: Parallel, conical, or welded in high-speed steel with special recess.

Milling in three dimensions the active teeth are located on the periphery (cylindrical surface) of the tool, and the tool axis is parallel to the surface to be machined. The tools used in tangential milling are called cylindrical or tangential milling cutters. The main disadvantage of this process is that the tool tends to have greater vibration, so fixing it with greater precision is necessary, the part to be machined is necessarily fixed because the cutting movement is inconsistent1, soon there will be greater wear of the part and its useful life is reduced.

The chip thickness starts at zero and increases until the end of the cut. The cutting edge must be forced into the cut, creating a rubbing, or burning effect due to friction.

To quantify the cutting speed and feed speed, feed rate and cutting time, some equations will be established to relate cutter dimensions and rotation which are some of the initial equations to start. For milling and turning, the cutting speed is in equation 1:

$$Vc = \frac{(\pi \times d \times n)}{1000} \left(\frac{mm}{min}\right) \tag{1}$$

Where d is the tool diameter (mm); n is the number of revolutions per minute (rpm). The advance speed is given by equation 2.

$$Vf = f \times n \left(\frac{mm}{min}\right) \tag{2}$$

Where *f* is the advance is travel speed in each revolution (mm/revolution) and *n* is the number of revolutions per minute. The advance is given by equation 3.

$$F = \frac{l}{n} \ (mm/rev) \tag{3}$$

Where *l* (mm/min) is the length machined; *n* is the main shaft rotation and f (mm/rev) is the feed per rotation. For the cutting time we will use the equation 4.

$$Tc = \frac{Lm}{I} \ (min) \tag{4}$$

Where *Tc* (min) is the cutting time; *Lm* (mm) is the maximum part length and *I* (mm/min) is the length machined per minute. So, the machine example would have the sequence: The cutting speed for our 3mm diameter cutter with a machine rpm of 15000 will use 50% of its rpm. Applying the equation 1: $Vc =$

$\frac{(\pi \times 3 \times 5000)}{1000}$ = 47.1698 m/min.

Right in logical thinking our tool without any friction or friction we found this value for the best performance of our tool using a 3mm diameter cutter. With these data we can still calculate the tool cutting time using the formula, we will use a 100mm piece for calculation. Applying the equation 2: Tc= 100/47.1698 = 2,12 (min).

What is the feed rate per revolution when the main shaft rotation is 5000 rpm and the machined length per minute is 47.1698 mm/min.? Applying the equation 3: f = 47.1698/5000 = 0.00943 mm/rev

2.1. CNC Technology

The first job assigned was to John Parsons and his partner Frank Stulen, at Parsons Corporation, where he was an FAA contractor, and experimented with using the concept of data storage held on punched cards to define and machine parts. Thus, the beginning of CNC machines (computerized numerical control) appeared (GROOVER, 2013, p.112).

Presenting the evolution of technology and CNC followed this advance, creating increasingly automated systems, in 1958 a new language was created, the APT (automatically programmed tool) translated into Portuguese as an automatically programmable tool, created by Douglas Ross from MIT (Massachusetts Institute of Technology), thereby further reducing human interference in the machining process.

CNC tools are machines that do not need constant supervision by an operator, thus improving their manufacture. Numerical control is a system that allows the control of machines, being used mainly in lathes and machining centers. Allowing simultaneous control of several axes, through a list of movements written in a specific code (Lamb, 2015, p.30) the code sent to the machine follows a language pattern called G-code. It is the name given to the programming language created from the need for industrial machinery that used Command systems (CNC), later it will be explained.

The piece is designed in a cad (Computer Aided Design) software, and immediately afterwards it is directed to the CAM (Computed Aided Manufacturing) program, where in this program the G-code file is created, within it the standards that will be made will be established, the tool used, the cutting speed and the depth. Since the information is sent to the machine tool, where the instructions are read line by line and executing the selected drawing. The drawing can also be replicated in the CAM software, to increase its productivity and make parts in scales in a single schedule.

In order to obtain a competitive advantage and successfully survive in the current globalized business environment, the industry has incorporated automation techniques to meet the need for rapid adaptation to changes in the production system, ensuring acceptable production volume and product variability (MAGGIO, 2005).

For this, to improve the machines to develop products with greater precision and make a part different from what already exists on the market, a need is made. The integration of evolution with technology becomes essential for these demands and requirements to be met.

The axis of a CNC refers to the displacement in a direction to its Cartesian plane, since the number of axes that a CNC has is linked to the number of simultaneous machine directions. Bearing in mind that the primary axes of (X, Y, Z) in their linear Cartesian coordinates, aim at the displacement of the machine, however the rotation axes are created 3 new axes called angular, thus the rotation on the X axis becomes axis A , the Y axis becomes the B axis and the Z axis becomes the C axis.

3. Mechanical, electronic elements and cost

3.1. Linear guide

The milling machines have guides to enable proper alignment with the spindles and provide smooth movement on the CNC machine axes. According to Costa (2006) "machine manufacturers started to use linear guides instead of traditional busbars, as they have high precision, excellent rigidity and smoother displacements". Spindles and guides must work smoothly to reduce friction and the equipment to have the minimum of error. It is necessary to analyze the type of movement used (vertical, horizontal, or inclined) considering the forces and loads to increase the machine's useful life. Also according to Costa (2001), the spindles receive axial loads, and the linear guides allow the action of forces and moments in different directions, however all loads must be considered in the selection of components, however, for the execution of the project, such loads can be disregarded since that are too low.

3.2. Spindle

It is a straight bar formed by threads and continuous steps with an angle of 30º. This device is used in the execution of almost all industrial processes and applications that require a linear movement, this spindle has relatively great friction, however, it exerts a high tensile or compression force, and is still capable of transmitting high torque, which is the force which tends to turn or rotate objects.

It is widely used in industries and in machines, friction presses, load elevators, residential elevators, lathes and in milling machines and CNC machines. on stops and standardized elements and many accessories. About our project, the Tr8 spindle with a 2 mm pitch was selected so that there was greater precision during the machining process below the spindle precision account in relation to the steps.

3.3. Coupler

According to Kassouf (2004), "it would be ineffective to consider in a project a stepper motor or a high precision servo motor, if the components connected to them, such as: Couplings, reducers, positioners, ball screws, linear guides that they were unable to maintain in the system the level of precision and "repeatability" so desired "

This need for power transmission of the pass motor has led industries to develop couplers that have the minimum clearance possible, since it connects the stepper motor with the spindle, in this case to the axis of the machine under study. Its main functions are the adjustment of the minimum misalignment, reduction of vibrations and loads to connected equipment due to not forcing the motor bearings, thus optimizing its useful life.

3.4. Stepper motors

Stepper motors are widely used in machine designs that need better control and precision, since the stepper motor works in open and brushless loop that divides a complete rotation into several stages, this topic, since the stepper motor step works in open loop, this topic will detail its operation and the types of stepper motors on the market.

Step motors are electromechanical elements that convert electrical pulses into mechanical movements, obtaining minimum angular variation values.

According to Betiol (1989), "its power is digital electrical, or it drives, and its rotational movement is incremental". The speed of a stepper motor is given directly by the frequency of pulses and the rotated angle is related to the number of pulses applied. Unlike the brushless DC motor that rotates when direct current is applied, the stepper motor rotates at angles, thus increasing its machining accuracy, thus using the principle of electromagnetism. With the purpose and synchronous characteristics, the stepper motor is widely used in the construction of CNC machines, 3D printing, among other purposes. Due to these characteristics, it ensures practically constant positioning and speed control, plus precision, durability and simplicity are indispensable elements.

The stepper motor uses the same principle as all electric motors, Magnetism. Starting from this concept knowing that it does not rotate continuously, but in stages per rotation, thus creating angles per stage, where the permanent magnets represent the stator and the rotor is a coil of copper wires circulating the electric current. This current generates a magnetic field and the coil behaves with a magnet. The current being controlled, the forces of attraction and repulsion make the rotor rotate.

In the case of the stepper motor, this function of the electromagnets turning on and off in a sequence so that the rotor moves from one electromagnet to the other, where the motors have an iron shaft and surrounded by them has the coils. When voltage is applied to the coils, the rotor tends to align with the stator in the case of permanent magnet, and tends to find a minimum working space for the variable reluctance, so the coils are energized in a sequence in order to move the stator and axis for the operation of the stepper motor.

3.4.1. Types of stepper motors

According to Souza (2013), "depending on the construction characteristics, stepper motors can be classified into three types: permanent magnet, variable or hybrid reluctance".

• Permanent magnet stepper motor

Used mainly in computing, it has a smooth axis, generating simple and inexpensive mechanics, its advantage is that its magnetic field can be added to the magnetic field of the coils, giving a greater power, or Torque, but seeing that its magnets are not notches, have less precision in their execution, so the poles are alternative to the rotor axis. Upon receiving voltage the coils create magnetic fields, thus aligning the rotor to the stator field, so a sequence is created with the next stator so that the axis aligns with the coil, having this logic visible that energizing the coils in sequence the motor stride rotates at fixed angles. Within this engine we have the possibility of resolving it so that we can have greater precision during the machining process, however the increase in the number of phases and, consequently, the increase in the number of poles, can decrease the life of the engine, as it would result in temperature rise, even if the voltage is the same as the temperature between the coils can damage the circuits.

• Variable reluctance stepper motor

Also called switching variable reluctance, they consist of 3 to 5 coils connected to a terminal in common between them. common among them, it presents an advantageous resolution in relation to the permanent magnet, however little used due to its low torque. Its shaft is made of toothed non-magnetic soft iron and has no magnet, because when its magnetic field is energized, the rotor moves to reduce spaces between the stator and the teeth. The spindle teeth were designed so that, when aligned with a coil, they are misaligned with the next one, and so on, so that the coils are loaded in a fixed sequence, thus having the rotation of the motor. As with the permanent magnet, its resolution can be increased by increasing the coils per phase.

• Hybrid engine cost

This engine mixes the two technologies, thus giving greater torque and greater precision in the steps, ranging from 3.6º and 0.9º. Its axis consists of two groups of teeth, emphasizing the opposite poles, and having a toothed rotor that better guides the magnetic flow. The magnetic rotor has two bodies, each for a pole, so that the poles can be organized in a way that alternates to rotate the motor, so it has the same principle as the others of energizing the coils in sequence.

• Types of wiring

The motors are mainly biphasic, having their variation in being unipolar or bipolar, being that in the unipolar they have two windings per phase, being able to have a cable in common between each phase. The unipolar motor simplifies the operation because to operate them, there is no need to reverse the current in the drive circuit. In the bipolar motor, there is only one winding per pole, the direction of the current is changed in the circuit.

3.5. Cost

Table 1 below is the amounts spent for the execution of the project with materials that the author had, materials reused and supplied by friends, for the machine execution.

Table 1 – Costs

Items	Quantity	Cost (R$)
Stepper motor	4	0
CNC shield	1	25,15
Stepper motor drivers	4	44,46
Arduino	1	56,43
Power supply	1	16,9
DC connector	1	5
Jumpers	20	22,99
Mini grinding machine	1	0
Left Y-axis motor support	1	70
Left X-axis car	1	0
Grinding Cart	1	0

Left bearing support Y axis	1	0
Right Y-axis motor support	1	0
X-axis right carriage	1	0
Y-axis right bearing support	1	0
Z axis car	1	0
Coupler	4	47,43
wood	1	0
Trapezoidal spindle 500mm	2	117,30
Trapezoidal spindle 300mm	1	74,57
Trapezoidal spindle 150mm	1	65,48
12mm linear bearing	4	53,40
688ZZ Bearing 8mm	4	32,40
500mm linear guide	2	20
300mm linear guide	2	20
150mm linear guide	2	20
Metal chestnut	4	35,24
Total	68	726,85

4. Conclusions

4.1. Mechanical part assembly

As the whole process was done by 3D printing, the parts alone were finished and ready for assembly, initially it was made on an MDF board to reduce costs, since the aluminum profile would contribute to a final cost higher. Using a square and ruler, the middle of the MDF (Medium Density Fiberboard) was marked to then drill and fix the parts of the machine tool base.

In this process, on each Y axis, 1 500mm guide rod, 1 2mm trapezoidal spindle, 1 nuts to reduce spindle clearance and maintain accuracy, 1 8mm / 5mm coupler, join the spindle to the stepper motor , 1 stepper motor, in addition to 2 M3 x 25mm screws, 1 608zz bearings, for the correction and alignment of spindle rotation in its final part.

- **X-axis assembly.**

For the construction of the shaft, 2 300mm guide rods, 1 300mm trapezoidal spindle, 1 8mm / 5mm coupler, attach the spindle to the stepper motor, 1 stepper motor 2 M3 x 25mm screws for fixing the stepper motor the X-axis part, 1 brown for the spindle, since the X-axis parts received two LM12UU bearings for the linear guide for better displacement and alignment during the manufacturing process, 1 608zz bearings, for the correction and alignment of rotation of the spindle in its final part

- **Z-axis assembly**

The following components were used in this axis, 2 guide rods with 14mm, 1 trapezoidal spindle with, 18mm / 5mm coupler, joining the spindle to the stepper motor, 1 stepper motor 2 M3 x 25mm screws to fix the stepper motor to z-axis carriage part, 1 brown for the spindle, 2 LM12UU bearings, 1 608ZZ bearing for correction and alignment.

4.2. Electronic part assembly

The Shield V3 board is connected directly to the Arduino, there the pinouts will direct and where to place each pin of it, in addition to the drivers being embedded in the board, and with their calculated Vref and put in their tripods.

To calculate the reference voltage, it is necessary that the formula used is according to the step used within the project, in our case we will use 1/16 microsteps.

$$Vref = 8.Imax.Rcs \tag{5}$$

Vref is the reference voltage, coils constant = 8; *Imax* is the maximum amperage of stepper motors, and R_{CS} is the Resistor present in driver 4988.

Knowing that the stepper motors used are of dimensions that follow the Nema 17 standardization (SCHNEIDER, 2020), they have 3.8 kgf.cm of torque, step of 1.8° and maximum current of 1.2 A per phase, looking in the driver used we see that our resistor has 100mΩ or 0.1Ω then our used vref will be a value of 0.96V or 960 mV, following the equation.

In terms of power supply, the shield has its work within 12V to 36V, so it was chosen to work with an ATX source, and from the specifications, it was defined that the power supply must provide 12 V and 11.7 A . The power supply chosen was the standard ATX used in computers, with 264 W of power and voltage outputs of + 3.3V, + 5V, + 12V and -12V. The + 12V output provides currents of up to 14 A.

The tool is the part of the CNC machine that cuts the raw material. In a CNC router it is basically a high-speed motor that has on its axis a fixing rod (clamp) of the cutting tool called a milling cutter.

The spindle used in this work was the Black & Decker micro grinder with variable speed from 5,000 to 27,000 rpm and 180 W of power, 127 V. This is an inexpensive option that brings satisfactory results for work with light woods and polymers. If the user has a longer duty cycle, a more powerful motor or even another type of tool can be installed, such as a router.

The cutter is the part that is in contact with the raw material. Made to machine the material, they are built with a series of teeth and edges that cut the raw material in the direction of movement of the CNC machine, giving the desired shape. There are several types of cutters, for the most diverse uses and types of material, from roughing, drilling, finishing, engraving, among others.

After its assembly, it is necessary to install the GRBL firmware in the arduino IDE, so the procedure follows the reasoning. Initially, it is necessary to go to the Github website and download the GRBL 0.9J firmware, or whichever is more updated at the moment, after the download a zip file will be created on the computer's desktop, which must be unzipped.

Second step is to insert the GRBL file into the arduino library, to do that go in sketch and select the GRBL folder, now you can upload the firmware into your microcontroller, go to files> examples> grbl> grbl upload, then just click on transfer and wait for the completed information.

Universal CNC code sender was chosen for CNC control, as it is an easy-to-learn controller, and has a high command line, so it is necessary to install it on the computer, access the github website and download the zip file, and unzip the file on the desktop, the controller uses a java program for its execution, however it is only necessary to view the .windows file and double-click to start the program.

Having your follow-up, it is necessary to configure the GRBL control lines, in order to provide the machine with the working area limits, initial position and other commands, to view the settings, type in the $$ command line, from the $ 0 lines up to line $ 27 there is no need to make changes to the project, since no limit switches have been installed for the configuration.

The lines $ 100, 101, 102, are the resolution part of the machine so to make this calculation it is necessary to have the knowledge of the motor steps, the spindle step and the selected microstep configuration, as we are not using the Gt2 belt the formula this will be used.

$$Resolution = \frac{microstep \times stepmotor}{spindle\ pitch} \quad (6)$$

The obtained resolution for this case is 1600, so this value obtained will be placed in each line to configure the resolution of your machine, the verification of the high value means that we will obtain greater precision during its machining, so we can also resort to the use of measurement materials to make the necessary corrections to the values obtained .

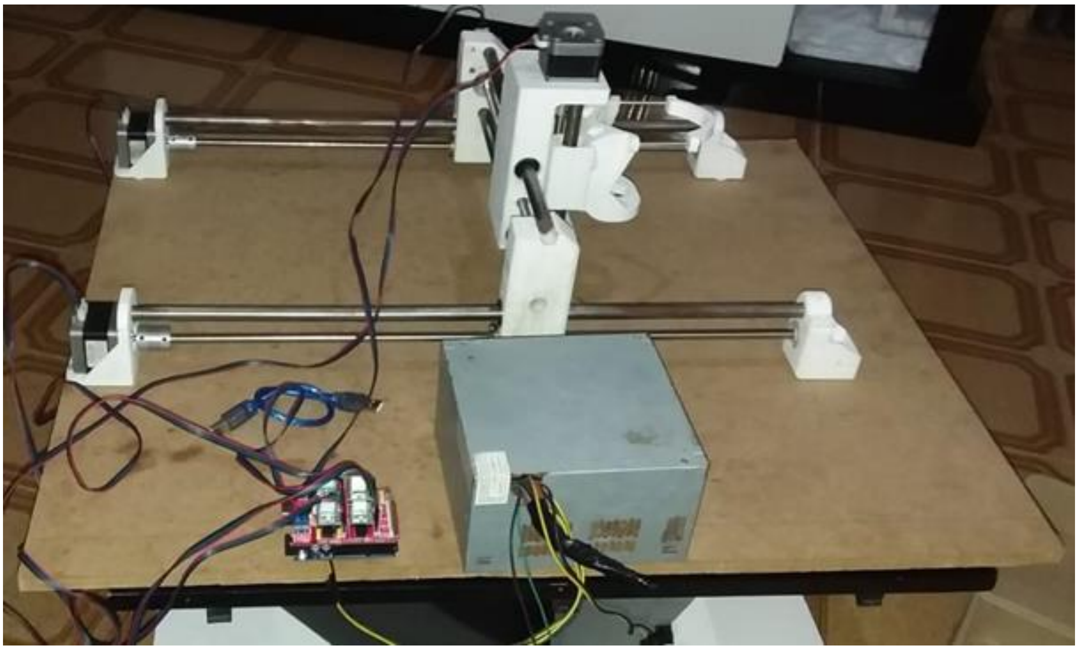
The lines $ 110 to $ 122 are referenced to the speeds of the stepper motor, so the speed of it will be selected by trial and error, in order to improve the resourcefulness of the machine and work with the highest possible speed without generating breakage of the milling material or that machining loses its quality.

The lines $ 130 to $ 132 refer to the dimensions of the machine proposed at work, so it is necessary to place the spindle measurements required by the author for the work to be carried out. All settings will be saved in the EEPROM (Electrically Erasable Programmable Read-Only Memory), so even if you turn off the Arduino, the settings will be kept so that it does not require configuration rework.

4.3. Final assembly

The assembly was completed with a total of three weeks, the steps were produced through the main structure in the case of MDF, alignment of the Y axes and fixation on the wood, X axis and Z axis, and after assembly of the stepper motors, installation of the electric components, so the machine is ready as figure 1.

Figure 1 - Final assembly



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