DOI: 10.48011/asba.v2i1.1293

4-Axis CNC Milling Machine for Production of Dental Prosthesis ⋆

Nei da Silva Paz Neto * **Marcus V. Americano da Costa** **

* *Post-Graduate Mechatronic Programm, Federal University of Bahia, 02 Professor Aristides Novis St., Salvador, BA-40210910, Brazil (nei_spn@hotmail.com).*
** *Department of Chemical Engineering, Federal University of Bahia, 02 Professor Aristides Novis St., Salvador, BA-40210910, Brazil, (marcus.americano@ufba.br).*

Abstract:
This paper presents the development of a 4-axis CNC milling machine for making dental restorations. The machine was developed to help spread knowledge about CAD/CAM to future professionals in healthcare area, including automation engineering. The CAD/CAM systems can be found in dental clinics and specialized laboratories with a high added value, as it brings reliability, precision, and speed to the prosthesis developed and, thereby, increasing the quality of the final product. With this high cost, not all dental professionals can have this type of technology. However, it is demonstrated the possibility of building these systems at a reduced cost and applying them to restorative dentistry. Therefore, this work results in instigating of the engineering education and training future professionals in mechatronics research with applications to the Odontology.

Keywords: Numeric control; dental prosthesis; milling machine; computer aided manufacturing; dentistry.

1. INTRODUCTION

In recent years, the goals of manufacturing systems have become more intense due to global competition in product development. In order to reach the market quickly, products need to be manufactured within time frames that are commonly used to produce prototypes (Koren, 2010). In this context, it is possible to see that the current market is even more competitive, aiming at an efficient production where the increase in demand and the delivery time has become inversely proportional quantities. Thus, process automation enters as ally of companies, directly impacting manufacturing processes in many aspects, such as reducing production time through the assistance of machines, increased productivity corresponding to increased demand, reducing costs, standardizing products and services raising its quality. The accelerated development of information technology and electronics has provided more than necessary tools for the improvement of production processes through automation.

Based on foregoing, the CNC (Computer Numerical Control) can be mentioned. This technology has been used in several sectors, such as mold making, making metal parts, laser cutting, 3D printers, milling, turning, drilling, among others, as demonstrated in the works of Habsi and Rameshkumar (2016), Cus et al. (2007) and Rodriguez et al. (2016). According to Deshpande et al. (2018), the CNC is a conventional machine that the operator, depending on the type of product desired, decides and adjusts several of its parameters such as feed, depth of cut and angulation, controlling the movements of the process manually. It is a specialized and versatile form of automation and its applications cover a great number of systems, although it was initially developed to control the movement and operation of machine tools.

It is possible to combine the system with computational platforms. The integration between CAD (Computer Aided Design) and CAM (Computer Aided Manufacturing) systems results in an improvement in production, making processes more accurate and products with a higher quality. This combined technology has been applied in different types of industry. CAM system machines raise the automation level of the production, minimizing manual labor and adding quality and value to the product.

In the work of Spilling (2014), Lopes (2003), Moreira (2015) and Martins (2016), it is notable the development of numerically controlled machines and CAM systems with different purposes, with a focus on prototyping, rapid prototyping, self-improvement and even manufacturing additive. In this context, odontology is an important area on which the computer design, automation and manufacturing process have been applied.

Mathematical modelling and simulation techniques have been employed to evaluate dental implants. In the paper of Detolla et al. (2000) and Peixoto et al. (2017), the importance of computer-aided design and the finite element

⋆ The authors are grateful to the Foundation of Support for Research of the State of Bahia (Fapesb) for the research grant that helped to carry out this study.

methods (FEM) applied to dentistry draws the attention of researchers in this area. FEM makes it possible to understand the stresses along the surface of an implant and on the bone surfaces around it. The technologies served to improve the shape of the implant and the location of its installation in a patient's mouth, also serving to assist in the design of the restoration minimizing efforts.

In particular, the history of CAD/CAM systems applied to dentistry dates back to the late 1970s, when the CAD/CAM systems applied to dental restorations start with the work of Francois Duret, Bruce Altschuler, Wener Mormann and Marco Brandestini (Liu, 2005).

In 1984, Duret developed the Duret System, which was marketed as the Sopha Bioconcept System, demonstrating the ability of CAD/CAM to generate single parts from complete restorations. However, this system was not successful in the dental market due to its complexity and cost. The first commercial CAD/CAM dental system available was CEREC, developed by Mormann and Brandestini (Liu, 2005). This system remains today one of the main systems used in several laboratories and clinics around the world.

CAD/CAM systems in dentistry offer the manufacture of procedures with standardized quality in a short period of time. They have the potential to minimize technical inaccuracies and reduce the risk of infectious contamination. This allows the application of new materials with high resistance and excellent biocompatibility combined with adequate mechanical strength, provisions for aesthetic designs, excellent fit accuracy and longevity. However, these advantages must be balanced against the high initial cost of CAD/CAM systems and the need for additional training (Mantri and Bhasin, 2010).

The difficulty of obtaining accessible machines and the need to foster practical knowledge in the development and application of CAD/CAM systems is mainly due to the fact that today the main technologies are owned by large companies in other countries. In Brazil, most papers and works involving milling machines are focused on making parts or printed circuit boards and most of them having only 3 axes (X, Y and Z).

Thus, this paper takes as basis and motivation the project RepRap realized by Bowyer et al. (2011), where the objective was to develop a prototyping machine that had the ability to reproduce its own parts. The RepRap project enabled the development of additive manufacturing technology. The research promoted the development of low cost 3D printers in which, until that time, 3D printers were developed only by large companies with huge amount of resources. On the other hand, its applications are still limited as there is a need to study materials, reduce printing time, print quality and other variables.

Currently, there are several types of 3D printing and 3D printers with low cost that can be applied in education from elementary school to university assignments. Thus, it is possible to observe that the research brought results such as the increase in the number of researchers and related projects, improving technology and making 3D printing increasingly accessible to everyone.

Therefore, in order to encourage and consolidate the knowledge of dentistry and mechatronics areas, a small 4 axis CNC machine of low cost capable of milling dental prostheses is proposed in this work. This project motivates the dentists and, especially the engineering community, since many of them are unable to access to the machines because of their high cost. However, now they are able to access a low-cost system to manufacture their own restorations or perform a prototype of them in a chairside manner (in the clinic). Unite theory and practice brings us important improvements to engineering education (de Araújo et al., 2020). The machine is developed based on open sources projects for 3D printers and 3 axis CNC milling machines, designed using the software like Sketchup and Fusion 360, and using materials like aluminum and PLA (Polylactide).

The paper is organized as follows: In section 2, the whole mechanical design is developed. In Section 3, the choice of electronic components and their applications in the mechatronic system are explained. In Section 4, it is presented the computational tool used to manage the machine in addition to the CAM program. The results obtained are discussed in Section 5, and the paper ends with the conclusions in Section 6.

2. MECHANIC

2.1 Process description

The materials and methods used for the development of the proposed milling machine is explained in detail in this section. As can be seen in Figure 1, the machine's operating cycle consists of five main steps:

(1) Select the material (raw material) that is used to make the part and place it on the machine manually, attaching it to the holder to leave the blank fixed.
(2) In the CAM program, the tooth file with the .stl extension is imported to perform the machining path calculation and select tools required by the strategy defined by the operator.
(3) After that, the operator generates the text file with the necessary G code by selecting the post-processor (Mach3) that is responsible for converting the machining paths and tools used in the G code language.
(4) Interpreted by a program, Mach3 is responsible for executing line by line of code and sending the commands to the controller board which operates the movement of the axes by sending signals to the stepper motor drivers.
(5) Finally, the prosthesis milling process starts.

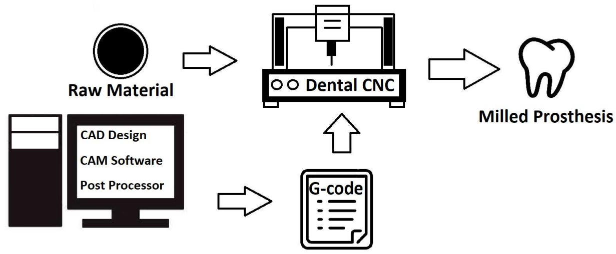

Figure 1. Flow of the dental CAD/CAM system.

As it will be seen later, all the machining procedure realized by the proposed project, as well as its functions and operations, contain multidisciplinary approaches such as mechanical, electrical and electronics, and computational (hardware and software).

2.2 Mechanical Development

The 3D design of the machine is developed for adjustments and measurements using Sketchup, a CAD program widely applied in several areas, such as Architecture, Civil, and Mechanical Engineering. Each piece is designed in the program based on the technical drawing provided by its manufacturer. Thus, it is possible to perform dimension adjustments, axis movement tests and fix position of the parts. Other important advantage of the CAD program is the prediction of the final result of the machine. The 3D model drawn is shown in Figure 2.

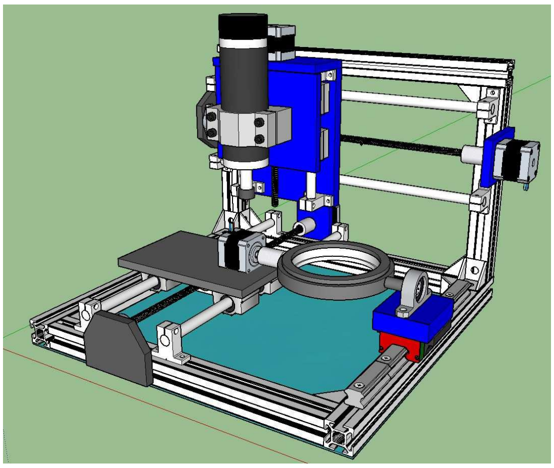

Figure 2. Machine developed in the CAD software Sketchup.

The main material to compose the structure of the machine is aluminum, in this case structural aluminum profile. A desktop type (small size) machine is proposed in this work, reducing its cost since there is not a high quantity of the aluminum profile. The choice of this profile is due to the fact that the CNC is a machine that is in a constant motion. Therefore, a rigid material with low flexibility and excellent fixation is needed to compensate the dynamic and static efforts. Furthermore, among other applications, the structural aluminum profile is used for small and medium-sized industrial machines, eliminating the need for welding as it is assembled with screws and nuts.

The possible parts and pieces that can compose the machine are analyzed considering its specific functions in order to achieve an appropriate final result. In this case, it is necessary to study the machine elements and the main parts and pieces that make up a numerically controlled milling machine. Thus, the types of machine elements are studied, such as fastening elements (bolts and nuts), support elements (bearings and linear guides), and transmission elements (belts and pulleys). A major requirement for achieving success in a milling system is ensuring the linearity of the machine axes.

For the development of the project, the machine elements that are chosen are components commonly used in CNC machines and found easily for sale by specialized companies. Some components chosen are KFL08 and KP001 bearings, flexible coupling, MGN12H linear guide, Scs12uu pillow block, Sk12 support, among others. The linear ballscrew used on the machine has a diameter of 8 mm with a thread pitch of 2 mm, which reflects on the machine speed and precision. The lower the thread pitch, the less speed the axis have, but with more precision. If one step control is given with the motor shaft coupled to the linear ballscrew, the axis advance is given by 2 mm/200 = 0.01 mm of advance per motor step. This implies that the minimum distance that the operator can expect the machine to move is 0.01 mm. The choice of the thread pitch is taken on the basis that CAD/CAM systems are applied to the prosthesis with the objective of gaining precision compared to conventional manual methods developed by prosthetics.

Finally, some parts of the mechanical system and the machine also are drawn by a CAD software and produced by a 3D printer that uses the FDM (Fused Deposition Modeling) printing process. The raw material is the PLA (Polyactide), a biodegradable material widely used in 3D printing. Most 3D printers are able to work with PLA, as compared to other materials they need lower extrusion and table temperatures in addition to having high strength.

3. ELECTRIC/ELECTRONIC

The machine axes must move the tool to the necessary positions and carry out the roughing process of the raw material, milling the piece previously drawn in the CAD program. For this, a controller that receives commands from the machine program and sends signals to the stepper motors drivers is required. In this work, it is proposed the Breakout Board, which is a controller widely applied on CNC machines. The scheme is illustrated in the electric wiring diagram in Figure 3.

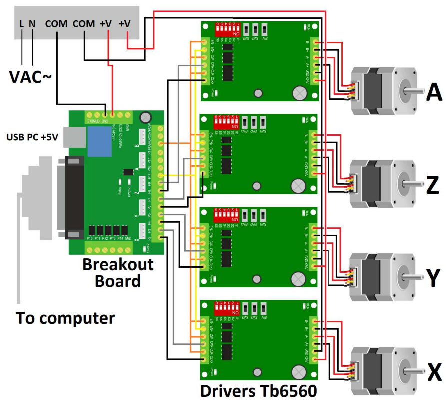

Figure 3. Eletric Wiring Diagram.

The Breakout Board has output for up to 5 stepper motor drivers and is compatible with the Mach3 program, the program responsible for interpreting the G code and sending the signals to the controller. Its communication is given by the standard parallel port and the board has inputs for limit switches, emergency buttons and whose indicated input voltage varies between 12-24 V. KH56JM2U109 motor by Nidec Servo is used as stepper motor in the four axes of the milling machine. Although it is a standard Nema 23 motor with 1.8 º pitch, 2 A current, torque of 0.4903 $N{\cdot}m$, unipolar, can be employed in bipolar configuration in this project.

The power supply has bivolt input of 110-220 V, output 12 V of voltage, and 10 A of direct current. This source serves to power the stepper motors, where each one needs 12 v 2 A. Thus, assuming a situation in which the four axes are moving simultaneously and with maximum efforts, it is required 12 V and 8 A equivalent to 24 W of power per motor, totaling 96 W of necessary power. It is employed the XZ-120-12 power supply with 120 W of maximum power compatible with the machine design. Moreover, Er11 spindle has its own power supply, as it needs 110 VDC and 500 W of power given by a bivolt source with speed regulation by PWM (Pulse Width Modulation) connected to a potentiometer, as shown in Figure 4.

Figure 4. Kit spindle Er11/power supply/spindle clamp.

The driver is responsible for the communication between the controller and the stepper motor. The driver chosen to compose the project is the Tb6560 3 A based on the Toshiba 6560 IC and developed to control stepper motors with high performance. Among the characteristics, the driver has an operating voltage between 10-25 VDC, protection against undervoltage and overcurrent, rated current of 3 A with peak of 3.5 A, and has the following modes of operation: 1/1 steps, 1/2 steps, 1/8 steps, and 1/16 steps which influence the accuracy of the machine depending on the operation to be used.

4. COMPUTER AIDED MANUFACTURING

It is relevant to mention that to coordinate the functions and movements, it is indispensable a computational platform of communication between the operator and the machine. Thus, it is proposed the Mach3, a program developed to manage and supervise machines such as milling, lathes, laser cutters, among other numerically controlled machines. Using a graphic interface (See Figure 5), the operator can apply the essential settings for a CNC machine, such as: speed adjustment, steps/mm, machine referencing, displays to visualize the position of the axes, etc.

Still, Fusion 360, a software developed by Autodesk (an important American corporation that makes software for technological industries), is applied on this project. As can be seen in Figure 6, the program allows the creation of 2D drawings and 3D modeling in addition to preparing the project developed for production, either by additive manufacturing or milling. Fusion 360 also has tools for

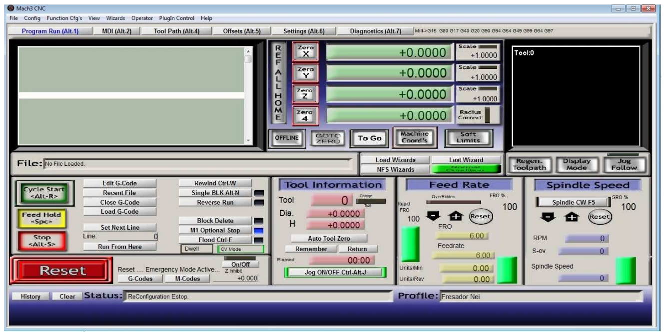

Figure 5. Main screen of the mach3 program.

modeling objects previously scanned from importing files with .obj and .stl extensions. Fusion 360 is a CAD and CAM tool which allows to develop the object and prepare it for manufacturing. This tool is essential for activities whose goal is to develop machining paths based on imported parts with (.stl extension) and to generate the G code necessary to the machine parts. After configuring all the parameters needed for machining, the operator must select the post processor Mach3. Finally, the Fusion 360 transforms all parameters and variables in programming lines that are interpreted by Mach3 that sends the signals to the controller.

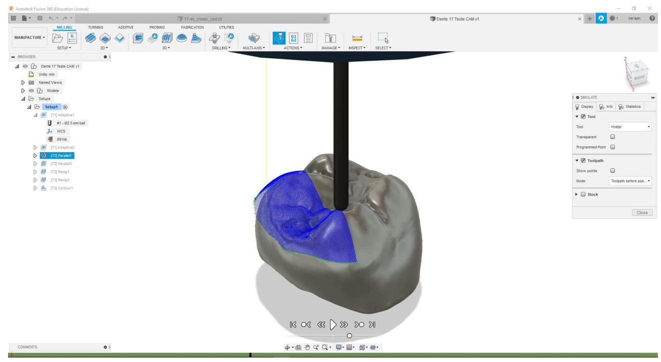

Figure 6. Fusion 360 milling simulation.

5. RESULTS AND DISCUSSION

In this section, the results of the 3D printing of the parts referring to the mechanical part of the machine, assembly of the structure and electrical panel are presented. Also, the settings made on Mach3 and the machining strategy developed to milling the restorations is covered in detail in order to demonstrate the development of the proposed machine.

As discussed in Section 2, many parts commonly used in CNC machines compose this project, and other parts were being developed to suit the project. These are designed in a CAD program and printed in PLA. The PLA used is that of the Fortek brand which has 1.75 mm in diameter. Approximately 1330 g of PLA filament is necessary to print the mechanical structure parts which took 94 hours and 47 minutes of time.

The printer has a working area of 235x235x250 mm and alternative layer resolutions from 0.05 mm to 0.35 mm, which are ideal for printing several pieces with varying sizes that the project has. The minimum resolution of 0.05

mm is useful in some cases for that some parts have a great final finish, aiming easy fitting without the need of manual finishing after printing. The extruder table and nozzle temperatures used for the PLA Fortek Gray filament were 185 °C and 60 °C, respectively. In Figure 7, it is shown the drawing developed from the base for the X and Y axis motors and their respective 3D printing performed beside.

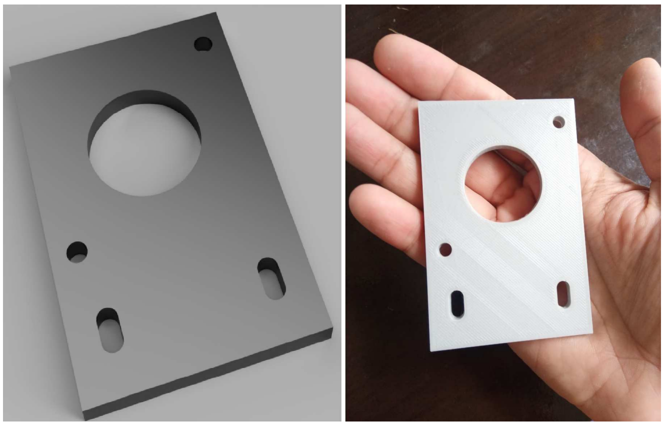

Figure 7. Left: 3D design of Motor X and Y Base/Right: 3D printed piece.

The machine developed in this work is shown in Figure 8, which follows the operating principles of any numerically controlled machine, starting from the idea of using CAM software to generate the necessary programming lines (G code) to position the axes and move them. The structural aluminum profiles were cut with the aid of a mono-cut saw that helps in fixing the profile and in the linear cut resulting in a straight surface at the ends of the profile.

The profiles were aligned and screwed using angle brackets for fixing. It was not chosen to weld the profile joints for the sake of machine maintenance and may be necessary for the operator to disassemble the machine in order to align some axis or modify any existing part in the set. The alignment of the axes is a concern during the assembly of the mechanical structure, since the machines need to have completely linear movements. This helps in the precision of the machined parts and in the effort required by the motor to rotate the spindle coupled in its axis.

For tests during assembly, a microcontrolled circuit was made using the Arduino Nano and an Easydriver A3967 stepper motor driver. With the circuit, it is possible to perform the necessary movements to check the axis alignment. The machine has final dimensions 410 mm lenght, 410 mm width and 375 mm height.

During the tests of movement of the X axis (A axis follows while the axis is moved), it was observed a small gap between the ends - the base of the X axis where the stepper motor of the A axis is moving and the opposite end where the bearing is located. Thus, the linear guide does not follow the movement causing a shear stress in some parts.

It is extremely important to correct this fault, since the set must accompany the movement simultaneously. First, it was thought that replacing the flexible coupling by a rigid coupling would solve it, but that was not the only reason for the problem. Moreover, the diameter of the holder ends are very thin and the infill used to fill the part

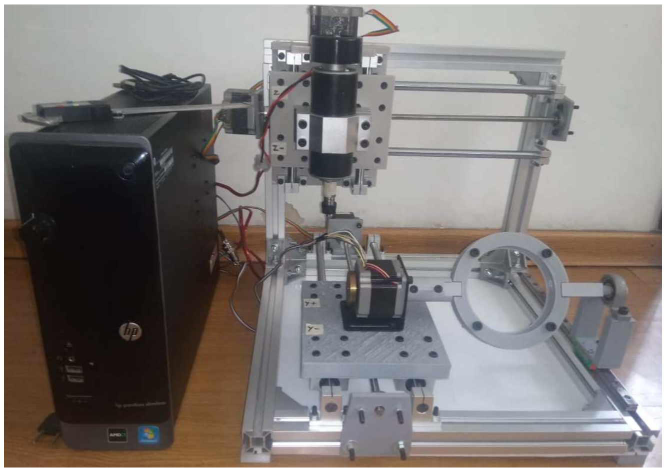

Figure 8. CNC machine assembled.

internally was 20%. Therefore, increasing the diameter and the percentage of infill to 80%, the flexion that occurred in the part ceased. Besides, a coupling was designed to join the motor-A axis to the holder.

The developed part improved even more the linearity along the axis during the movement, but other problems appeared. The coupling did not support the effort resulting from the torque applied, when screwing it to the motor axis, causing a rupture of its layers as shown in Figure 9. A solution for this is to make the coupling in aluminum using a lathe.

Figure 9. Damaged coupling.

Following the diagram of the electrical circuit developed to make the necessary connections between the breakout board and the drivers of each stepper motor in addition to their proper electrical connections, the complete circuit of the machine with its components was assembled inside a PC (Personal Computer) cabinet with their power supplies. The GX16-4P connector was applied to connect the stepper motor of each axis to its respective driver. GX16-4P has an excellent connection between male and female with a thread to ensure the connection, great electrical insulation and easy soldering of its terminals. The circuit mounted is shown in Figure 10.

After assembling the mechanical structure, electrical panel and connecting the motors to the drivers, it is necessary to make the first configurations in the Mach3 software. As an example of the configurations performed, it is possible to mention the standard units used, which is set in millimeters, the address of the computer's parallel port so that the program can communicate with the controller board, in addition to the configuration of steps per mm.

The steps per mm formula is found in the controller's manual which is $Steps\ per\ mm = \frac{(360/1.8)\cdot x}{l}$, where x is

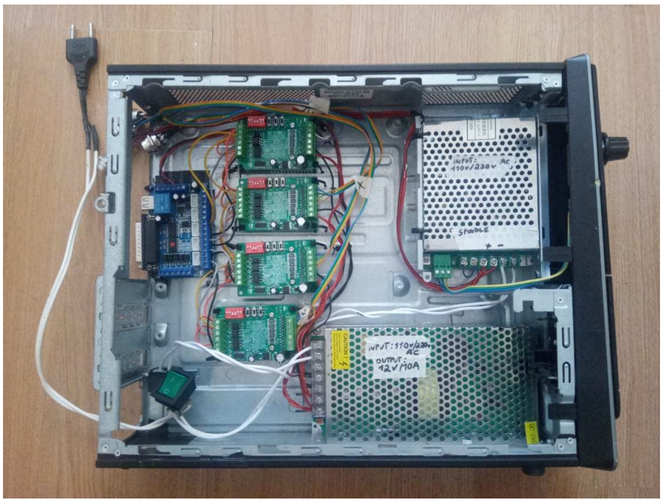

Figure 10. Electric panel of the milling machine.

micro steps, and l is spindle thread pitch. Thus, the value calculated for the passors is $Steps\ per\ mm = \frac{(360/1.8)\cdot 2}{2} = 200$ steps per mm, which indicates that the motor has to take 200 steps for the axis to advance or retract 1 mm. Subsequently, maximum feed calculations is performed for each axis separately.

With the CAM tool of the Fusion 360 software it is possible to create machining paths which is the path that the milling cutter will pass to cut the raw material and mill the restoration. To carry out the first tests, the machining strategy being developed is divided into the following parts:

(1) Roughing 1 (2.5 mm diameter cutter with spherical top, A Axis: 0°).
(2) Roughing 2 (2.5 mm diameter cutter with spherical top, A Axis 180°).
(3) Initial finishing (1.0 mm diameter cutter with spherical top, A Axis: 0°).
(4) Initial Finish 2 (1.0 mm diameter cutter with spherical top, A Axis 180°).
(5) Finishing 1 (0.6 mm diameter cutter with spherical top, A Axis: 0°).
(6) Finishing 2 (0.6 mm diameter cutter with spherical top, A Axis 180°).

The A axis assists in reducing the movement of raw material by the operator for machining the sides of the piece, limiting only the tool change between steps. Besides that, more detailed machining of parts with complex anatomy with restorations is allowed if the machining path settings are well defined before post-processing.

Finally, the initial tests will be carried out on a universal block used in dental CAD/CAM systems. The material is 98.5 mm in diameter and 16 mm thick. Wax is a material commonly used in restorative dentistry, as it allows the manufacture of ceramic parts (lithium disilicate) applying the injection process and metal parts by means the foundry to make them, in addition to being an easy-to-machine material.

6. CONCLUSION

This paper presented a 4 axis CNC milling machine for making dental restorations. A CNC machine of low cost was developed using commercial parts and the aid of additive manufacturing. The proposed project seeks to instigate the study of engineers and researchers in the development of automatic equipments with reduced cost applied to restorative dentistry, aiming at the greater access of professionals to this type of technology. Given the lack of studies in the scientific literature related to CNC machine applied on odontology, the current research provides an innovative project that can promote the creation, production, and thereby the increase in the number of machines available to dental professionals. Moreover, it is possible to apply the system in education and training of future professionals of the dental prosthesis, and mainly to stimulate automation engineers working in healthcare area. The machine is currently in the settings and adjustments phase to later starts the test phase of restoration process.

REFERENCES

Bowyer, A., Jones, R., Haufe, P., Sells, E., Iravani, P., Olliver, V., and Palmer, C. (2011). Reprap: The replicating rapid prototyper. *Robotica*, XXIV, 177–191.

Cus, F., Zuperl, U., and Gecevska, V. (2007). High-speed milling of light metals. *Journal of Achievements in Materials and Manufacturing Engineering*, XXIV, 357–364.

de Araújo, R.G.B., Americano-daCosta, M.V., Joseph, B., and Guzmán, J.L.S. (2020). Developing professional and entrepreneurship skills of engineering students through problem-based learning: A case study in brazil. *International Journal of Engineering Education*, 36, 155–169.

Deshpande, S.V., Karthik, P.U., D, N.K., Kumar, D.V., and Badrinaryan, D.K.S. (2018). Design and fabrication of 3-axis CNC milling machine. *International Journal of Engineering Research and General Science, Nepal*, VI, 34–38.

Detolla, D., Andreana, S., Patra, A., Buhite, R., and Comella, B. (2000). The role of the finite element model in dental implants. *Journal of Oral Implantology*, XXVI, 77–81.

Habsi, R. and Rameshkumar, G.R. (2016). Design and fabrication of 3-axis computer numerical control (CNC) laser cutter. *International Journal of Multidisplinary Sciences and Engineering*, VII, 7–16.

Koren, Y. (2010). *The global manufacturing revolution: Product-process-business integration and reconfigurable systems*. John Wiley & Sons, New Jersey.

Liu, P.R. (2005). A panorama of dental cad/cam restorative systems. *Compendium of continuing education in dentistry*, XXVI, 507–513.

Lopes, G.T.F. (2003). *The Design of a CNC Mill for Product Prototyping*. Master's thesis, Grand Valley State University, Grand Rapids, Michigan.

Mantri, S.S. and Bhasin, A.S. (2010). CAD/CAM in dental restorations: An overview. *Annals and Essences of Dentistry*, V.II, 123–128.

Martins, S.R.M. (2016). *Um Sistema CAM para prototipagem rápida por adição de camadas*. Master's thesis, Federal University of Bahia, Bahia, Brasil.

Moreira, A.F.L. (2015). *Máquina-Ferramenta CNC para Gravação.* Master's thesis, Faculty Engineering of the University of Porto, Braga, Portugal.

Peixoto, H.E., Camati, P.R., Faot, F., Sotto-Maior, B.S., Martinez, E.F., and Peruzzo, D.C. (2017). Rehabilitation of the atrophic mandible with short implants in different positions: A finite elements study. *Materials science & engineering. C, Materials for biological applications*, 80, 122–128.

Rodriguez, J., Ikonomov, P., and Choudhury, A. (2016). Development of a 3d printer and CNC milling desktop machine for manufacturing labs. *American Society for Engineering Education - Conference & Exposition*, 123rd Annual, 1–9.

Spilling, T. (2014). *Self-Improving CNC Milling Machine.* Master's thesis, University of Oslo, Norway.