

DEVELOPMENT OF A MULTIFUNCTIONAL DIDACTIC CNC MILLING MACHINE WITH OPEN ARCHITECTURE

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Abstrac.: *At Univali, the Computer Engineering course has among its objectives the development of systems whose implementation are designed through integration of hardware and software systems. Machine tools have been automated and the automation is given by this integration between hardware and software. A previous project allowed to design a milling machine, applied to rapid prototyping. The obtained results improve the machine to build parametric surfaces designed in CAD tools. The natural progression of this machine is fit it to numeric control systems, common to machine tools used in automated production in industry. This paper deals with the design and implementation of a high level didactic programming system for the milling machine, using G-code programming to reach this objective. The didactic software is composed for a mathematical post-processing system and a set of procedures that allow interfaces with CAD tools and circuit boards design tools. Another interface allows automatic programming of the machine in G-code. The set of function allowed the milling machine to produce milling surface and perforates circuit boards. Didactic-pedagogic issues are discussed in this paper, because this milling machine will be used in practical classes Computer Engineering and Industrial-Mechanical Engineering of Univali. Another relevant aspect is the open-architecture programming, which permit future researchs projects to improve the system. Final results are presented in two parts manufactured by CNC milling: a free surface milling and a perforated circuit's board.*

Keywords. *Computer numerical controlled – CNC, Hardware-software interface, G-code.*

1. INTRODUCTION

The pedagogic practice of many disciplines from engineering courses focuses on the necessity to provide to students practical experiences at laboratories (Simas *et al.*, 1997). Laboratory experiences, allow students to face up to the theory developed at classroom with intrinsic limitations to the practical study (Franklin and Powell, 1989). In this case, it's up to teacher develops education strategies to complement its classes.

The Univali (Universidade do Vale do Itajaí) has a research line dedicated to develop low coast laboratory equipments to application on practical classes at its graduate courses: Computer Engineering and Industrial-Mechanical Engineering (Ramirez *et al.*, 2005) (Velooso and Ramirez, 2003). The efforts realized have showed positive result on the student's academic performance (Teive, 2007). One of these lines of equipments is related with industrial automation.

The modern automation process uses models created in computer to design parts and products. The product's viability created in computer depends on a physical analysis of its characteristics and is necessary to build a prototype of the computationally designed model (Kumar *et al.*, 1996).

There are many processes that allow building a prototype from a model, one of this processes is called rapid prototyping.

The models designed by computer are building for automated machines that from a process, like milling, becoming the physically real model of a project, creating the product prototype.

The rapid prototyping is defined as an activities aggregation that permits assemble physical three-dimensional models direct from a CAD/CAM drawing (Liou, 2006).

The rapid prototype systems have a big interest at new products development. In an initial stage, they are useful to test the design and functionality of the projected components, soon after its possible to obtain, from them tools for production and with lower costs and quickly, pre-series to test the components and design of tools for production. The rapid prototyping should be considered as a basic tool in a system of simultaneous engineering (Liou, 2006).

The axis number of a milling machine indicates its potential to construction of a product. Usually milling machines has 3 to 5 axis defining its mobility and consequently its limitations. At Univali exists a small milling machine which is being realized an automation process through another research project. This article presents one of this contributions for the automation process, developing a trajectory planning system using modern algorithms such as CADG tools (Farin, 1998) doing it operate as a CNC machine.

A CNC machine is electronic equipment derived from numeric controlled systems commanded by programs implemented with high-level languages (Lynch, 1993). The programming type most used is based on preparatory command known as G-code (Machado, 1989) (Omirou and Barouni, 2005) (Lee, 2006).

At this milling machine a first research was developed and post-processing routines were developed (Reis *et al.*, 2008). In that paper a trajectory planning was made aiming to build with the milling machine surface prototypes designed in CAD software.

This research has the objective of developing routines to compile rapid prototyping programs to G-code to use it at the milling machine. With this implementation will be possible to use the milling machine in others laboratories classes, including disciplines from production area of Industrial-Mechanical Engineering and software area of Computer

Engineering. The open architecture characteristics allow futures projects to be developed in this equipment. The principal aspects of the software and of the hardware are discussed and practical results are presented to validate the proposed post-processing software. The validation are based on a real construction of a free form surface is manufactured by CNC machine and a perforated circuit-board.

2. RAPID PROTOTYPING

The term rapid prototyping means a set of methods and technologies used to fabricate physical objects directly from data generated from computer aided design – CAD (Novaski, 2000).

Part of rapid prototyping process are milling and turning. This processes, despite being classical and many times considered old, they have financial and technological advantages mostly valid for complex components production, which are necessary material removal for building internal cavities, such as to fabricating turbines components (Novaski, 2000).

Stand out as rapid prototyping machines, the CNC milling machine with 3 or 5 axis, typically used on flexible manufacturing in industrial scale (Morris, 1995).

The rapid prototyping allow the designers to quickly create tangible prototypes from their designs, instead of two-dimensional pictures. These prototypes are visually helpful during prior discussions about the project with employees and customers. It is expected and in fact, it is estimated that the time and costs economy provided for the application of rapid prototyping techniques on the model construction is around 70% to 90% (Novaski, 2000).

Rapid prototyping techniques also permit to obtain high level quality parts of mass production, its called rapid manufacture. In fact, the rapid prototyping is the best process of manufacture, when is needed to produce small lots of parts and/or in case of complex components.

The term “rapid” associated to this processes is relative. Furthermore, the construction of some prototypes can take from 3 to 72 hours, depending of the object size and its complexity. These processes are faster than conventional methods, such as machining, which could take days or even months to build just one prototype.

Rapid prototype process can be defined as a manufacture performed by layers, in other words, consists in a process where some specialized algorithm “slices” the CAD component model in many layers according with a series of specifications, this layers are arrange one above another. Next, through fabrication process, such as milling, the component is built according to a set of trajectories previously programmed. The evolution of computers and processing capacity allowed this interaction between CAD designs and prototyping process could meet the quality and efficiency specifications (Sarma and Dutta, 1997).

The fabrication process of a prototype through milling basically consists of three steps:

- Post-processing and interpretation of data from CAD design;
- Mathematical model of the project;
- Computation of trajectories for achieving the milling process.

The interpretation of CAD data is usually made from IGES project files (Jacobs, 1998). IGES files are the basis for equating mathematical curves and surfaces of the project components.

3. TRAJECTORY PLANNING

Modern techniques from CAGD area (Computer-Aided Geometric Design) (Davies and Qiulin, 1987), (Farin, 1998), (Wysk *et al*, 1998), (Simas, 2008) have enabled the development of specialized and optimized algorithms to calculate specific parallel trajectories for fabrication process such as welding and milling.

From a didactic view, prototyping is usually applied to parameterized surfaces that facilitate computational modeling. To calculate the milling trajectories, are used formulations that enable the measurement of local properties of a point on the surface. These properties are translated into measurements of normal and tangential vectors, and these variations on the surface (Farin, 1998).

There are methods that allow the formulation to obtain these data, such as Spline, Bezier and B-Spline (Davies and Qiulin, 1987). The formulation of these areas is based on measurements of specified points and local properties on these points such as vectors of inclination. This paper presents a formulation based on B-Spline patches. Other methods have equivalent formulation, because they use the same references, but one advantage of the method of B-Spline over the Bezier method is the fact that changing only a control point, the entire Bezier surface needs to be recalculated, with B-spline changing a point causes only local effect, there is no need to recalculate the entire surface (Zeid, 1991).

The B-Spline curves provide an effective method for generation of curves defined by polygons. In fact, the B-Spline curves are a generalization of Bezier curves. In addition to sharing the most features of Bezier curves, the B-Spline has some advantages. Besides the ease of modeling, also appeared in Bezier curves, with B-Splines is possible the local control of the shape of the curve instead of the global control provided by Bezier. Unlike the method of Bezier, the theory of B-Spline curves separates the number of control points of the curve degree. The B-Spline surfaces are an extension of B-Spline curves, but in two parametric directions. A set of points arranged in a two-dimensional matrix

represents the control points of that surface. As with curves, the degree of the surface is independent of the number of points of control (Zeid, 1991).

The milling trajectories in rapid prototyping are obtained from the calculation of parallel paths on the surface. The acquisition of parallel paths aimed at the optimization of the process parameters.

The trajectories planning on parameterized surfaces can be facilitated using the parametric space as a reference for calculating the paths that the tool should follow. There are at least two basic techniques to generate trajectories on free surfaces: isoparametric (Toledo, 2000), which the paths are obtained keeping constant distance on the parametric space, and the scallop-height, (Sarma and Dutta, 1997) (Suresh and Yang, 2004) where the paths are calculated maintaining the geometric distance on the surface. In this work is used the isoparametric technique to planning trajectories on the Bezier parametric surface.

3.1. Isoparametric trajectories

A point in three-dimensional space on a parameterized surface has the general formulation given by Eq (1). (Davies and Qiulin, 1987) (Zeid, 1991)

$$r(u, v) = \begin{bmatrix} x(u, v) \\ y(u, v) \\ z(u, v) \end{bmatrix} \quad (1)$$

where u e v are parameters that describe the surface and $x(u, v)$, $y(u, v)$ and $z(u, v)$ are coordinates of a point on the surface calculated as functions of parameters u and v .

The equating of surfaces by Bezier formulation ensures continuity of the boundaries between surface patches. In the case of machine tools just check the continuity of orders 0, 1 and 2 (The continuity shows that the derivatives of order 0, 1 and 2 are kept constant in these limits). These continuities are guaranteed if the parametric formulation has order three, in other words, surfaces made with polynomials of order three satisfy the continuity conditions (Qiulin, 1987).

The parameter u and v usually are normalized to vary in the range [0,1]. The formulation of a Bezier surface is given by Eq(2). (Davies and Qiulin, 1987).

$$r(u, v) = \sum_{i=0}^{n_i} \sum_{j=0}^{n_j} P_{i,j} N_{i,j}(u) N_{i,j}(v) \quad (2)$$

where $N_{i,j}$ is the characteristic polynomial of B-spline.

A path on the surface can be obtained, for example, letting the parameter u with fixed value and by varying the parameter v . Thus it is possible to obtain a sequence of points that define a path.

By varying the parameter u to another fixed value and once again change the parameter v is obtained a second path which in the parametric space is parallel to the previous. These paths are called isoparametric (Toledo, 2000).

The distance between the paths on the surface is obtained by adjusting the distance between the parameters. In thinning operations, as desired for the process, of rapid prototyping this methodology for obtaining this paths is appropriate, in opposite to process of coating by welding, where the distance to the surface must be controlled (Simas, 2008).

4. NC PROGRAM

A NC (Numerical Control) program is composed of a series of sequential instructions related to the piece to be manufactured. Each preparatory instruction is specified in a format that can be accepted, interpreted and processed by a CNC system, currently known as "G code", available in standard EIA RS-274 and ISO 6983-88 (Iso, 1981)(Pereira, 2003).

To make a CNC machine actuate, the NC commands are used, through them the information necessary for the manufacture of a particular piece is extracted. A command line program in a CNC may have information on the type of movement (rapid movement, linear or circular interpolation, etc.) spatial information (position, speed, etc.), miscellaneous information (on/off, miscellaneous features). To generate the NC commands, it's necessary to take care of machine limitations, the characteristics of the CNC and the data for the part to be produced.

Among the advantages of CNC programming stand out: (Lynch, 1993), (Gibbs and Crandell, 1991) (Machado, 1989)

- High productivity;
- Versatility in production;
- Decrease the amount of tailings;
- Reduced programming time;

- Ease of programming machine tools;
- Reducing the length of programs;
- Reducing the setup machine tools;
- Reducing the cycle time of machine;
- Decrease of the involvement of operators.

Modern CAD systems allow the post-processing of geometric entities presents on drawings in “G” programs specifics for one machine.

5. CAD SYSTEMS

CAD systems, (Computer Aided Design) usually are software that uses computer graphics techniques for interactive way. The use of CAD systems provides several advantages, such as: (Souza, 2007)

- Increase the productivity of the designer. CAD systems help the designer to reduce their time to design, editing, correcting and updating;
- Improves the quality of the design allows the designer more run, creating analysis and considering a greater number of alternative designs;
- Improve the documentation of designs. The intense production of a CAD system is superior to manual, with minor occurrence of errors;
- Creation of a database related to industrial materials, dimensions and manufacturing data.

6. MILLING MACHINE

Aiming for a low cost milling machine was built using easy access components and adequate precision for teaching applications. The milling machine used in this project is shown in Fig. 1.



Figure 1. Milling machine built

Each axis of the milling machine is presented as a prismatic joint and is powered with unipolar stepper motor. The Figure 2 depicts each of these axes.

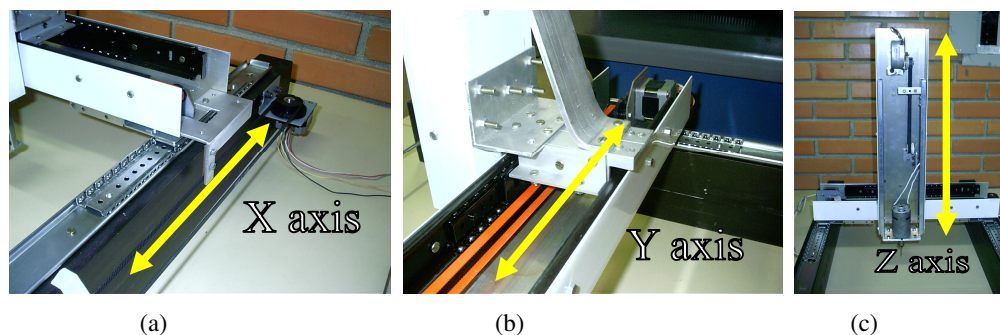


Figure 2. Introducing each axis: (a) 'X' axis; (b) 'Y' axis e (c) 'Z' axis.

The milling machine was built with "U" shapes made with aluminum and recycled step motors. The prismatic joints were implemented using sliding drawers as shown in Fig. 2-a. Whole structure was mounted on a laminated card for easy transport.

The milling machine transmissions were built using recycled toothed belt pulleys.

7. UNIPOLAR STEPPER MOTOR CONTROLLER

To drive the engine was used to control an unipolar stepper motor controller, model SMC-U-V XYZ 1:30, the controller is depicted on Fig. 3.



Figure 3. Unipolar stepper motor controller, model SMC-U-V XYZ 1:30

This controller works in CNC mode applied to CNC machines. The controller has an input control standard STEP/DIR/ENA, and the configuration of current and resolution steps is via jumpers for each motor, which allow having motors of different voltages and currents connected to controller. Besides these features, this model has relays to drive the cutting tool, end course inputs for all three axes and entry for emergency stop. Another important feature is the power rectifier circuit that simplifies and reduces the final cost, because it needs just one transformer with 18 VAC/4 A.

8. PROPOSED SOLUTION

8.1 Intermediate file format for generating code G

The file must be in *ASCII* format and each line must contain a minimum set of parameters to be interpreted. To generation trajectories for milling or drilling, each line must follow the pattern:

```
<Real X><blank space><Real Y><blank space><Real Z (optional for drilling) ><blank space><Real Speed (optional)><end of line>
```

where: *Real X*: number in the real number format that defines the position on X axis; *Real Y*: number in the real number format that defines the position on Y axis; *Real Z*: number in the real number format that defines the position on Z axis; *Real Speed*: number in the real number format that defines the speed that it must take to achieve the specified point on this line, the *blank space*: the table *ASCII* character 32 (0x20 hexadecimal) and *end of line*: character 10 of table *ASCII* (0x0A hexadecimal)

For trajectories planning for drilling, the speed parameter must be defined in the settings in the program.

Examples of valid real numbers:

0.1	125.123	1235	12e1
.1122	354E1	0.54e-12	549E-15

8.2 Drilling trajectories definition

The drilling trajectories are generated considering that the machine must maintain a convenient distance above the plate during horizontal movements. When the drilling process starts, the movements should be imposed only to the 'Z' axis, while the axes 'X' and 'Y' are fixed.

8.3 CAD post-processing to G-code generation

The process can be divided into three stages, in agree with following steps:

- Post-processing
- Translation
- Execution

The stages of post-processing and translation have been implemented in C++ language. A simple diagram depicted on Fig. 4 resumes the data flow in the software.

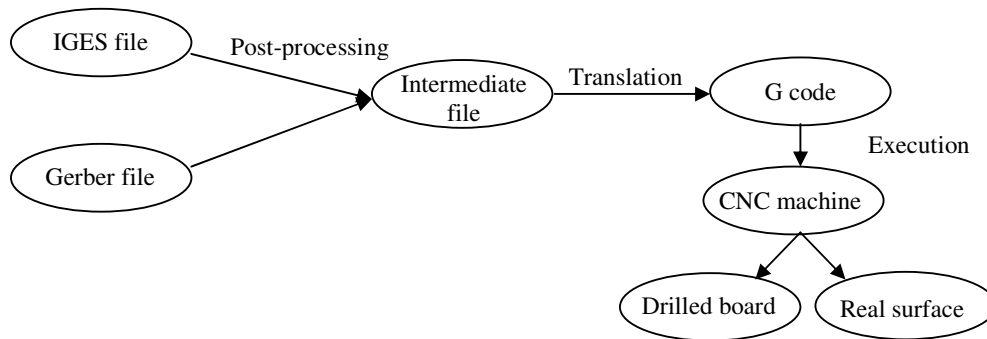


Figure 4. System diagram

In agree with the Fig. 4, before the stage of post-processing has been defined in software, a *B-Spline* surface, Fig. 5, or a printed circuit board, Fig. 6, and they must be exported in IGES or Gerber file respectively.

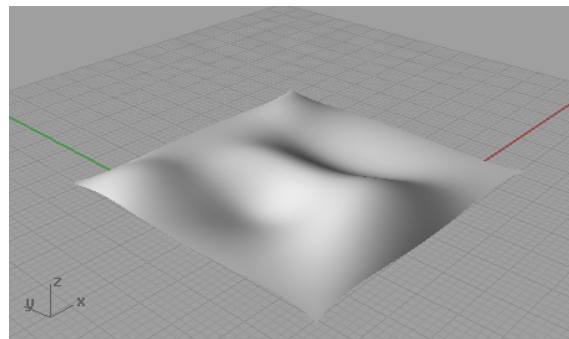


Figure 5. The B-Spline surface obtained in CAD.

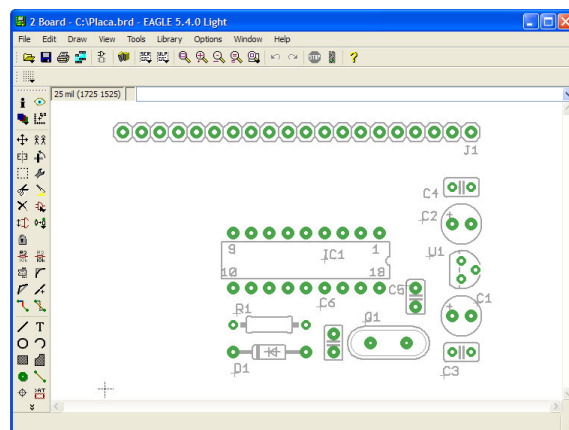


Figure 6. A circuit board designed in software.

On the stage of post-processing, the CAD files (IGES or Gerber) are read to obtain the necessary data about the project. After obtaining these data, they are interpreted to be created a intermediate file containing the trajectory that the CNC machine will do to achieve the expected process: milling or drilling. In the case of surfaces, the data obtained are the control points of the surface and, through these points, is possible the reconstruction of the designed surface. An intermediary surface results can be seen in Fig. 7a, and having read these points of control, is possible to generate a milling trajectory, depicted on Fig. 7b.

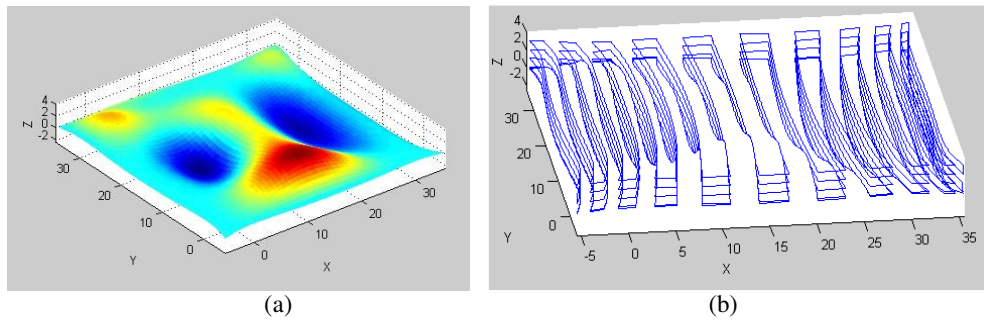


Figure 7. (a) Free surface made; (b) Planned trajectories for the milling machine. Distance of 0.05 in the parametric space.

During the stage of translation, the program reads each line of the intermediate file and interprets information in order to generate the G-code, or sequence of codes, more appropriate.

On execution stage it is loaded the generated G-code in a CNC program to programming the milling machine to produce a real part. This G-code could be a printed circuit board with holes for insertion of electronic components or a real surface. It can be observed on Fig. 8 the CNC drilling on a printed circuit board in a simulation program.

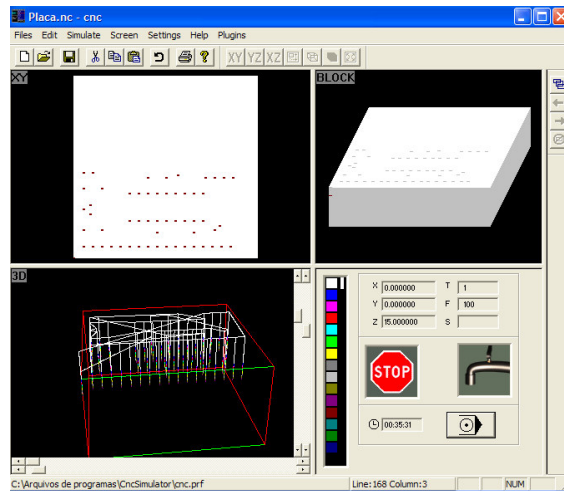


Figure 8. Printed circuit board at CNC simulator

Figure 9 shows a real physical model of the holes generated by the milling machine.

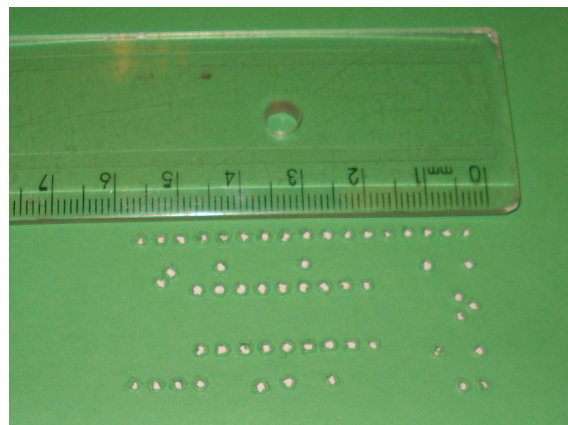


Figure 9. Physical hole in a real model.

Figure 10 depicts the prototype manufactured by the didactic CNC milling machine of the surface drawn in CAD that was presented in Fig. 5 and Fig. 7a.

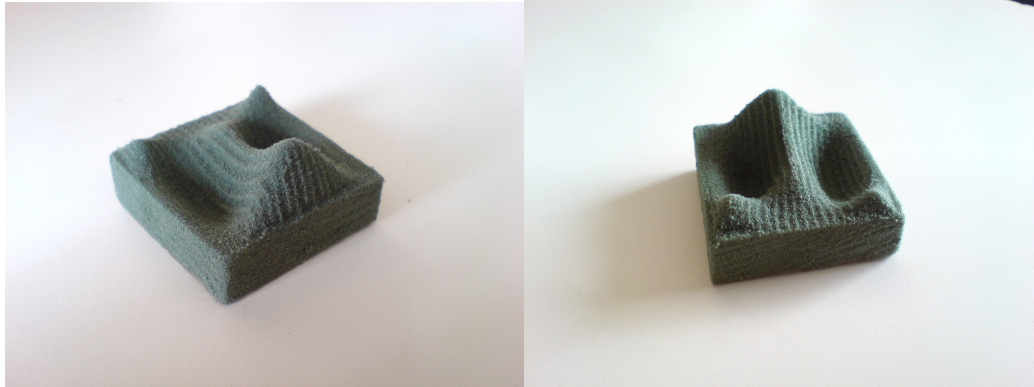


Figure 10. Real model for the obtained surface.

Figure 11 depicts a snippet of G code that generated the surface seen in Fig.10.

```
N000001 G1 X-5.42 Y-5.42 Z0.70 F600.00
N000002 G1 X-5.37 Y-5.24 F600.00
N000003 G1 X-5.33 Y-5.07 F600.00
N000004 G1 X-5.28 Y-4.89 F600.00
N000005 G1 X-5.23 Y-4.71 F600.00
N000006 G1 X-5.18 Y-4.53 F600.00
N000007 G1 X-5.14 Y-4.35 F600.00
N000008 G1 X-5.09 Y-4.17 F600.00
:
:
N006296 G1 X21.51 Y6.82 Z0.05 F600.00
N006297 G1 X21.53 Y6.52 Z0.08 F600.00
N006298 G1 X21.55 Y6.23 Z0.11 F600.00
N006299 G1 X21.57 Y5.94 Z0.14 F600.00
N006300 G1 X21.59 Y5.65 Z0.17 F600.00
N006301 G1 X21.61 Y5.36 Z0.20 F600.00
N006302 G1 X21.63 Y5.07 Z0.22 F600.00
N006303 G1 X21.65 Y4.79 Z0.25 F600.00
N006304 G1 X21.67 Y4.51 Z0.28 F600.00
N006305 G1 X21.69 Y4.23 Z0.30 F600.00
N006306 G1 X21.71 Y3.95 Z0.33 F600.00
|
:
:
N012267 G1 X26.32 Y28.05 Z-0.02 F600.00
N012268 G1 X26.30 Y27.80 Z-0.04 F600.00
N012269 G1 X26.27 Y27.55 Z-0.07 F600.00
N012270 G1 X26.25 Y27.30 Z-0.09 F600.00
N012271 G1 X26.23 Y27.04 Z-0.12 F600.00
N012272 G1 X26.20 Y26.78 Z-0.15 F600.00
N012273 G1 X26.18 Y26.52 Z-0.18 F600.00
N012274 G1 X26.16 Y26.26 Z-0.20 F600.00
N012275 G1 X26.14 Y25.99 Z-0.23 F600.00
```

Figure 11. Fragment of the G code program.

9. CONCLUSION

This article presented a design of a rapid prototyping system which has as main elements a milling machine, a system of post-processing CAD files, a controller of unipolar stepper motor and a translation system for the trajectories generated by the CAD post-processor into G code.

The milling machine prototype was carried out to be low cost and meet the needs of laboratory experiments in practical classes of Computer Engineering and Industrial -Mechanical Engineering of Univali

In this work were discussed the stages of system project that translate trajectories to G code, developing its specification and integrating the solution with a previous project. The program developed in C++ interprets data for drilling the printed circuit board or milling of surfaces for use in the classroom. The focus of this work was to design the whole system, through all the steps, from CAD design CAD in software to its prototype.

The results showed flexibility in the use of machinery and were satisfactory. With the drilling of plates, there is a facility for the production of printed circuit boards for disciplines such as Logical Projects and Microcontrollers (Computer Engineering) and can be used in other disciplines of engineering courses of UNIVALI

The perspective is the design of a controller for the stepper motor, in order to reduce the milling machine cost. Another perspective would be the development of optimization algorithms for the process of drilling.

10. ACKNOWLEDGEMENTS

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