A PROCESS PLANNING APPLICATIVE FOR RAPID PROTOTYPING TECHNOLOGY

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Abstract*. In general, a software for Rapid Prototyping (RP) has to read the part geometry in STL (STereoLithography) format, slice it electronically, generate information for layer addition and send these data to the RP machine. This work presents the development of a RP software to achieve that. The main objectives are to obtain autonomy on the processing parameters and to develop a system which could be used in different RP technologies. In this way, the proposed software treats the initial stages of the process, which are common to the majority of the RP technologies, in a generic way and the peculiarities of each one are addressed individually. Today, the system can already deal with the initial stages of the RP process for relatively complex geometries and was implemented for the Fused Deposition Modeling (FDM) technology. Some difficulties are reported and the system feasibility is demonstrated with the good results obtained in some case studies.*

Keywords*: Rapid Prototyping, Layer Manufacturing, Process Planning, STL Processing*

1. Introduction

Rapid Prototyping (RP) is a manufacturing process based on the Layer Manufacturing (LM) principle, which allows three-dimensional physical models to be obtained using information directly from a 3D CAD (Computer Aided Design) model (Fig. 1). It has been used for more than fifteen years in many areas, usually in the product development process. The RP technologies available in the market are based mainly on the following processes: photo-polymerization, laser sintering, semi-fluid material deposition and three-dimensional printing (Beaman *et al.*, 1997). The main process planning tasks are the same for all RP technologies, which are basically: orientation determination, slicing the 3D CAD file, support generation, layer filling in strategies or path planning and fabrication (Rajagopalan *et al*., 1995, Kulkarni *et al.*, 2000). Each RP technology uses dedicated software for process planning (Kulkarni *et al*., 2000). In many cases, these softwares are less flexible than a user would like it to be, not allowing, for instance, to create new processing strategies. This can pose difficulties to work on process optimization. In addition, there is not a Brazilian RP technology yet and this emphasizes the importance of carrying out some development in this area.

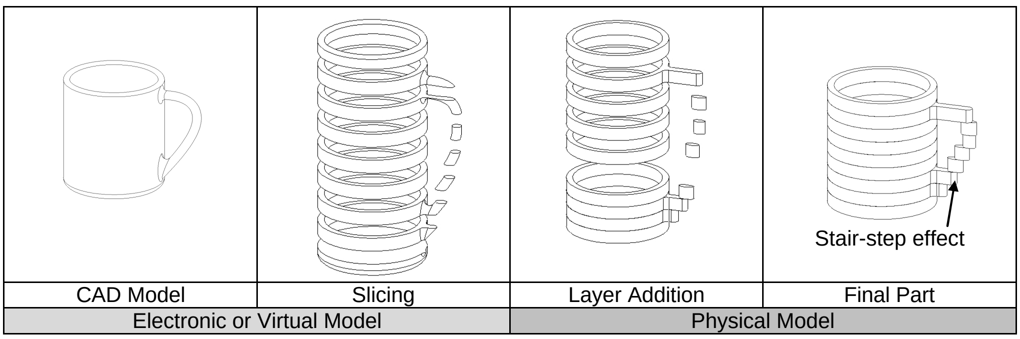


Figure 1. Layer manufacturing principle – main stages

This work presents the early stages in the development of a software for RP process planning, to generate data to build a part via LM technology. The proposed software intends to deal separately with the initial stages of the manufacturing process, which are common to the majority of the RP technologies, and then, with the peculiarities of each process in specific modules. In this way, the software can be divided in some generic and specific modules. The main objectives of this project are to develop an applicative which can be used in different RP technologies and to obtain autonomy on the processing parameters. The Tooling Research and Development Group (NUFER/CEFET-PR) has been developing this applicative, so far baptised as RP3 (from RP Process Planning). The RP3 system can deal already with the initial stages of the RP process, for relatively complex geometries, and with the Fused Deposition Modeling (FDM) technology, in a specific module. The development of the RP3 main modules is presented in this paper and some case studies for the FDM process are reported demonstrating its feasibility. Some difficulties found so far are also reported.

2. FDM technology

The FDM technology was developed by Stratasys, Inc. (USA). It uses two materials, one for the part and one for the support structure, needed for overhanging geometries. These two materials are supplied as filaments in coils or cartridges. Each plastic filament is unwound from the coil and supplied to a specific extrusion nozzle. The two nozzles are heated to melt the plastics and are mounted in an extrusion head which controls a mechanical stage that moved in the X and Y directions. The part nozzle deposits a thin bead of extruded plastic to form each layer over a table. The table moves incrementally in the vertical direction (Z), allowing the addition of new layers. The plastic hardens immediately after being squirted from the nozzle and bonds to the layer below. The entire system is contained within a chamber which is held at a controlled temperature, much lower than the nozzles. The created support structures are later removed either by breaking them away from the object or, more recently, by using a water-soluble support material, simply washed away. Amongst the materials available for the process are Acrylonitrile Butadiene Styrene (ABS), and more recently polycarbonate (PC) and poly(phenyl)sulfone.

One of the most used filling strategies to build a layer is the raster, which the main processing parameters for the FDM technology are presented in Figure 3. The FDM technology uses proprietary software for process planning called Insight. The data format to control the FDM machine was also developed by Stratasys and is known as Stratasys Modeling Language (SML). The SML is written in a text format file. Once the data to build a part is ready, they can be sent to the machine using the Insight or via an external module called SML Sender. This SML Sender opens the possibility to send to the machine a SML generated by another applicative rather then the Insight.

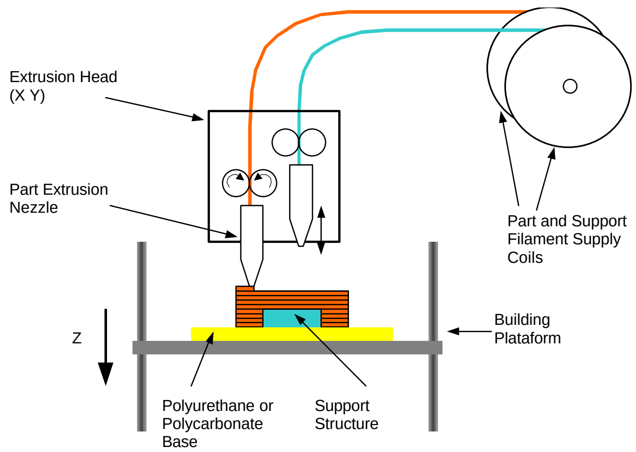


Figure 2. FDM Principle from Stratasys, Inc.

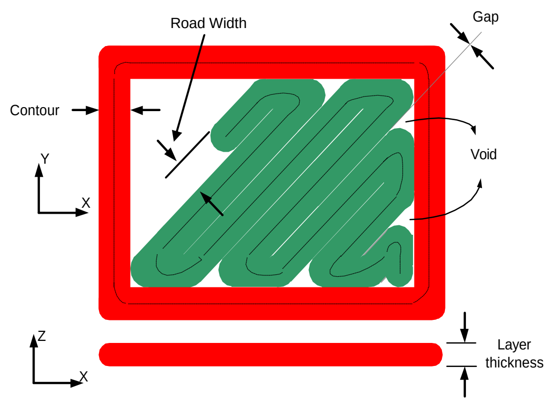


Figure 3. Main FDM raster parameters

3. Layer Manufacturing Process Planning Tasks

The main LM process tasks mentioned before (orientation determination, slicing the 3D CAD file, support generation, path planning and fabrication) needs to be detailed in some few more stages, which are presented below. According to Kulkarni *et al.* (2000), the process of filling in the interior of the layer is accomplished by means of path planning. They refer “path” as being the trajectory followed by the depositing/curing/cutting medium in any LM process. Therefore, path planning includes determining the geometry/topology of the paths, computing the paths and determining appropriate process parameters.

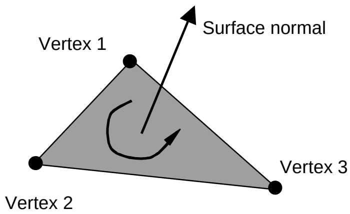
3.1. Generating and Reading the STL Format

The most common way to send information from any CAD system to any RP process is via STL (STereoLithography) format. The STL format was developed by 3D System Inc. in 1987, to overcome problems such as loss of information of the IGES (Initial Graphics Exchange Specification) format and has become a standard input for all RP techniques (Jacobs, 1996, Dolenc and Mäkelä, 1996, Kumar and Dutta, 1997). The STL format approximates the surfaces of the model by using small planar triangles, creating a faceted representation of the part geometry (Fig. 4a). The description of each triangle in a STL-model consists of the X, Y and Z coordinates for the 3 vertices and a surface normal vector pointing to the outside of the model. An ASCII representation of a STL-format and its geometrical interpretation can be found in Fig. 4 b and c. The STL format can be generated by the CAD systems either in ASCII or Binary.

(a)

```
solid <solidname>
 ....
        facet normal ni nj nk
                outer loop
                        vertex v1x v1y v1z
                        vertex v2x v2y v2z
                        vertex v2x v2y v2z
                endloop
        endfacet
....
endsolid <solidname>
```

(b)



(c)

Figure 4. An example of a STL part (a) and the interpretation of STL-file format (b, c) suggested by Kumar and Dutta (1997)

3.2. STL File Verification

According to Kai *et al*. (2003), several problems plague STL files, such as: (1) Gaps (cracks, holes, punctures) that is, missing facets; (2) Degenerate facets (where all its edges are collinear); (3) Overlapping facets; (4) Non-manifold topology conditions. The STL file verification can be done with the aid of a CAD system or during the file reading by the LM software. The majority of these problems will generate an open slice during the next step of the process, which is unacceptable by the technology, therefore the file must be correct before that.

3.3. Part Orientation and Scaling

A part is usually oriented in a manner that minimizes the number of layers, for time and cost reasons. However, some other points affect the decision on how to orient a part. For instance, when surface finish is imperative, it is possible to position the part in order to maximize or improve it in a specific region of the part. The stair-step error (also referred to as 'staircase' or 'aliasing') due to the layerwise manufacturing (Fig. 1) can be reduced by choosing the best build orientation possible, taking into account the curvature or slant of the part surfaces. In other cases, part strength might be more important, and one can choose the best orientation to deliver that (the parts are weaker in the direction of the layer piling). To allow that, the system has to permit part orientation control, either via user decision or using some built in knowledge. For instance, there are some methodology developed that can help to orient the part to minimize staircase effect, such as the one reported by Frank and Fadel (1995) and Xu *et al.* (1999). In addition, some adaptive slicing methods considering the possibility to adopt variable layer thickness have been proposed to improve surface finish by controlling the staircase (Suh and Wozny, 1994, Dolenc and Mäkelä, 1996, Beaman *et al*., 1997).

Depending on the LM technology, shrink must be compensated in order to have an accurate part. This is usually done by scaling up the part geometry. This scaling is often performed on the 3D STL file, prior to slicing, but there are cases where it is done after slicing, *i.e*. on the 2D contours. The FDM technology is one example of the latter.

3.4. Slicing

Slicing is done by intersecting the 3D model with planes that are perpendicular to the direction of building (Fig. 5). During the slicing procedure, the slicing plane is displaced by a layer thickness value each time a new layer contour is calculated. The 2D contours generated consist of line segments (polyline), which points are obtained by intersecting the sides of the each triangle with the slicing plane. Beaman *et al*. (1997) presents Eq. (1) to be solved to obtain the intersection points. In this equation, V_1 (x_1, y_1, z_1) and V_2 (x_2, y_2, z_2) are the vertices of one triangle side and I (x, y, z) is the intersection point to be obtained. The k parameter is the proportional ratio between $\vec{v}_1$ (vector connecting V_1 to I) and $\vec{v}_2$ (vector connecting I to V_2).

$$\frac{x - x_1}{x_2 - x} = \frac{y - y_1}{y_2 - y} = \frac{z - z_1}{z_2 - z} = k \quad \Rightarrow \quad x = \frac{kx_2 + x_1}{k+1}, y = \frac{ky_2 + y_1}{k+1} \qquad (1)$$

The 2D contours obtained are closed when the STL file is perfect. The stair-step error, caused by the approximation of the angled or curved surfaces with stacked layers of material, is exacerbated when constant thickness is used, which is the case of the majority of the RP technologies (Beaman *et al.*, 1997). Because of the stair-step effect, there is always a trade-off between accuracy and surface finishing.

Usually, the slicing task is performed for the entire STL file and then the system moves to the next step (path planning). However, in the Laminated Object Manufacturing (LOM) process from Cubic Technology, it is performed on line, where the height of the layer is obtained from a measuring system in the machine and then the software calculates the cross section. This procedure increases the accuracy of the part in the Z direction (Jacobs, 1996, Kai *et al.*, 2003).

Until this stage, the process planning can be considered the same for the majority of the LM technology. The next stages are very much depending on the peculiarities of each process.

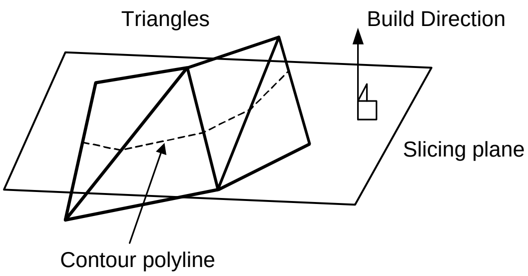


Figure 5. Line segments resulting from slicing a STL model

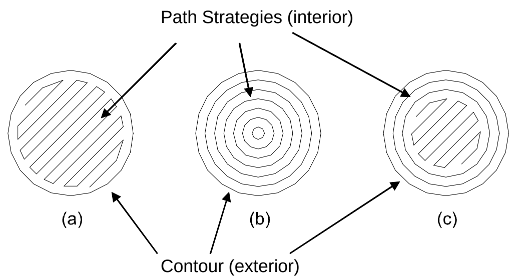


Figure 6. Path strategies: (a) raster, (b) offset and (c) a mix of raster and offset

3.5. Support Calculation

Some RP processes require support for features that are not connected to the main body of the part in any stage during the process (Fig. 7). This results in the need for more process planning in these processes, because the systems must determine automatically the regions that require support structures. This calculation is based on the identification of all normal vectors that points downward. Some RP do not require support structure due to the nature of the process. For instance, the surrounding powder not sintered by the laser in the Selective Laser Sintering (SLS) process acts as a natural support for the part during the building. The same happens to the LOM and the three-dimensional printing process.

3.6. Strategies for Path Planning

According to Kulkarni *et al.* (2000), path planning can be thought of as consisting of two components, interior and exterior strategy. In addition to generating the geometric coordinates of paths, the interior path planning problem is also concerned with the effects that different paths have on the LM process, and on the part (part strength and manufacturing time). These effects vary depending on the process and, hence, the path planning for the different LM processes are different. The exterior path planning would affect part finishing and accuracy and usually is done contouring the 2D perimeter of the part. Typically contour (external) and raster (internal) layouts have been tried in many LM technologies (Beaman *et al.*, 1997). Figure 6 shows an example of the contour combined with the raster, offset and a mix of the two strategies (interior). Other rather more specific layouts have also been proposed such as: spiral paths and space filling curves for the FDM process, the patented star-weave pattern for Stereolithography (SLA), contour and external hatching for the LOM process (details of these strategies can be found in Beaman *et al.*, 1997, Kulkarni *et al.*, 2000). The angle of the raster strategy used in the FDM process (Fig. 6a) is alternated by 90 degrees each layer, in order to increase part strength.

3.7. Post-processing and Part Building

Once the strategy and all the processing parameters are defined, the final processing stage is to generate the data in the exact format required for each RP machine. This task is similar to the post-processing needed in a CAM (Computer Aided Manufacturing) system. This stage can pose some difficulties once the data format used by each technology is proprietary and not always available to the user.

4. The RP3 System Development Approach

Not all tasks described above are implemented yet in our RP3 system. Some of them were left to be developed later, prioritising the crucial tasks. This solution was adopted in order to have some quick results which would validate the RP3. As mentioned before, this applicative was thought to have some generic modules, to perform the tasks which are common to all RP processes and specific modules to each technology. Figure 8 presents this general structure. Today the following modules are implemented: STL reading and slicing (generic modules), and support calculation, path planning (only contour and raster) and SML generation (specific modules for FDM technology). Although the slicing task is considered a generic module, the applicative can be easily re-organized in order to shift it to a specific module, for instance, to accommodate on line slicing as observed in the LOM technology. The various modules were developed using Microsoft Visual C++ 6.0 compiler, following the Object Oriented Programming (OOP).

The STL reading module was implemented in a way that it automatically detects if the file is in ASCII or binary format, comparing some characters in the heading. The three vertices and the normal vector of each triangle are stored in a list of triangle. At the end of the reading function, the minimum and maximum coordinate for each direction (X, Y and Z) are identified, which allows the determination of a 3D envelop of the part to be processed. The STL file verification has not been implemented yet, therefore, the applicative assumes that the file is correct. Additionally, it is assumed that the part was modelled in the CAD system in the exact position to be built and no scale factor is applied. The latter assumption will cause considerable dimensional errors in the part due to the no compensation of the shrinkage.

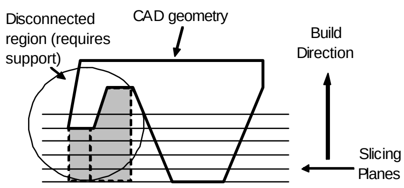


Figure 7. Example of support requirement

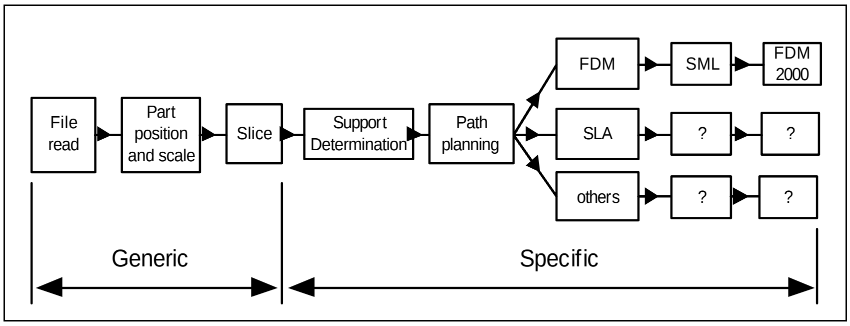


Figure 8. Flow chart of the RP applicative

The slicing starts with a determination of a horizontal plane with a constant z coordinate. Equation (1) is used to obtain the intersection points in each layer. The 2D polyline obtained is stored in a slice list and the slicing plane is incremented by a value corresponding to a layer thickness. An algorithm is responsible to orient the intersection points in order to define external contours (counter clockwise) or internal contour (clockwise).

In this version of the RP3 for the FDM technology, the support determination was not implemented as it should be, i.e. automatic calculation of the support structure. Instead, the support is defined using the projected area of the whole part.

The next step is to obtain the contour path for the FDM process. This is done by calculating an offset of the 2D polyline obtained in the slicing. The offset distance (d) corresponds, initially, to half the deposited filament thickness, measured in the XY plane (Fig. 3). The filament thickness is defined as road width. Figure 9 shows schematically the methodology used to calculate one point of the offset (P), where three points of the polyline ($P1$, $P2$ and $P3$) need to be considered, one before ($P1$) and one after ($P3$) the reference point ($P2$).

The only internal path strategy implemented so far for the FDM was the raster (Fig. 6a). To calculate the raster, first it is necessary to obtain another offset contour, called raster contour. The offset distance was initially defined as $3d$ from the original 2D polyline. Then, a raster line is defined with the inclination α in relation to the X direction (Fig. 10). The intersection points between the raster line and the raster contour are obtained. The raster line is incremented by a distance r, which depends on the road width and gap value (Fig. 3), and the new intersection points are calculated. The distance r is defined as being the road width minus the gap. The gap parameter can be positive zero, or negative. The latter is used when a better filament packing in a layer is desired, increasing the part strength. After all intersection points have been obtained an algorithm defines a continuous raster path by connecting the all points. In the next layer, α is incremented by 90 degrees and the process is repeated. The raster module does not support yet the presence of islands in the interior of the 2D contour.

The final step of the process planning is to generate the SML file to be sent to the machine. Because it is a proprietary format, with a lot of variable to be interpreted and a logic to be understood, this module took a lot of time to be implemented.

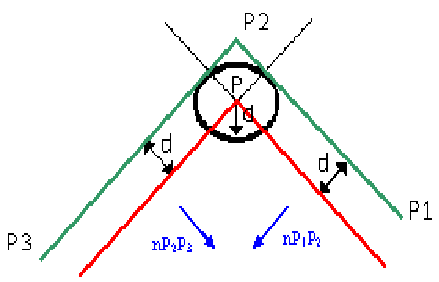


Figure 9. Offset determination

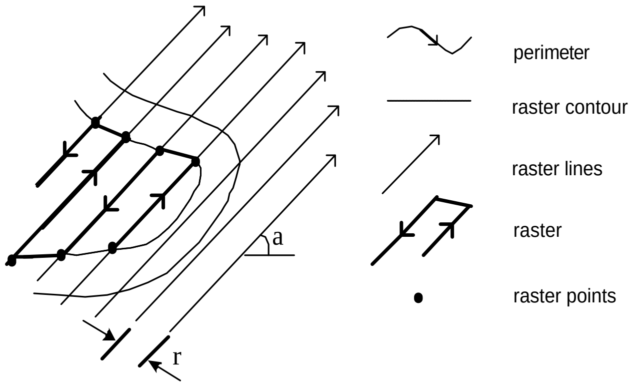


Figure 10. Raster determination

5. Case Studies

For the development of the RP3 algorithms, many test cases have been done with different part geometries, from simple to quite complex ones. One of the test part used was the mug (Fig. 4a), in two positions, up right and rotated by 90 degrees. Another test was a tensile test specimen.

5.1. Mug

The objective of this case was to test the slicing and offset calculation algorithm. The mug (see Fig. 4a) was chosen because of the rather complex geometry, mainly in the handle region. Figure 11 presents the 2D polylines and its respective offsets for a layer close to the base (a) and in the middle (b) of the mug. Figure 11 c and d show two slices of the rotated mug, one layer out of the handle region and one exactly in this region respectively.

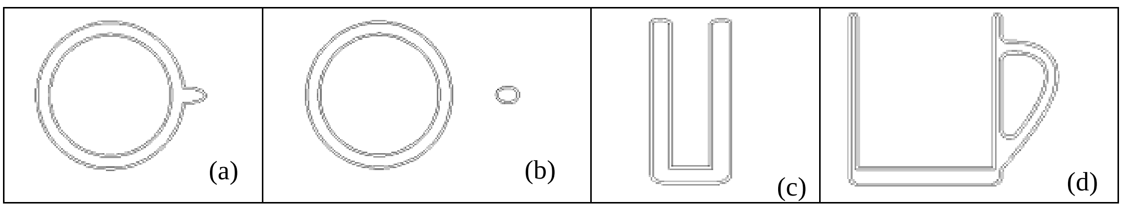


Figure 11. Slice and offset examples of the mug positioned up right (a and b) and rotated 90 degrees (c and b)

5.2. Tensile Test Specimen - Complete

The objective of this case was to test the support, path planning and SML generation modules of the RP3 software. Hence, a simpler geometry was selected to avoid requirements that are not yet supported by the applicative. Figure 12 presents the tensile test geometry used for this study. The part was positioned exactly as it is shown in Fig. 12 (X-Y plane) and so the support module was able to identify the support geometry. In order to process the geometry, a set of default processing parameters for the FDM 2000 used by the Insight was selected. Table 1 presents these parameters. No scale factor was used in the test because, as mentioned before, this module is not yet implemented.

Table 1. FDM 2000 parameters used in the part building

Layer thickness (mm)	Contour width (mm)	Road width (mm)	Gap (mm)	*d* (Road width/2) (mm)	*r* (Road width) (mm)	Raster offset (3*d*) (mm)
0,250	0,508	0,508	0	0,254	0,508	0,762

The layer thickness specified for this test part generates four layers to be processed. Figure 13 shows the results of the contour and raster strategy for one layer. In this figure, the lines represent the centre of the material filament to be deposited. After the generation of the SML file, it was sent to the FDM 2000 machine available in the NUFER/CEFET-PR via the SML sender. Figure 14 shows the part being built in the machine.

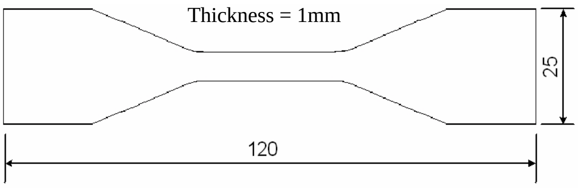


Figure 12. Geometry of a tensile test specimen

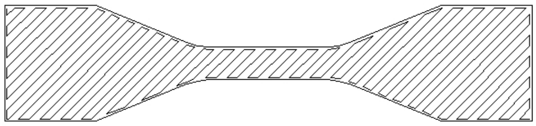


Figure 13. Contour and raster defined by the applicative

From the analysis of the first part obtained it was observed that the voids between the contour and the raster lines (see details in Fig. 3) were quite large, allowing light going through the part. This was observed around the entire part. To have an idea of the dimensional deviation, the specimen was measured using a calliper with resolution of 0.02mm. Table 2 shows the average measurement results for the three main dimensions. The considerable deviation was expected because no scale factor was used.

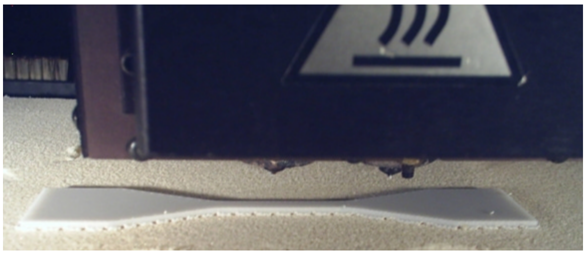


Figure 14. Tensile test specimen being built in the FDM 2000

Table 2. Dimension results for the tensile test specimen

Length (120mm)	Width (25mm)	Thickness (1mm)
118.45	24.10	0.95

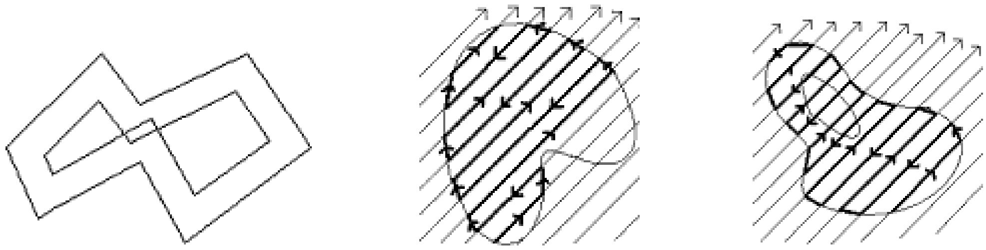
5.3. Tensile Test Specimen - Half

Based on the results of the first test, it was decided to carry out another test aiming to minimize the voids. The distance of the raster offset was the chosen parameter to try to achieve that. The distance between contour offset and the raster offset in the first test was 2*d* (or equal to the road width). Three new values were tested corresponding to 1/2, 2/3 and 3/4 of 2*d*. The other parameters were kept the same as presented in Tab. 1. Because the tensile test specimen geometry is symmetric, and to save time and material, only half of the geometry was processed. After the part has been processed by the RP3 with the three different distances, the three SML were sent to the FDM 2000 machine to be built.

The analysis of the voids in the three parts using a magnifying-glass revealed that, in the part with 3/4 reduction, the voids were much smaller than the first test, but there were still some small voids that allowed the light going through the part. With the 2/3 reduction part, no void were observed and with 1/2 reduction, there were no visible voids but, some deformation of the region between contour and raster started to appear, showing that the reduction factor was more than the required one.

6. Some Difficulties Found and Future Works

During the RP3 development some special cases were identified, which posed difficulties to the programming. Some of them were addressed and some were left to deal with later. When the STL file is large, with a great number of triangles, the slicing module takes a considerable processing time. This is because the slicing routine is analysing all triangles in the part to calculate the intersection points. This time can be minimised if the routine was prepared to check for intersection points only in a list of the triangles that are included in a strip limited by an initial and a final *z*. The algorithm to calculate the offset from a polyline can find problem of self intersection in some region (Fig. 15a). It was found in the literature solution for this problem when using 2D splines, but not polylines. This case still needs to be addressed. During the raster determination procedure, some situation, as the presented in Fig. 15b and c, imply that the raster path has to be divided in more than one segment. The solution to these cases has been programmed but is not yet fully tested.



(a) (b) (c)

Figure 15. Cases to be addressed in the RP3 software: (a) offset self intersection, (b) split raster and (c) island

Some of the future works planned for this project are to:

- address the difficulties presented above;
- implement the modules that still need to be developed (mainly: orientation and scaling, support calculation, new strategies in path planning);
- adjust the processing parameters to produce a more accurate part;
- test new strategies to build part aiming to increase part accuracy, strength and reduce manufacturing time;
- develop an user interface to facilitate the use of the RP3 software.

7. Discussion and Conclusions

The task to develop a software for RP process planning can be considered a quite big one. A lot of process details need to be considered together with some programming difficulties that need to be overcome. Therefore, a team with very good knowledge of the LM technology and programming is required to reach good results.

Although the FDM module is yet in an early stage, it is already allowing building parts which are not very complex in geometry. Because the FDM technology works with the SML format and provides the FDM-Sender system, which are accessible outside the proprietary Insight software, the RP3 post-processing module was successful. A research is needed on how the other technologies work in order to develop new specific modules. Apart from that, as the RP3 was planned from the beginning to have modules for different RP technologies, the inclusion of a new specific module seems not so difficult.

There is still a lot of development to do in the RP3 software to reach a point to be considered reliable and, maybe, to be used in a Brazilian RP machine. However, the results so far are encouraging, showing that the software is feasible and will be possible to test new idea related to processing parameters and strategies. This is what motivates the group to keep on working.

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9. Responsibility notice

The authors are the only responsible for the printed material included in this paper.