

A Web-Based System for Mapping Features into ISO 14649-Compliant Machining Workingsteps

J. C. T. Benavente, J. C. E. Ferreira

Abstract—The rapid development of manufacturing and information systems has caused significant changes in manufacturing environments in recent decades. Mass production has given way to flexible manufacturing systems, in which an important characteristic is customized or "on demand" production. In this scenario, the seamless and without gaps information flow becomes a key factor for success of enterprises. In this paper we present a framework to support the mapping of features into machining workingsteps compliant with the ISO 14649 standard (known as STEP-NC). The system determines how the features can be made with the available manufacturing resources. Examples of the mapping method are presented for features such as a pocket with a general surface.

Keywords—Features, ISO 14649 standard, STEP-NC, mapping, machining workingsteps.

I. INTRODUCTION

SINCE the 1800's the mass production paradigm has been practiced in manufacturing companies, and this is due to its efficiency and low cost. In the 1960's flexible manufacturing systems became more common in manufacturing companies. This is due to the market demands that companies become more agile and flexible in order to meet the expectations of their customers quickly, and still beat competitors in quality and price [1], [2].

In recent years globalization has led manufacturing companies to implement continuous improvements in their production methods. Computer numerical control machines have an important and critical role in the current manufacturing scenario. Since they appeared they have contributed to the automation of processes, besides giving support to high speed and precision machining [3]. Advances in computers have given significant additional capabilities to these machines.

Currently there are several machines with different controllers, which lead to software and hardware incompatibilities. There is a need for systems to be interoperable in order to enable flexibility within the company [2], [4]-[6].

A significant number of studies have identified that the use of integrated information models is the key to achieving interoperability and sharing between different phases of product development.

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The ISO 14649 standard (also known as STEP-NC) provides a high-level information model regarding the product, such as the use of features for modeling parts and manufacturing operations, and this standard has been considered as an adequate tool to overcome the problems mentioned above. Thus, for a market where high variability of the parts being produced is quite common, the change in the features that compose the part is faster and easier than changing the G code [7] for machining the part, enabling companies to respond more quickly to changes in the design of parts, as well as to help accelerate the decision-making related to part manufacture.

In this paper we present a system that maps the features into arrays of machining workingsteps. The system is applied to pockets with general profiles and surfaces.

II. FRAMEWORK OF THE PROTOTYPE

The process planning activities are very important in industry, since they seek to determine how the parts should be manufactured. Among the major process planning decisions are the selection of operations, the set of cutting tools, and cutting conditions [8].

In the context of ISO 14649 standard (known as STEP-NC) there are entities that have attributes related to the design of the part, that is, its shape ("What to make"), and entities that contain information related to the manufacturing process ("How to make").

The entities that contain design information have as superclass the entity MANUFACTURING_FEATURE. This entity covers features of the type REGION (surface), TWO5D_MANUFACTURING_FEATURE, and TRANSITION_FEATURE, as shown in Fig. 1 in an EXPRESS-G diagram [9]. Note that the MANUFACTURING_FEATURE is associated with a part through the attribute its_workpiece, which has a set of operations (its_operations) that when executed lead to the geometric shape corresponding to the feature.

The machining workingsteps represent the machining process for a specific area of the part, and they are always associated with a feature. They specify the relations between the feature and the operation to be performed on it, thus creating an unambiguous specification that can be performed [10].

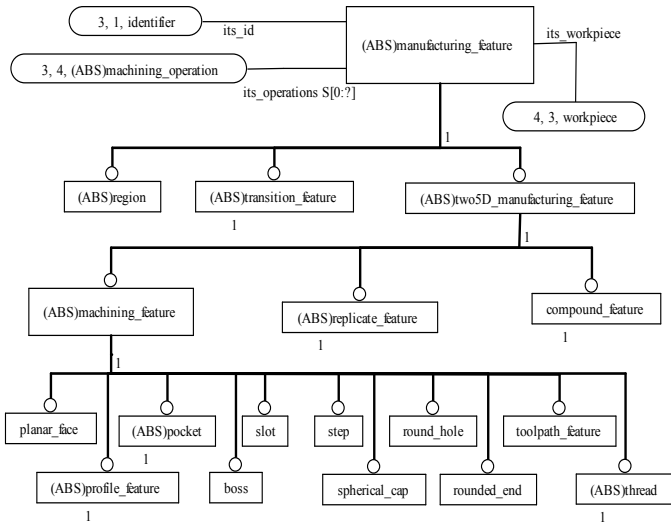


Fig. 1 MANUFACTURING_FEATURE entity and its subclasses

Essentially, a machining workingstep comprises a single machining operation, a single tool and its machining conditions. Fig. 2 shows the machining workingstep entity represented in a UML diagram (for simplicity, it will be referred to as Workingstep).

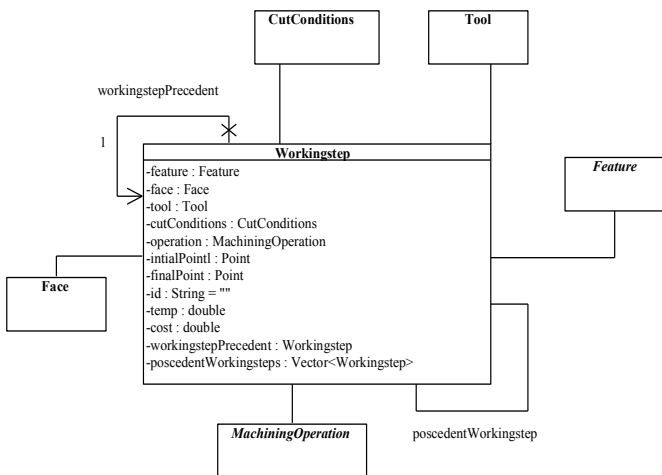


Fig. 2 Workingstep class modeled in UML

A. Mapping Features into Workingsteps

The mapping task consists basically of creating arrays of machining workingsteps and associating them with a feature. The execution of these machining workingsteps results in the complete removal of material from the feature. The creation of arrays of machining workingsteps must be done by mapping classes, and for each type of feature there should be a mapping class. Fig. 3 shows an IDEF0 diagram of this activity, and this task involves five other sub-tasks, which will be described below.

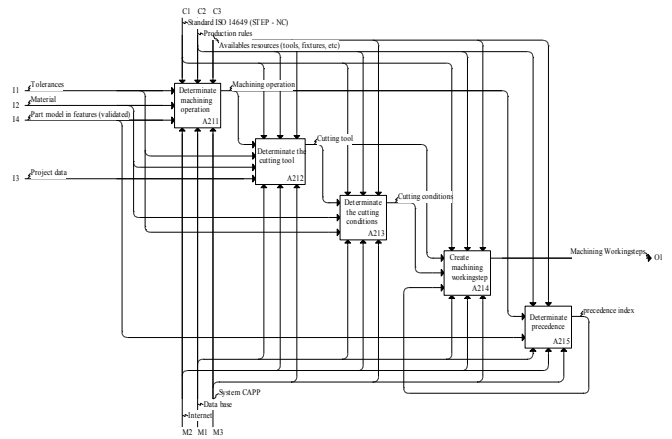


Fig. 3 IDEF0 diagram of the activity mapping features into machining workingsteps

1) Determining the Machining Operations

To obtain the shape of each design feature, machining operations must be performed in certain regions of the workpiece. For example, in the case of blind holes with a flat bottom (Fig. 4), drilling operations are not enough, since the twist drill leaves the profile resulting from movement of the drill, which is a conical tip. In this case a second operation is needed, which may be milling or reaming.

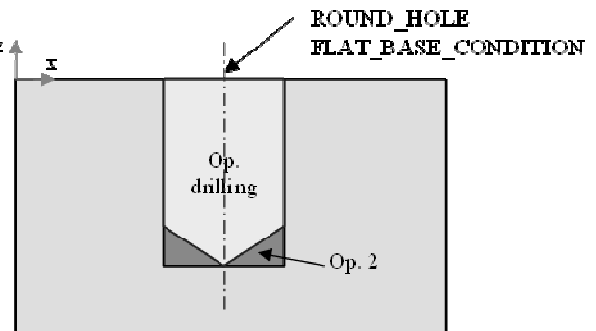


Fig. 4 Blind hole with a flat bottom and its associated operations

The UML modeling of machining operations adopted in this work follows the structure suggested by the ISO 14649 standard. Basically this structure consists of a general and abstract class called MachiningOperation, which is the parent class of machining operations, that include: center drilling, drilling, reaming, boring, face rough and finish milling, side milling, end rough and finish milling, and milling of free-form surfaces. Fig. 5 shows a UML diagram of machining operations.

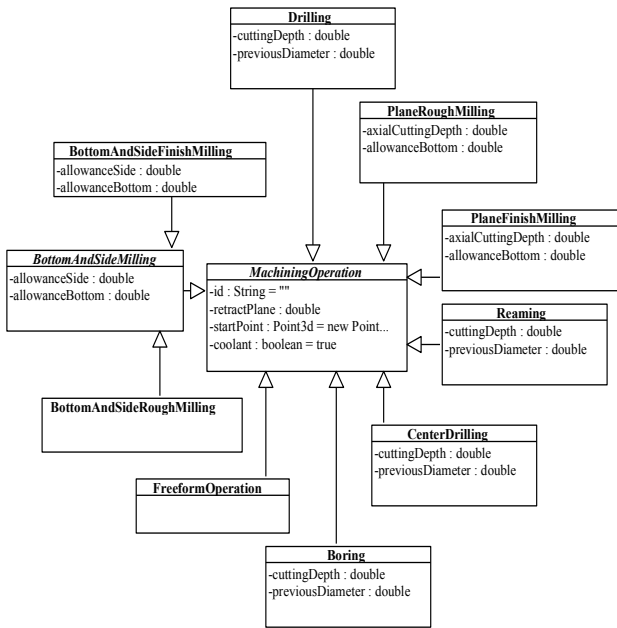


Fig. 5 Machining operations modeled in UML

2) Determining the Cutting Tools

In this step a cutting tool is associated with the machining operation selected in the previous step, and the structure for modeling tools is shown in Fig. 6.

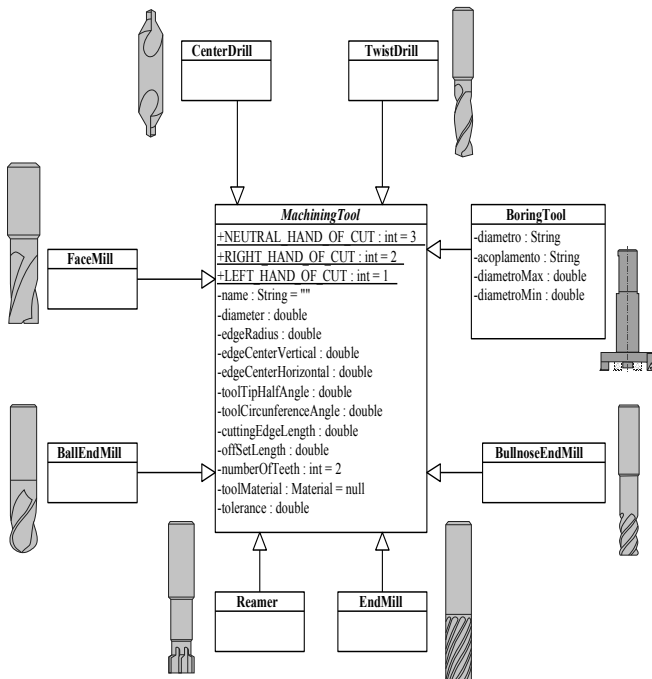


Fig. 6 Cutting tools modeled in UML

3) Determining the Machining Conditions

The machining conditions are determined according to the type of operation. The cutting tool manufacturers normally inform the recommended cutting data to obtain the desired results. A database can be queried to determine the cutting conditions.

4) Creating the Machining Workingsteps

After obtaining the manufacturing information, the machining workingstep is created, leaving only the precedence and descendant attributes to be assigned in the next step, and such attributes are shown in UML in Fig. 2.

5) Determining the Precedents

The machining workingsteps are linked through associations of precedents. These precedents are established according to certain manufacturing rules. For example, center drilling operations must precede drilling and reaming, as shown in Fig. 7. If there is no precedent machining workingstep, this attribute is set to null. Table I shows the machining workingsteps, their precedents and descendants for the part in Fig. 7.

TABLE I
 PART IN FIG. 7 MAPPED INTO MACHINING WORKINGSTEPS, PRECEDENTS AND DESCENDANTS

Feature	Machining workingsteps	M. WS precedent	WS descendants
Closed Pocket	WS 1 (Rough milling)	null	WS 2, WS 3, WS 4
Round Hole	WS 2 (Center drilling)	WS 1	WS 3 WS 4
	WS 3 (Drilling)	WS 2	WS 4
	WS 4 (Reaming)	WS 3	null

No vertical lines in table. Statements that serve as captions for the entire table do not need footnote letters.

*Gaussian units are the same as cgs emu for magnetostatics; Mx = maxwell, G = gauss, Oe = oersted; Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.

It should be noted that a machining workingstep can have a precedent or none (void), and a set of descendants or none (void).

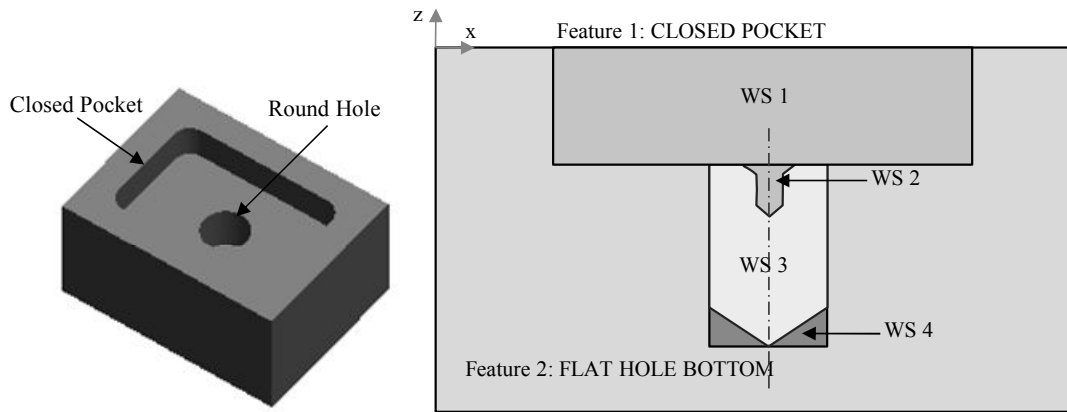


Fig. 7 Part mapped into machining workingsteps

III. IMPLEMENTATION

In the IDEF0 diagram of the system shown in Fig. 3 it can be noted that the input for this activity corresponds to the part modeled by features. This module was developed by the authors in the described in [11].

A. Defining the Cutting Tools

A set of cutting tools should be assigned to the project being executed by the user, and these tools can be stored by the user in a database if he/she will use the same set of tools to machine a different part.

The tools can be created through the user interface as shown in Fig. 8. The user can also choose tools from a tool catalog in the database on the server, as illustrated in Fig. 9.

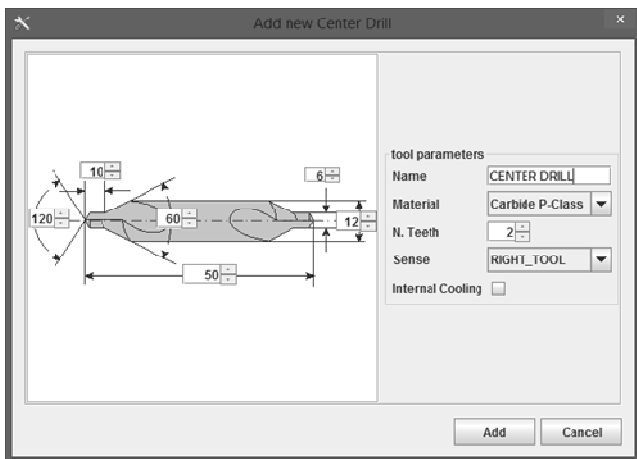


Fig. 8 Interface for creating the new cutting tools (example: center drill)

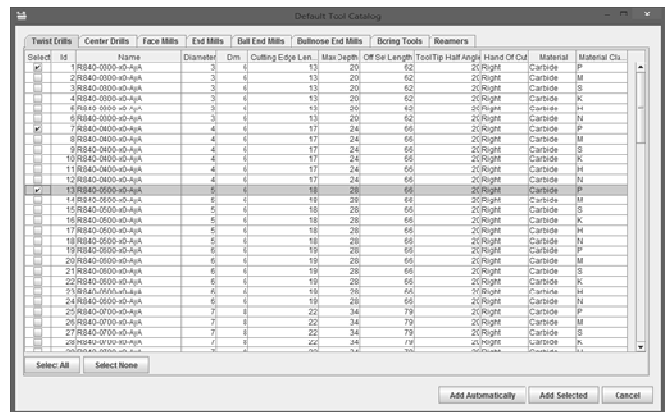


Fig. 9 Catalog of cutting tools available in the database on the server

B. Mapping Features into Machining Workingsteps

For each type of manufacturing feature there is a specialized class that subdivides the total volume to be removed into sub-volumes. Each of these sub-volumes is a machining workingstep. A description of cases such as mapping pockets and Béziers surfaces are given below.

1. Mapping Pockets Having a General Profile

In Fig. 10 it is shown an example part with several pockets and holes. As described in Section II A, the mapping of this feature is carried out by applying the following steps:

(a) Determining the Machining Operations:

Pockets are usually obtained by milling processes, holes by drilling processes, reaming, etc. Therefore, in this case, the operation chosen by the system is milling.

(b) Determining the Cutting Tools:

The system chooses the tools from the toolset assigned to the project (see Section III A). The criterion used here is that the cutter with the largest diameter available that enters the pocket must be used. If volumes still remain to be removed, a second tool is chosen.

Consider the pocket with a general profile in Fig. 10, whose edge is marked in orange. The system chose two tools: one with a 20mm diameter, and another with 8 mm diameter. Fig. 11 shows the machining areas covered by each tool.

(c) Cutting Conditions:

The system sends a query to the database requesting the cutting conditions recommended by the manufacturer for the chosen tool. With this information, the machining workingstep is created and displayed in tree form as shown in Fig. 12 (a).

(d) Determining the Precedents:

As can be seen in Fig. 11, two machining workingsteps must be executed in order to obtain the shape of the pocket with a general profile. The machining workingstep WS 1 will be executed first, while the one called WS 2 will be executed later, and will have WS 1 as precedent. Since these two are executed, the volumes related to hole 1 and pocket 2 can be removed, which are within pocket 1. Fig. 12 (b) shows the results in a tree structure, where the machining workingsteps that do not have precedents are at the highest level, while those with precedents are inside the folders on which they depend.

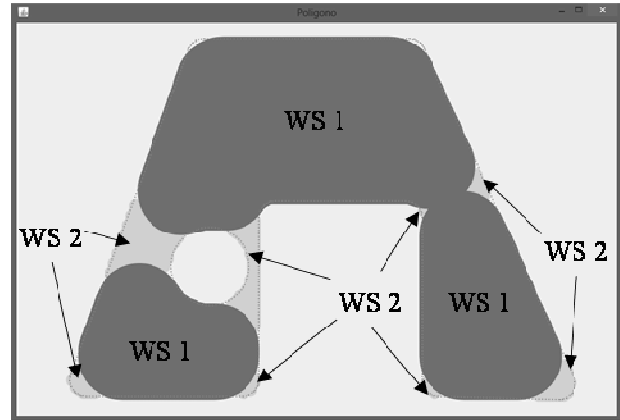


Fig. 11 Dividing the areas according to the tool diameter

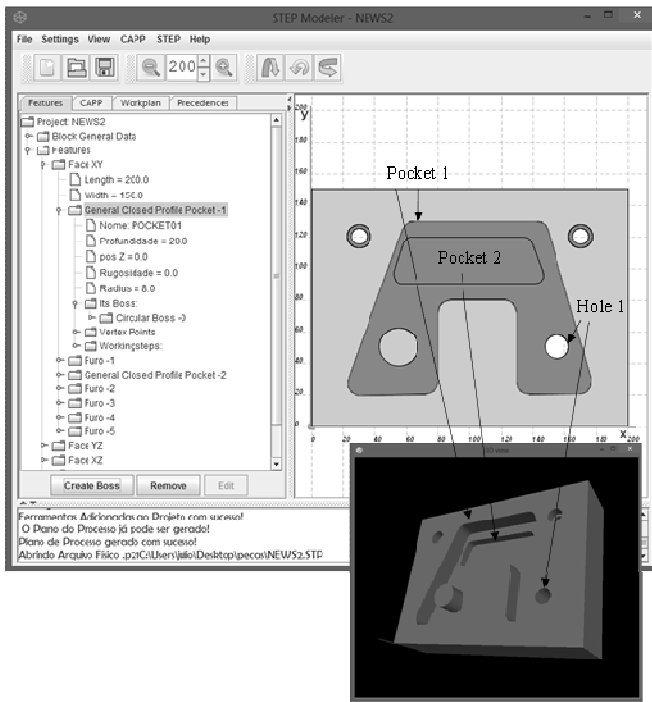


Fig. 10 Part with different pockets and holes

It should be noted that the exclusion of a machining workingstep causes the exclusion of all descendants machining workingsteps. For example, for the part in Fig. 10 the exclusion of WS 2 does not allow the operations associated with hole 1 (i.e., HOLE01_WS01 and HOLE01_WS02 in Fig. 13) and pocket 2 (POCKET02_WS01 in POCKET02_WS02 in Fig. 13) are performed because there is still material to be removed from pocket 1.

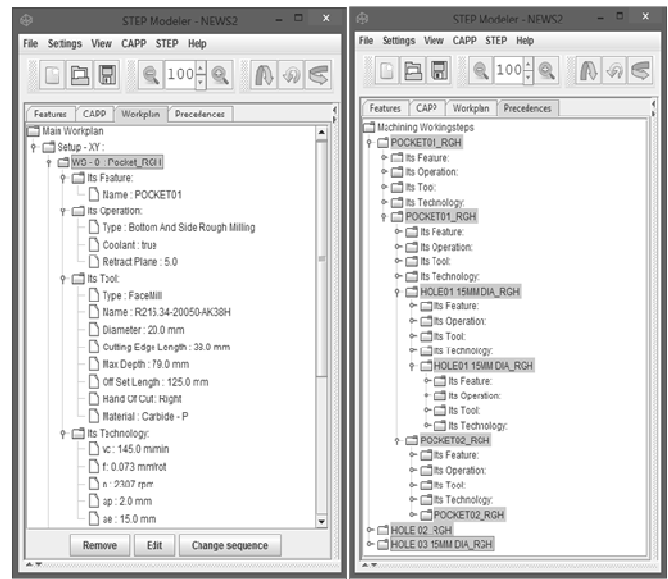


Fig. 12 (a) Machining workingstep created by the system, (b) Precedent machining workingsteps in a tree structure

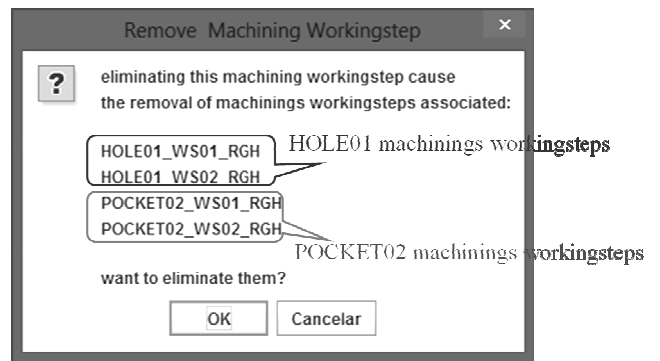


Fig. 13 Machining workingsteps associated with the machining workingstep POCKET02_WS02

2. Mapping the Bézier Surfaces

In the case of Bézier surfaces, the surface shown in Fig. 14 is considered. The procedures for mapping this surface are similar to those described above. Machining can be performed

through the execution of three machining workingsteps as shown in Fig. 15.

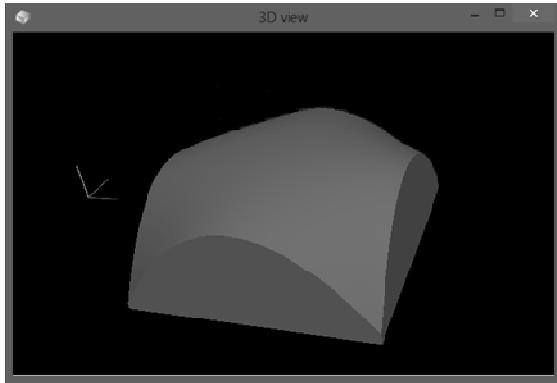


Fig. 14 Bézier surface to be mapped

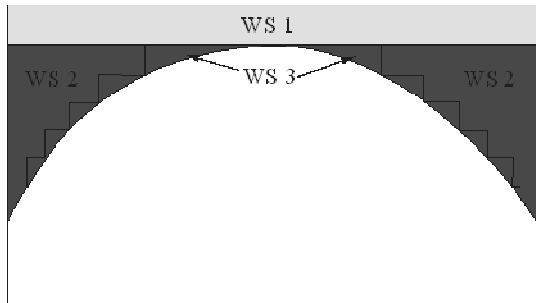


Fig. 15 Machining workingsteps associated with the Bézier surface

(a) Choosing the Machining Operation:

If the surface is located at a very large depth with regard to the workpiece, a first milling operation is selected (BOTTOM_AND_SIDE_MILLING entity in the ISO 14649 standard) in order to remove the material more quickly.

The second operation will also be rough milling (WS 2 in Fig. 15), but the difference from the previous one is that the first one uses the zigzag strategy (Fig. 16), whereas the second uses the CONTOUR_PARALLEL strategy, according to [12] (Fig. 17).

The third operation (WS 3 in Fig. 15) will be the free-form milling (FREE_FORM_OPERATION entity in the ISO 14649 standard), as shown in Fig. 18.

(b) Choosing the Cutting Tools:

For the first and second machining workingsteps (WS 1 and WS 2 in Fig. 15) end mills may be used.

For machining WS 3, a ball end mill can be used to accomplish the exact shape of the surface. For convex surfaces the largest ball end cutter available can be chosen. For surfaces where there are concave regions, it should be verified which cutter can machine it completely. The system chooses a ball end cutter that has the largest diameter, since it can be used throughout the surface. Fig. 19 shows a curve where the cutter cannot remove some material (located in the concave region), and therefore this tool would not be selected to machine this surface.

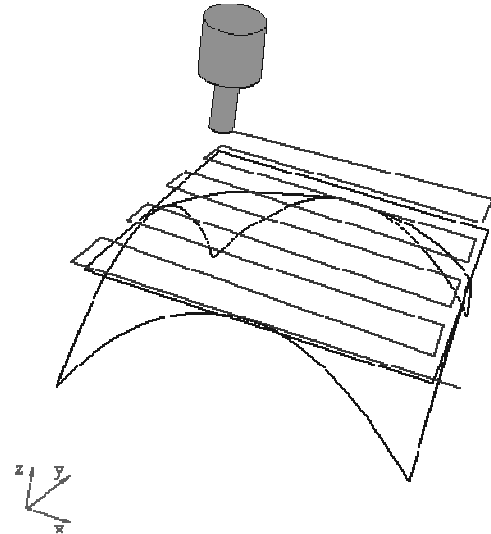


Fig. 16 Operation corresponding to the first machining workingstep of the surface (WS 1 in Fig. 15)

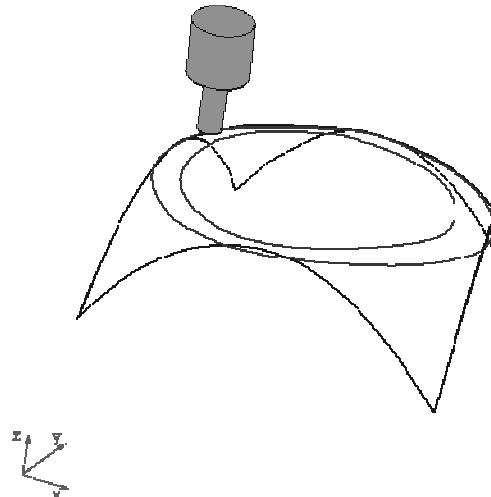


Fig. 17 Operation corresponding to the second machining workingstep for machining a Bézier surface (WS 2 in Fig. 15)

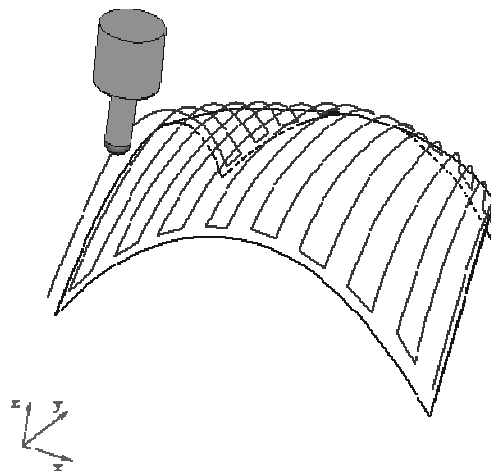


Fig. 18 Machining operation corresponding to WS 3 in Fig. 15

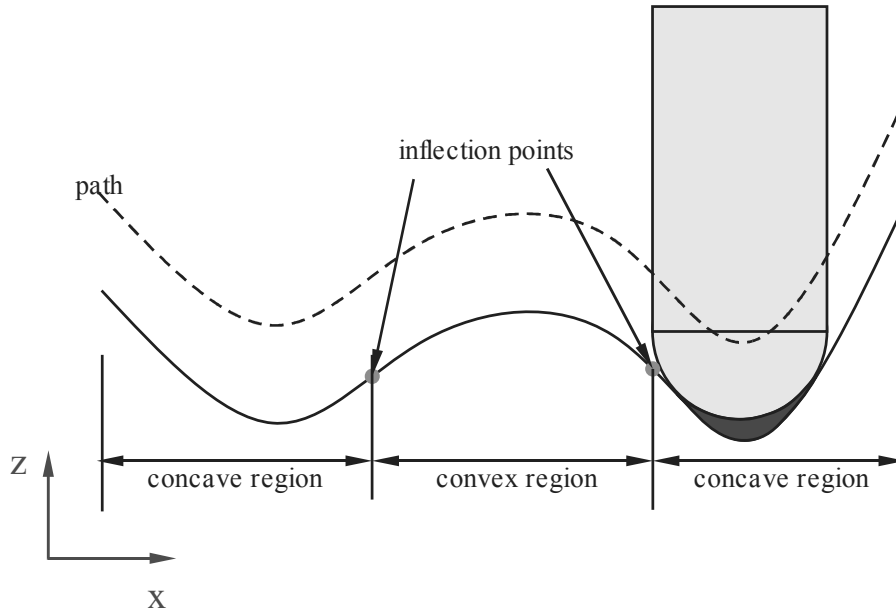


Fig. 19 Material left by a ball end milling tool due to its large diameter

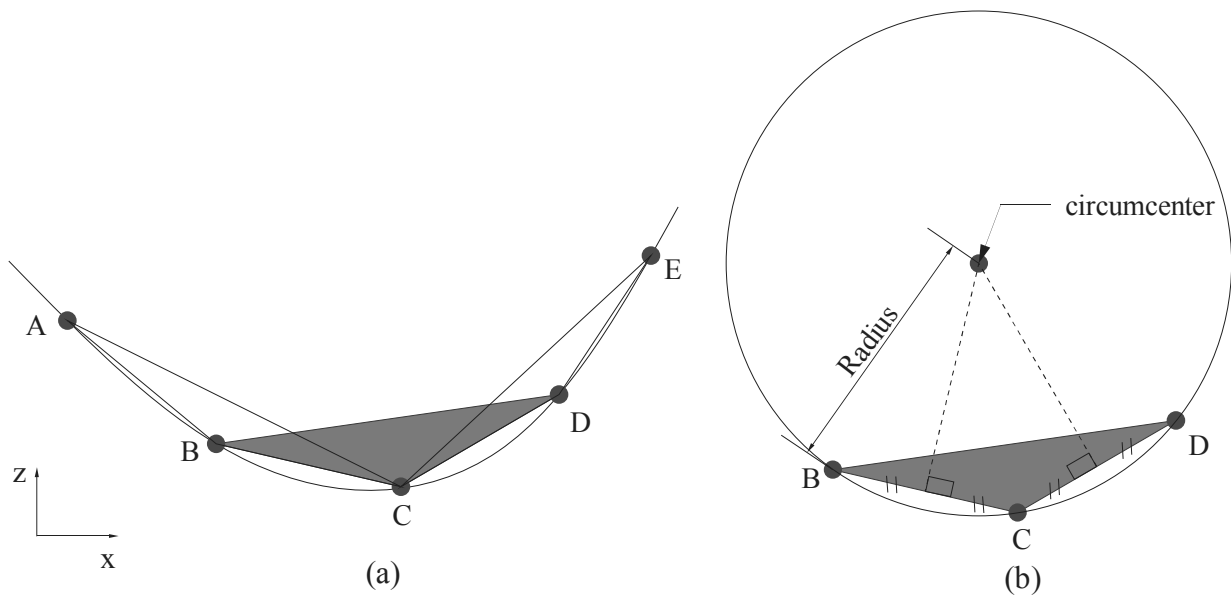


Fig. 20 Segmented curve: (a) triangles formed by segmenting the curve, (b) circle passing through the three points, and its center is the circumcenter of the triangle

Note that for a Bézier surface this verification should be performed along the x and y directions. The diameter of such ball end cutter can be calculated by dividing the surface into a finite number of segments. For each pair of segments a triangle is calculated, and then its circumcenter is determined. The distance between the circumcenter and a point on the segment is the radius of the cutter that fits within that pair of segments. Fig. 20 (a) shows the division of a curve into triangles ABC, BCD, and CDE, whereas Fig. 20 (b) shows the circle defined by the three points of triangle BCD.

(c) Cutting Conditions:

Similarly to the case of pockets with a general profile, the

system searches the cutting conditions data recommended for cutting tools in the database.

The result of the mapping of the surface in Fig. 14 is shown in Fig. 21 (a) in a tree structure. This mapping module sends workingsteps containing all manufacturing information to the module called "Generator of Neutral Code" described in [11], responsible for mapping into ISO 14649 entities through the Standard Data Access Interface (SDAI) [14]. The neutral file [15] generated by the generator module is illustrated in Fig. 21 (b), where the feature and its machining workingsteps can be seen.

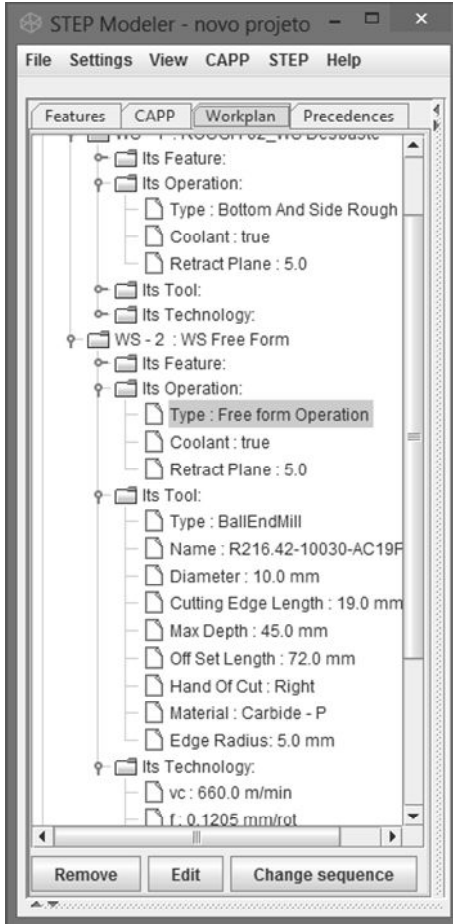
After generating the full program in the STEP-NC standard, a new generation of CNC controllers should be able to

interpret the high-level information contained in machining workingsteps and execute them, thus eliminating the use of the G code.

A module called "tool path generator" presented in [13] is able to interpret the information of machining workingsteps,

generates tool paths, and transforms them into G code commands for conventional CNC machines.

Fig. 22 shows such tool paths performed in a commercial CNC simulator.



(a)

```
#39=REGION_SURFACE_LIST(' ',#2, (#25,#62,#77),#40, (#44));
...
#44=BEZIER_SURFACE(' surface -
',4,4, ((#45,#46,#47,#48), (#49,#50,#51,#52), (#53,#54,
#55,#56), (#57,#58,#59,#60)), .UNSPECIFIED., .F., .F., $);
#45=CARTESIAN_POINT('control vertex
', (0.0,0.0,43.28818002921527));
#46=CARTESIAN_POINT('control vertex
', (0.0,33.333333333333336,0.0));
...

#25=BOTTOM_AND_SIDE_ROUGH_MILLING($,$, 'Bottom And Side Rough
Milling', 5.0, #33, #26,
#31, #32, $, #34, #35, #38, 2.0, 15.0, 0.0, 0.0);
#26=MILLING_CUTTING_TOOL('R216.34-20050-AK38H', #27, (#29), $, $, $);
#27=FACEMILL(#28, 4, .LEFT., $, 79.0);
#28=MILLING_TOOL_DIMENSION(20.0, 0.0, 0.0, 38.0, 0.0, 0.0, 0.0);
...

#62=BOTTOM_AND_SIDE_ROUGH_MILLING($,$, 'Bottom And Side Rough
Milling', 5.0, #70, #63,
#68, #69, $, #71, #72, #75, 2.0, 7.5, 0.0, 0.0);
#63=MILLING_CUTTING_TOOL('R215.36-10050-AC22H', #64, (#66), $, $, $);
#64=ENDMILL(#65, 4, .LEFT., $, 52.0);
#65=MILLING_TOOL_DIMENSION(10.0, 0.0, 0.0, 22.0, 0.0, 0.0, 0.0);
...

#77=FREEFORM_OPERATION($,$, 'Free form
Operation', 5.0, $, #78, #83, #84, $, #85, #86, #89);
#78=MILLING_CUTTING_TOOL('R216.42-10030-AC19P', #79, (#81), $, $, $);
#79=BALL_ENDMILL(#80, 4, .RIGHT., $, 45.0);
#80=MILLING_TOOL_DIMENSION(10.0, 0.0, 0.0, 19.0, 5.0, 5.0, 0.0);
...
```

What to do
(feature)

How to do
(Machining workingsteps)

(b)

Fig. 21 Bézier surface mapped into three machining workingsteps

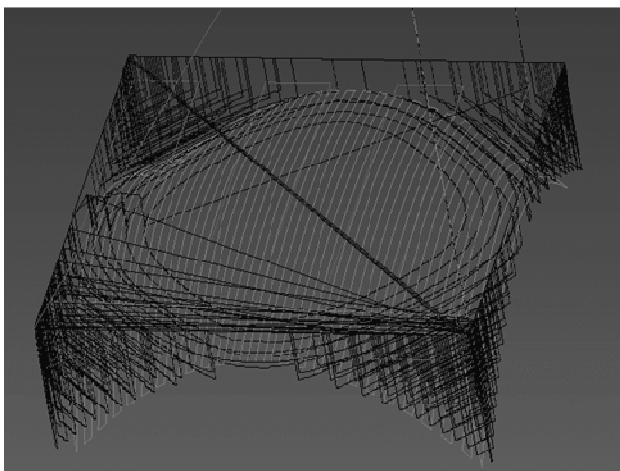


Fig. 22 Simulating the removal of the three machining workingsteps in the surface of Fig. 14

IV. CONCLUSIONS

The STEP-NC standard (ISO 14649) provides an object-oriented data model, and this enabled the integration between the module presented in this paper and the design and manufacturing module.

The implementation of this module was made using the Java language, and the system can be run by remote users in the link http://www.grima.ufsc.br/stepnc_project/.

The mapping of features into machining workingsteps was carried out considering the use of numerical control machines with three axes, and eventually the module may be extended so that the parts can be manufactured on machines with four or five axes.

In the future this module will be coupled to a process planning system, in which the presence of alternative operations and tools will be included, and in order to achieve that the Halevi matrix [16] or AND/OR graphs [17] can be

used. The presence of alternatives contributes to the selection of a process plan that is best suited to the production circumstances [8].

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