3D Morphing for Generating Intermediate Roughing Levels in Multi-Axis Machining

Pierre P. Lefebvre[1] and Bert Lauwers[2]

[1]KULeuven Belgium, pierre.lefebvre@mech.kuleuven.be
[2]KULeuven Belgium, bert.lauwers@mech.kuleuven.be

ABSTRACT

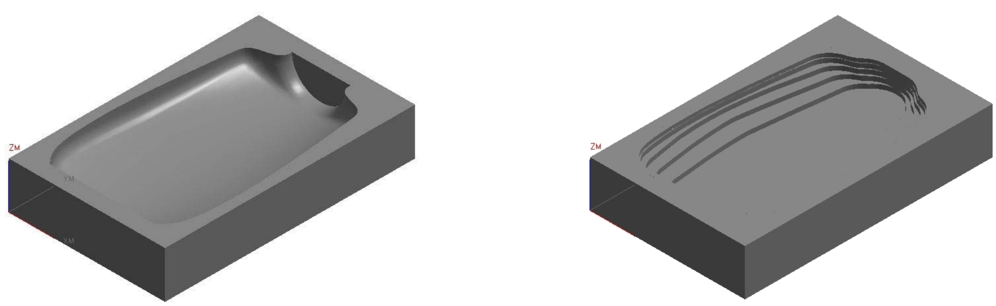
This paper discusses the application of geometry morphing techniques for the generation of intermediate steps for multi-axis rough milling operations. The typical roughing approach elaborates a 3-axis or 3-axis indexed tool path to remove the bulk of the material from the workpiece. These methods often lead to dynamically unfavorable intermediate geometry for deep cavity and/or taper-walled part shapes. The resulting 'stairs' shapes from these 3-axis methods cause a highly varying material removal volume during the finishing operations. Morphing techniques are investigated in this paper to generate smoothly varying intermediate geometry during the roughing phases of the machining process. These smooth intermediate surfaces advocate for applying 5-axis roughing methods instead of 3-axis methods.

Keywords: Morphing, CAD/CAM, 5-axis machining.

1. INTRODUCTION

In manufacturing technology, a phase-based approach is very common to shape a workpiece into its final form. The sequence therefore typically follows the template: roughing – semi-finishing and finishing [3]. An application area that follows certainly this sequence is the tool making industry (moulds and dies). Starting from a blank block of material the roughing phase removes the bulk of the material with heavy-duty cutters. This phase releases an irregular intermediate shape that needs further processing in the semi-finishing stage. When a small amount of stock offset from the final part shape is established by the semi-finishing phase, the finishing can finally be applied to produce the desired part shape. Meeting the tolerances and surface finish are the most important objectives for the finishing phase. These objectives stand in contrast to the objectives of the roughing stage. Rough machining needs fast and efficient material removal. In terms of time cost, the roughing phase can take 70%-90% of the total machining time.

The tool path generation for the roughing operations is almost always done in 2.5D mode. This means that the geometry of the volume to be machined (called the 'delta volume') is sliced by a set of parallel planes and that in each plane a 2D tool path is calculated (contour-offset, zig, zig-zag, etc.). The intermediate step to move between two successive parallel planes (.5 dimension) makes that the tool paths in these planes are not connected which results in the generation of the 'stairs' shape.



(a) (b)

Fig. 1. Rest material shape after roughing.

An example is given in Fig. 1(a). depicting a simple mould cavity. The intermediate shape after roughing in Fig. 1(b). clearly shows the 'stairs' shape in the rest material. An interesting remark is that the 'stairs' shape is more pronounced in the less steep area (the bottom region of the cavity in Fig. 1). The stairs discontinuities are unfavorable from a machining process dynamics viewpoint. They lead to heavily changing cutting loads. Especially for advanced machining techniques like HSM (High Speed Machining) or hard milling, such discontinuous situations should absolutely be avoided.

There are some possible solutions for this problem. A first possibility is the use of smaller cutter diameters and/or smaller step-down distances (distance between two parallel tool path planes) in order to reduce the 'stairs' geometry, however these methods lead to lower material removal rates, which is in contradiction with the objectives of the roughing operations, i.e. fast and efficient removal of big volumes stock material. Using small cutter diameters causes stability problems when machining. Long small cutters have to be applied to reach the bottom of the cavity, but the rigidity of such cutters is that weak that tool destruction will occur. Another possible solution is the application of feed rate optimization [7]. This technique continuously adapts the machining feed rate by slowing down the feed when the cutter arrives at a stairs step and by accelerating again afterwards. This technique is suited for balancing the cutter load, but the servo drives and the controller of the milling machine should eventually be capable to process highly varying feed rates.

A more pragmatic approach is to deal with the cause of the stairs shaped intermediate geometry, which is the 2.5D tool path generation technique. The stairs discontinuities can be removed by using full 3D cutting levels during the roughing phase instead of the 2.5D contours. Full 3D intermediate cutting levels suggest (not compulsory) the application of 5-axis tool path strategies during the roughing phase. Since 5-axis machine tools are being common in modern machining workshops, it is an interesting idea to use the 5-axis capabilities not only for finishing operations, but also for roughing operations in order to maximize the potential of such type of machinery.

The main question remaining is how to generate those 3D intermediate cutting levels for roughing operations. In the course of this paper, the possibilities of applying morphing technology for this purpose are investigated and discussed.

2. MORPHING TECHNOLOGY

Morphing can generally be defined as the process of smooth and continuous transformation of one shape into another shape. Morphing applications are very popular in computer animation. A clear distinction has to be made between 2D morphing techniques and 3D morphing techniques. 2D morphing or image morphing is the most used technique in animations. The source and target objects of the 2D morph sequence are pictures (pixel maps). The morph sequence is generated by a warping step (correspondence between image features) and a cross dissolving step (this is the interpolation step that generates a smooth transition between the pixels of the source image and the warped pixels of the target image). An example is given in Fig. 2. The warp step consists of defining manually correspondence points between source and target features. The features in this case are face elements like: eyes, nose, mouth, hair, ears, etc. Once the warp is generated, the cross dissolving interpolates picture pixels to generate the morph sequence.

Fig. 2. Example of image morphing between the pictures of both authors. [5]

Despite some analogies between 2D morphing and 3D morphing, the datasets involved are quite different. Therefore, 2D morphing is not further discussed in this paper. 3D morphing aims at generating morph sequences (set of intermediary shapes) between two distinct objects in 3D space. The key factor in 3D morphing technology is the data representation of the source and target objects in 3D space. Different techniques are developed for different geometrical representations. A clear classification of the geometry types and a detailed discussion on applicable technologies for each representation is given in the overview paper [9].

A weak point of morphing technology is that there is no objective quality measure for a morph sequence. Since morphing is essentially a transformation between two different objects, an infinite number of solutions exist for generating the in-between shape sequences. For animation applications, a lot of user-control is provided within the algorithms to manipulate the morphing parameters. The user can intuitively qualify a solution just by looking at it. The morph sequence for animations just should 'look' good. Adapting the user controls helps to move the morph sequence to the best looking one. The application domain targeted in this paper is somewhat different. The purpose of using morphing in this context is to generate intermediate surfaces in the delta volume in order to obtain smooth roughing geometry. Since the context here is machining, some process constraints can be used for the morph sequence generation. It is clear that the intrusion of the cutter geometry into the workpiece material (typically expressed by cut width a_e and cut depth a_p) is bounded. These minimum and maximum values can be used for constraining the intermediate geometry creation.

It was already mentioned that there exist several morphing methods according to the geometrical representation of the 3D source and target shape. The overview paper [9] classifies the possible geometrical representations into 3 categories:

1. Volume based objects, i.e. objects described as level sets of 3D space functions, or as voxel models.
2. Objects described as an elevation map over a planar domain.
3. Objects represented by their boundaries.

The investigations discussed in this paper are based on the object representation model in the third category i.e. BREP. The source and target surface of the morphing sequence are represented as an STL (StereoLithography / Standard Triangulation Language) model. Polyhedral surfaces are a specific case of boundary representation methods. The reason to use this representation is the direct availability of the STL model from the CAD model of the workpiece. Modern CAD systems offer a one-button-click operation to generate an STL surface model of (a part of) the CAD geometry. It would be interesting to investigate the other data representations, but this is beyond the scope of this paper and rather a topic of future research. As will be explained in the following sections a lot of evaluation has to be done to check the appropriateness of morphing techniques to generate intermediate geometry surfaces for roughing. The boundary representation method is here subject of investigation.

Besides aforesaid morphing methodologies, another rather different method is discussed in [2]. Bieterman discusses in that article his newly developed advanced tool path generation method for 2D pocket machining. Instead of parallel offset tool paths from the outer pocket contour, a spiral tool path at the center of the pocket is morphed towards the outer pocket contour. The algorithm is based on a formulation as an elliptic PDE boundary value problem. This approach establishes a smooth tool path for pocketing instead of the sharp tool path corners that continuously appear in tool path tracks generated by offsetting. For high speed machining applications this approach significantly reduces machining time, and improves tool life. The method is being applied in high speed machining of aircraft structural components typically containing huge amounts of pockets to reduce component weight while ensuring structural rigidity. Despite the 2D curve based approach is different from the 3D objectives in this paper, it was worthwhile mentioning since it is one of the rare methods based on the morphing ideas applied in machining technology.

3. ADJUSTING MORPHING TECHNIQUES FOR INTERMEDIATE SURFACE GENERATION

When studying literature on morphing techniques, it becomes clear soon that each application domain requires its own particularities for the morphing algorithms. So does this application of morphing for machining roughing operations too.

As summarized in [9] a lot of research effort has been put into the correspondence problem between the source and the target object. For boundary representation (BREP) objects, the morphing problem is split into two steps: the correspondence step and the interpolation step. These steps are analogous to the warping step and the cross dissolving step in 2D image morphing, but they require completely different algorithms. The correspondence problem tries to find a mapping between the BREPs (polygon meshes are frequently used) of the source and target objects. A big challenge is to establish correspondence between two polygon mesh models, which can differ a lot from each other (ex. car morphing into an airplane, a frog morphing into a prince, etc.). This correspondence is absolutely necessary for the second interpolation step to be able to generate the in-between morph shapes.

This paper suggests a different approach. Instead of trying to find a mapping between the different topologies from source and target object, the topology of the target object is made the same as the topology of the source object. This is possible since the target object is a blank surface in the case of rough machining. This is explained in detail in the following subsections.

3.1 STL as Data Model

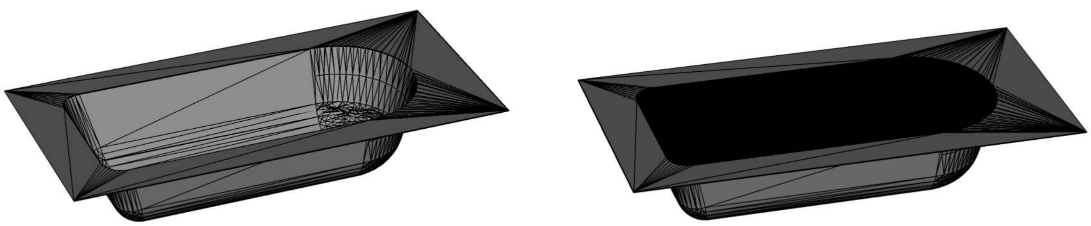
CAM systems obtain the geometrical model information of the workpiece from a CAD system. When both systems use a different geometry kernel, data interface problems often arise. STL is a candidate data interface format. Despite some disadvantages, STL is a good alternative for sculptured shaped work pieces (a lot of mould and die cavities belong to this class of shapes). In our previous work [10] algorithms have been developed for the processing of STL models for CAM applications. The benefits and drawbacks of STL are extensively discussed in [10].

STL is also a BREP polygon mesh and can be classified according to category 3 morphing data representation mentioned above. In this sense, the model is directly usable for morphing sequence generation. The performance of STL as BREP mesh for morphing is of course an important aspect of the investigations discussed in this paper.

The in-between surfaces generated by the morphing algorithm will also be STL surfaces. In that sense, each level of the roughing phase for the mould/die cavity will be a sculptured surface. The tool path generation algorithms developed for finishing operations can be used to machine each roughing level. Of course other cutting process conditions need to be applied and tolerance requirements are far less strict compared to finishing operations. 5-Axis machining tool paths become really interesting in this sense because of their ability to achieve high material removal rates [12]. 5-Axis tool path generation algorithms for STL surfaces have been developed in [8] and [6] for example.

3.2 Source Surface and Target Surface Topology Mapping

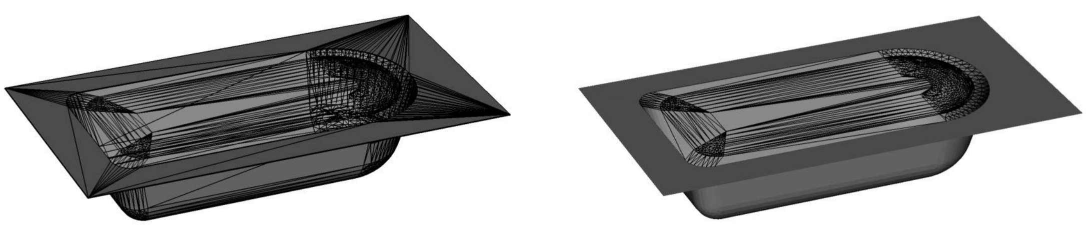
As already mentioned, the new idea in the method described in this paper is instead of establishing a mapping between source and target surface, forcing the topology of the target surface according to the source surface. The cavity shape of the workpiece is called the source surface. The blank surface from which the roughing operation starts (typically a plane through the cavity contour) is called the target surface. A simple example is given in Fig. 3. The left part Fig. 3(a). is the source surface of the cavity together with its surrounding surface, while the right part Fig. 3(b). represents the target by the black 'fill-up' surface.



(a) (b)

Fig. 3. (a) STL model cavity example. (b) Same STL cavity model with cavity blank surface.

The target surface is constructed by normal projection of the source surface facets onto the blank surface plane. This method guarantees the same topology between source surface and target surface for the morph sequence generation. Application of this method on the example in Fig. 3. results in the STL representation of the target surface as shown in Fig. 4. The left side Fig. 4(a). shows both the STL of the work piece (source surface + surrounding surface) and the target surface. To give a better idea about the target surface Fig. 4(b). only shows the STL of the target surface embedded in the rendered model of the work piece.



(a) (b)

Fig. 4. Projection of the source surface facets onto the target surface.

As can be seen from Fig. 4(b)., the STL model of the target surface is not an efficient representation for the blank surface plane. By default, the STL data format aims a surface triangulation that is as efficient as possible (least number of triangles) for a given surface approximation tolerance. When processing the blank surface by the default STL generation algorithm one would obtain a triangulation as pictured in Fig. 5. In this method, triangulation efficiency is sacrificed in order to have an equivalent topology between source surface and target surface.

This approach is a radical change for the correspondence problem in 3D morphing and can only be applied in applications like the rough machining discussed here, where there is some freedom in modeling one of the end geometries of the morph sequence. For animation morphing applications this method is not applicable and user interaction is still needed to successfully solve the correspondence problem.

By handling the correspondence problem in the way suggested here, the hard correspondence problem is actually by-passed and more attention can be paid to the interpolation problem.

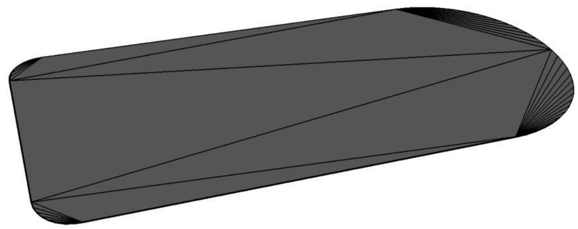


Fig. 5. Optimal STL triangulation for the blank surface.

3.3 Topology Data Structure

Because of the one-to-one topology mapping between source surface and target surface of the morph, an efficient representation scheme on behalf of the interpolation algorithms can be elaborated. The enhanced STL data structure developed in [10] is the basis for this topology data structure.

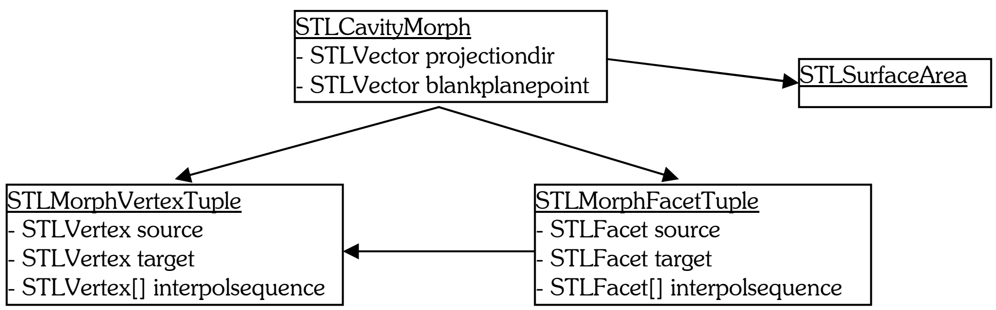


Fig. 6. Morph topology data structure scheme.

The classes STLMorphVertexTuple and STLMorphFacetTuple capture the topology equivalence. The first step is building the STLMorphVertexTuples. For each source vertex on the cavity surface, a target vertex on the blank surface is associated by projection. The interpolation step described in the next section generates intermediate vertices between the source and target vertex. After all the vertices of the cavity surface have been processed this way, the STLMorphFacetTuples can be constructed. Making use of the STLMorphVertexTuple it is easy to generate the STL facets at each level of the morph sequence. The final step is the connection of all newly generated facets with each other at each morph level. Since the connectivity of the source surface is given, the connectivity of the intermediate surfaces and the target surface can directly be derived. The result is that the STLCavityMorph class can supply STLSurfaceArea objects for each level of the morph sequence. These surfaces represent the intermediate roughing stages for the cavity.

3.4 Morphing Levels Interpolation

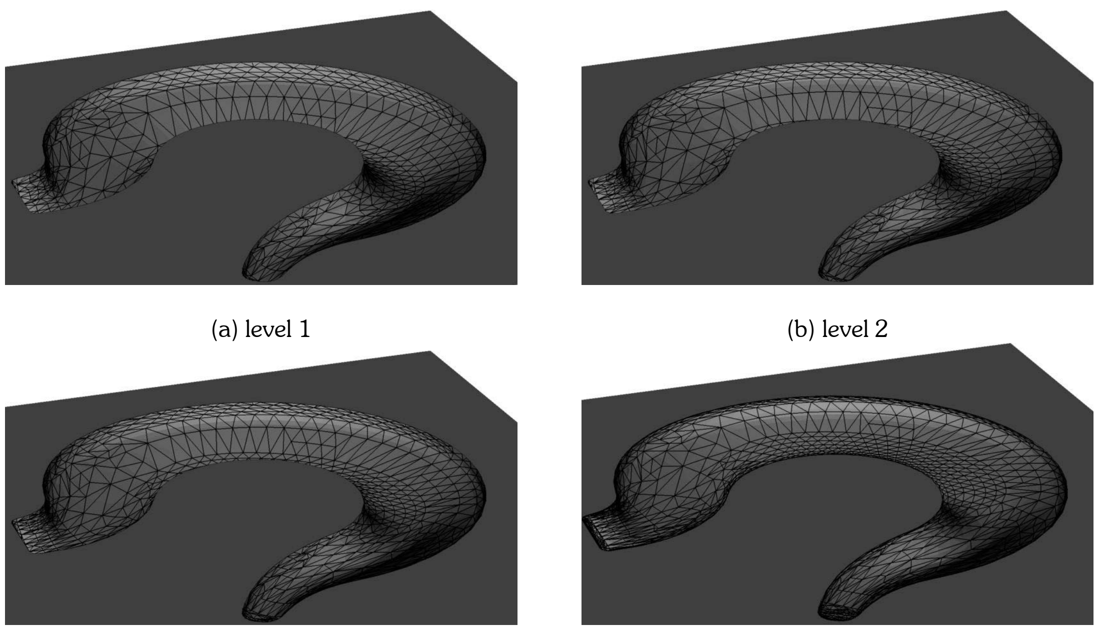
For the interpolation step in the morphing of BREP models, linear interpolation and Hermite spline interpolation are the most used techniques. In this work, both methods have been implemented and evaluated.

3.4.1 Linear interpolation

The linear interpolation is the easiest and most straightforward interpolation method. This method considers the line segment between source vertex and target vertex. That line segment is divided into equidistant segments according to the desired number of levels for the morph sequence. The number of morph levels depends on the cutter dimensions, cutting process conditions and the roughing tool path strategy. It is easy to extract the longest vertex tuple distance from the topology data structure presented in the previous section. This longest distance can be used for setting the number of levels in the morph sequence.

An example of different morph sequence levels generated by linear interpolation is given in Fig. 7. This example illustrates a mould cavity for a hook. The number of levels in this example was set to 6 (source and target surface level included and numbered source=0 and target=5). While at first sight the 4 pictures look almost identical, a closer look to the shape of the STL triangles of each morph level shows a clear deformation. The STL resolution for this example was especially set low to result in big facets in the model. Unfortunately this paper is restricted to screen captures of the model and cannot give the 3D impression of this model by interactive manipulation that clearly shows the smooth intermediate morph surfaces.

Using the longest distance to define the number of morph levels is a simple straightforward method. More advanced methods would also take the distribution and variation in source-target distance along the different vertices into account. It is clear that machining efficiency will be influenced if the cavity contains a small region that is rather deep compared to the rest of the cavity shape than a cavity with equally distributed depths. The linear interpolation method is rather suited for the latter case. It still lacks on technology data about 3D rough machining to elaborate systematic methods for handling this issue. Our current research is focused on this aspect.



(a) level 1 (b) level 2

(c) level 3 (c) level 5

Fig. 7. Morphing sequence example.

3.4.2 Hermite spline interpolation

The drawback of the linear interpolation is the lack of control on the intermediate points generation. To cope with this problem the Hermite spline interpolation is suggested. A Hermite spline is a cubic spline curve defined by two controlpoints at the start and end of the curve and the two control tangents at start and end point [4].

The parametric formulation for the Hermite spline is given by Eqn. (1) with the parameter $t \in [0,1]$.

$$c(t)=\left(\begin{bmatrix}2 & -3 & 0 & 1\\ -2 & 3 & 0 & 0\\ 1 & -2 & 1 & 0\\ 1 & -1 & 0 & 0\end{bmatrix}\begin{bmatrix}t^3\\ t^2\\ t\\ 1\end{bmatrix}\right)^T\begin{bmatrix}P_0\\ P_1\\ P_0^{'}\\ P_1^{'}\end{bmatrix} \quad (1)$$

The control over the curve shape is obtained by the parameters P_0, P_1, P_0' and P_1'. Fig. 8. shows a schematic example of these control parameters

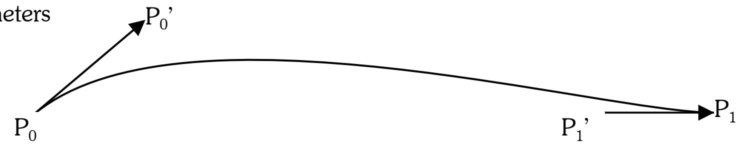


Fig. 8. Control parameters of the Hermite spline curve.

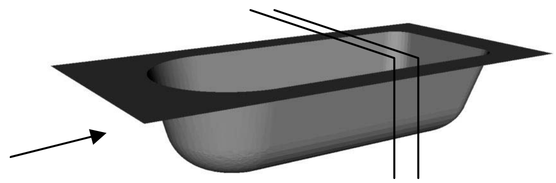
The control parameters of this type of curve are particularly interesting for the morphing interpolation problem. The endpoints P_0 and P_1 can be mapped onto the source vertex and target vertex of the morph sequence. This leads to a 3D Hermite spline curve. The remaining control parameters are the tangent vectors P_0' and P_1'. This paper suggests for the morph application to map these parameters onto the normal vectors of the source surface and the target surface. However the normal vectors have to be defined yet. The easiest one is the P_1' normal vector. This one accords to the plane normal vector of the blank surface. It is only needed to test whether this vector points towards the source surface of the cavity. This test is performed by making sure that $(P_1-P_0).P_1' < 0$.

The P_0' vector should be set to the source surface normal vector at the point P_0. Since the only dataset involved in the algorithms discussed here is the STL surface model, there is no direct availability of the surface normal vector at an STL vertex. Only STL facet normal vectors are available from the STL dataset. Since the mesh topology of an STL surface is sometimes highly irregular, averaging methods to calculate a vertex normal vector from the normal vectors of the surrounding facets often return unsatisfactory estimates. Alliez et al. developed in [1] a more robust method for normal vector estimation at a triangular mesh vertex. In our work [11] an implementation of this technique for workpiece STL models is described. The enhanced data model referred in section 3.3 contains this functionality of normal vector estimation at a non-edge vertex. This estimated normal vector is used for the P_0' parameter definition.

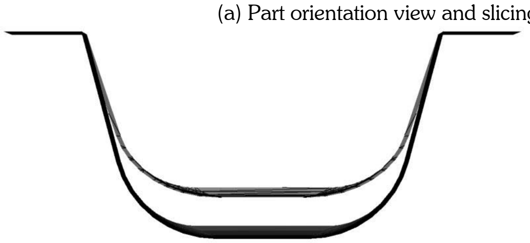
An important remark is that the normal vectors obtained from the data model to control the Hermite spline interpolation all have length 1. However, the P_0' and P_1' parameters do not have to be restricted to length 1. On the contrary, scaling the tangent vector allows manipulation of the morph sequence generation.

The control parameter variation is illustrated in Fig. 9. The simple cavity model is used and morphed into 6 levels (source level and target level included). For the paper print, the 3D model is sliced by 2 clipping planes schematically indicated in Fig. 9(a) so that the other figure components only show a small piece of the 3D surfaces involved. Otherwise the screen captures get too confusing. The linear interpolation technique is also added to show the difference. For the Hermite interpolation only the P_0' length parameter is changed. The pictures show clearly the varying level 1 morph surface shape according to the parameter variation.

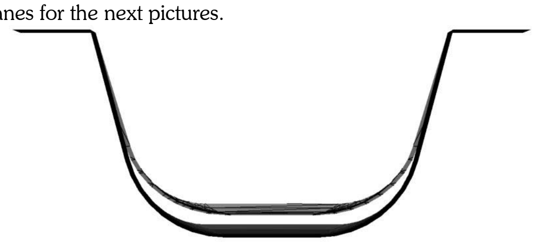
One remark certainly to be made is that if the P_0' length is set too high; illegal morph level surfaces can be generated since the vertex tuples are crossing each other. This should of course be avoided. Our algorithm contains a test to check if surface inconsistencies appear in the morph sequence. The STL facet normal definition is used for this purpose. The vertices of an STL facet are ordered so that the facet normal vector obeys the right hand rule when scrolling over the facet vertices. Because of the correspondence between vertices in the morph sequence, the orientation of a facet generated in the morph sequence can be checked. If following the right hand rule shows that the newly generated facet has a normal vector pointing in the opposite direction of the source / target facet normal vector (i.e. dot product < 0), an illegal intermediate surface will be created. The sensitivity of the morph sequence to this problem depends on both the shape of the cavity, but also on the STL mesh of the source cavity. For the case in Fig. 9. the limit is $|P_0'|=32$ to produce useful intermediate surfaces. As can be seen in Fig. 9(e) the $|P_0'|$ value exceeds the limit and the intermediate surface also shows discontinuities. Irregular STL meshes have a certain disadvantage at this point compared to regular triangle meshes. It still needs further investigation to identify cases where a remeshing would be appropriate to obtain a smoother morph sequence generation.



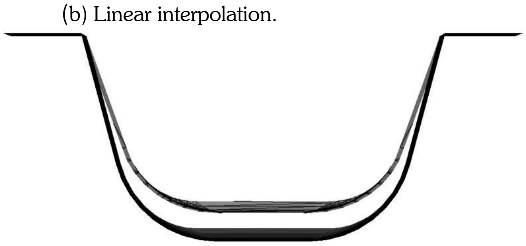
(a) Part orientation view and slicing planes for the next pictures.



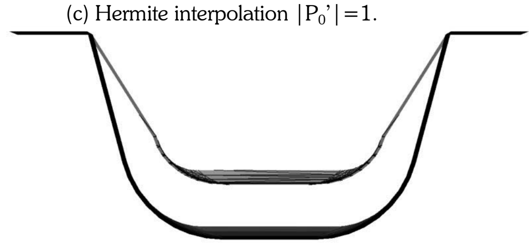
(b) Linear interpolation.



(c) Hermite interpolation $|P_0'|=1$.



(d) Hermite interpolation $|P_0'|=10$.



(e) Hermite interpolation $|P_0'|=50$.

Fig. 9. Level 1 morphing surface versus level 0 source surface for different interpolation variants.

It is clear that the Hermite technique offers a lot of extra control on the morph sequence generation, but it contains also a risk of generating illegal morph geometry if the control parameters are set to extreme values. The Hermite interpolation technique arranges the low-level morph surfaces suiting the source surface shape.
An important implementation remark to be made is that the intermediate level definition for the Hermite interpolation is based on equidistant subdivision of the parameter domain in the Hermite spline definition Eqn. (1). A question that still remains open is if it is necessary to use an arc length parameterization of the Hermite spline instead for this application for morphing. This will be discussed together with some other remarks in the next section.

4. DISCUSSION

In the previous section two morph interpolation techniques are presented for the generation of roughing intermediate surfaces. The fast and easy linear interpolation method is robust but offers no freedom to manipulate the morph surface sequence generation except by the number of morph levels. The more advanced Hermite spline interpolation method is more flexible in manipulating the intermediate morph surface shapes, but is more error prone when the controlling parameters are carelessly set. Since the linear interpolation does not allow a lot of control, it is in its current implementation only suited for cavities of low depth with not much shape variation along the cavity depth. For more complex shaped cavities and / or deeper cavities, the Hermite spline based method will be necessary for the morph sequence generation.
Since this paper discusses the basic developments for morphing techniques in multi-axis cavity roughing, a lot of knowledge still lacks on the parameter values to be set in order to obtain good machining process conditions. There is still a significant lack off knowledge on 5-axis rough machining technology. Questions like: What material removal rate variations are allowed? What is the influence of the tool posture during rough machining? How does the complex roughing surface shape relates to the roughing efficiency? etc. All these questions still remain unanswered.
Scientific research on machining technology is needed to answer the questions above and to finally answer the question which morphing method to use and eventually which parameter values to set. The framework for the 5-axis intermediate roughing surface generation is developed in this paper. Additional technological constraints should be added for practical application.

5. CONCLUSIONS

This paper presents a new approach for cavity rough machining of complex shapes (moulds and dies). The traditional approach for roughing these shapes is a 3-axis method with heavy-duty cutters. Although the traditional method is very efficient, its major drawback is the stock shape that is released which contains abrupt discontinuous geometry (called 'stairs'). The new approach in this paper suggests a substitution of this irregular geometry by smooth intermediate rough surfaces. Applying a morphing technique generates these surfaces. A 3D BREP based morphing technique is developed within this paper. The geometry model of the cavity is processed as an STL model. A novel approach to tackle the mesh correspondence problem for this class of applications is presented. This allows automated operation of the algorithm in contrast to the required user interaction needed for morphing techniques applied in computer animation. The interpolation step of the morphing is discussed with the machining process conditions in mind. Two interpolation techniques are presented. A simple but robust linear interpolation is put in contrast to a more flexible Hermite spline based interpolation that allows extra control on the morph surface shapes.

The resulting intermediate surfaces allow 5-axis roughing operations. Since 5-axis tool path generation techniques directly on STL models are gaining support by the research community, this method opens new perspectives for complete 5-axis machining. However today's lack of knowledge on 5-axis rough machining technology does not allow giving a clear advice yet on the selection of interpolation strategy and the according parameters settings.

Future research should concentrate on performance testing of 5-axis roughing methods. Other morphing techniques (based on other dataset types) are also worthwhile investigating for the application domain discussed here.

6. ACKNOWLEDGEMENTS

This research is funded by a specialization grant of the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen).

7. REFERENCES

[1] Alliez, P., Cohen-Steiner, D., Devillers, O., Lévy, B. and Desbrun, M., Anisotropic polygonal remeshing, *ACM Transactions on Graphics*, Vol. 22, No. 13, 2003, pp485-493.

[2] Bieterman, M., Mathematics in Manufacturing: New Approach Cuts Milling Costs, *Siam News*, Vol. 34, No. 7, 2001.

[3] Choi, B. K. and Jerard, R. B., *Sculptured Surface Machining: Theory and applications*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1999.

[4] Farin, G. and Hoschek, J., *Handbook of computer aided geometric design*, Elsevier Amsterdam, 2002.

[5] Fujimiya, M., *Morpher Application*, http://www.asahi-net.or.jp/~FX6M-FJMY/

[6] Jun, C.-S., Cha, K. and Lee Y.-S., Optimizing tool orientations for 5-axis machining by configuration space search method, *Computer-Aided Design*, Vol. 35, No. 6, 2003, pp 549-566.

[7] Lauwers, B. and Dejonghe, P., Simulation of milling operations: an effective support tool during NC-programming, *Proc. 13th Machine Tool and Manufacturing Technologies Congress*, San Sebastian, 25th – 27th October 2000, pp 1087-1106.

[8] Lauwers, B., Kiswanto, G. and Kruth, J.-P., Development of a Five-axis Milling Tool Path Generation Algorithm based on Faceted Models, *Annals of the CIRP*, Vol. 52, No. 1, 2003, pp 85-88.

[9] Lazarus, F. and Verroust, A., Three-dimensional metamorphosis: a survey, *The Visual Computer*, Vol. 14, 1998, pp 373-389.

[10] Lefebvre , P. P. and Lauwers, B., STL Model Segmentation for Multi-Axis Machining Operations Planning, *Computer-Aided Design & Applications*, Vol. 1, Nos. 1-4, *CAD'04*, 2004, pp 277-284.

[11] Lefebvre, P. P. and Lauwers, B., Multi-Axis Machining Operation Evaluation For Complex Shaped Part Features, *Proc. 4th CIRP Intelligent Computation in Manufacturing Engineering*, Sorrento, Italy, 2004.

[12] Vickers, G. W. and Quan, K. W., Ball-Mills versus End-Mills for Curved Surface Machining, *Journal of Engineering for Industry*, Vol. 111, No. 2, 1989, pp 22-26.