Tool path generation for flexible blade cutting

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Abstract

Free Form Thick Layered Object Manufacturing FF-TLOM is based on application of a reshapeable cutting device, which allows a free form shaping of thick polystyrene foam layers. Once manufactured, these layers are stacked to produce a physical model. Tool path generation for the heated flexible blade tool is a challenging task, since it influences the quality of the manufactured objects as well as the effectiveness of the fabrication process. The difficulties arise from the following facts: (a) when slicing is computed, the instantaneous tool positions are defined by matching the blade profile against the nominal shape of the CAD model, (b) the tool positions calculated relative to the cut layers have to be converted into the global reference frame of the layer cutting equipment, (c) the resultant tool path should maintain the achieved preciseness approximating the front surface of the layers, and (d) it is impossible to calculate all points of the tool path in real time.

This paper proposes an effective tool path calculation method for flexible blade cutting. The contour of the layers is converted into an ordered set of smooth and awkward boundary features. For the smooth boundary features, the tool positions are computed by dense sampling in order to achieve the optimal cutting.

Introduction

Large-sized, free form physical models (up to 6m and beyond) are applied in the household equipment, automotive, advertisement, and entertainment industry. And are applied for scenery pieces in movie film making, for stage settings in theatres, sculptures, ornaments and for large-sized human or animal mannequins. In scientific research and industry, these models support visualization of mathematical models, testing of human-product interaction, analyzing aerodynamic and hydrodynamic behavior, as well as aesthetic and ergonomic impressions [2].

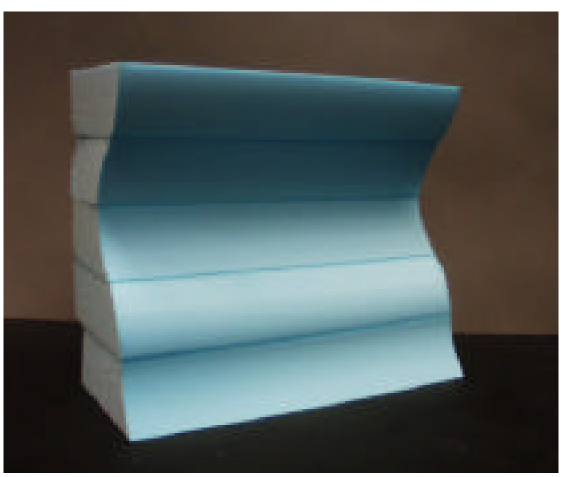

Figure 1 Typical FF-TLOM layer stacking

Physical models of extreme large format are typically made of plastic foams, which are cheap, soft and lightweight materials. Neither decremental nor incremental processes in themselves are well suited for large-sized applications. Normally the dimensions of the manufacturing equipment limit the dimensions of the manufactured objects. Therefore, object manufacturing in the large size domain needs dedicated fabrication technologies.

In the recent years thick layered object manufacturing (TLOM) has been demonstrated in [9], [5] and [3]. In these examples, the nominal shape is approximated by first order surfaces (ruled surface or slanted front surfaces), while the layer thickness is adapted to the required accuracy needs (adaptive slicing). Systems such as Trusurf, Formus and Shapemaker offer specific technologies to fabricate large-sized objects. The fabrication of large-sized free-form physical models by layered manufacturing had been in the focus of our research. In order to extend the conventional LOM technology to the large size domain, the research team of the authors successfully developed the free-form thick-layered object manufacturing (FF-TLOM) technology [1].

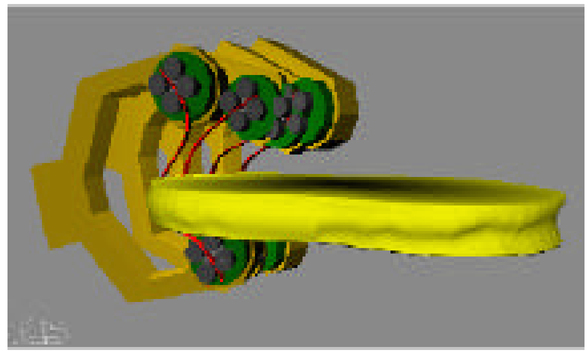

Figure 2. FF-TLOM process simulation

The FF-TLOM technology is based on free form shaping of the front surfaces of each layer, higher order approximation of the nominal shape, application of (very) thick layers, with the same or better accuracy and smoother outside surface of the model, and decomposition of the nominal shape (CAD geometric model) into smaller, easy to manufacture parts. The machined parts are assembled, or stacked, to form a physical model. Higher order approximation and free form shaping, however, require very sophisticated manufacturing techniques. The proposed technology uses thick high-density polystyrene foam layers, which front surfaces are shaped according to the principle of free form cutting. The cutting tool is an electrically heated, flexible blade. The profile, i.e. the curvatures of the blade is continuously adjusted according to the local nominal shape of the geometric model.

The flexible cutting blade f or cutting polystyrene foam. The is supported at both ends in a U-shaped frame structure. Both supports can rotate, thus introducing inclination at both ends of the blade. The shape (or curvature) of the blade is defined by the tangent vectors at the supports, the length of the blade, the position of the supports and the assumption that the blade takes its shape according to the least bending energy principle [6].

In figure 2, an example of free form layer cutting is presented. Cutting tests indicate the feasibility of the technology [4]. The actual cutting is performed by the heat radiated from the electrically heated blade, which locally melts the foam and creates a gap in which the cutting blade can proceed continuously, with low resistance. The material applied for the blade is very important, because it must have specific electrical resistance, and a minimal cross section, but at the same time, it must be rigid enough to sustain the tool shape during cutting.

and it is bent during cutting in a flexible, elastically way [10]. The cutter moves along the foam slab according to figure 3. The cutter frame motions are defined in fig-

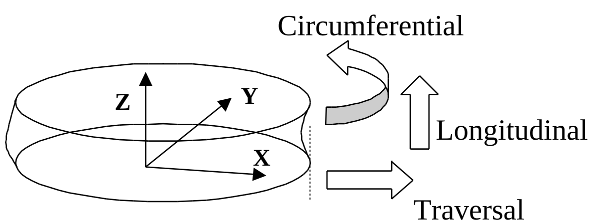

Figure 3. Principles of cutter movement along foam slab.

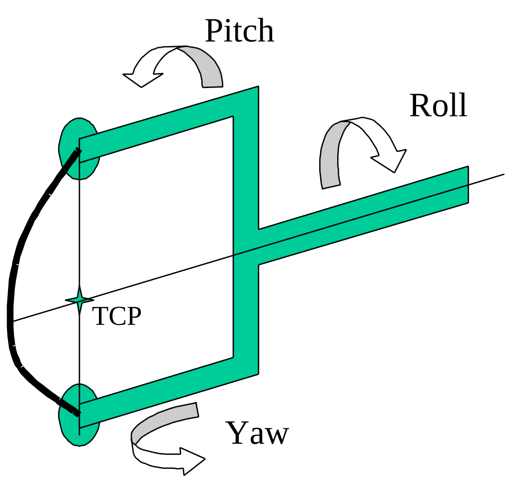

Figure 4. Cutter frame motions

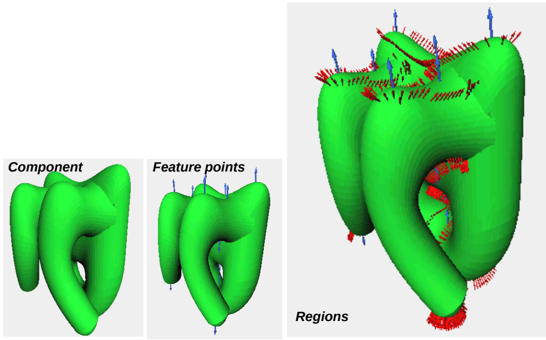

Figure 5 Decomposition preparation for segmenting

ure 4.
First the CAD-model is reduced to manufacturable elements. The decomposition is based on partly morphological and partly technological conditions. A segmentation orientation is chosen and a dense network of surface normal vectors is calculated. Points where these normal vectors are collinear with the segmentation orientation are special points and are called feature points. They indicate a higher level slicing unit, called segment, which are further sliced to get layers. During cutting of the front surfaces of a layer, the cutting tool pitch must be limited to avoid extremities. Those regions of the model, indicated by a set of normal vectors of specific properties, as shown in figure 5 need alternate segmentation. The advantage of segmentation of an object is that each segment can be produced with optimal slicing orientation. As a result of decomposition, the dimensional and morphological complexities are reduced and much better conditions for manufacturing are achieved.

Analysis of contour curve (Cc) features

We assume that the CAD model, (a) is either represented in NURBS (exact representation) or as a facetted approximated model, (b) is already decomposed in a component level, (c) is checked for consistency. Furthermore as a starting stage for tool path calculation, we assume that (d) a segmentation orientation has been chosen, (e) normal vectors and feature points have been calculated and fixed, and (f) regions of excessive pitch have been detected and indicated.

In the case of a NURBS representation the slicing contour is calculated from intersections with the slicing plane (2D hedgehog). The result is a dense, but discrete, set of points approximating the slicing contour. Straight lines interconnect the points and a closed polyline slicing contour is created. The facetted representation (e.g. STL) is sliced directly with a

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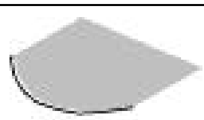
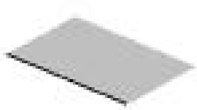
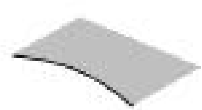
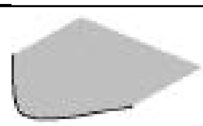
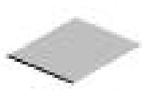
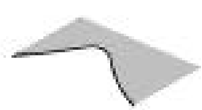
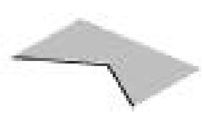
region	large				1
	medium				2
	Focal				3
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Table 1: Feature overview for FF-TLOM slicing contours

plane, which results in a closed polyline contour. Multiple slicing contours related to a slicing plane are possible, but the actual segmentation will not affect the principle of tool path generation presented, below. However, for a successful prototype manufacturing the calculated polylines must have a better accuracy than the expected accuracy of the prototype. Now, both representations have the same resulting representation. Each slicing contour consists of an interconnected set of points or a closed polyline.
The planning of the tool path requires the analysis of the calculated contours at the bottom and at the top of each layer. It is important to achieve the optimal constant maximum cutting speed and surface finish in cutting the slabs [4] with minimum cutting force. Therefore, the morphological properties of the contour curves have to be investigated. A curve, typically, consists of convex, straight and/or concave sections, which may extend to a large or medium part of the curve, or can be focal. The possible combinations are shown in table 1.
Contour curvatures spread over "large" regions correspond to moderate curvature and related gentle motions of circumferential cutting. A straight line in a slicing contour can be cut by one constant linear motion. The medium regions will invoke fiercer motions of the cutting tool and equipment. The concave cases, depending on the outer dimensions of the cutter, need special attention since they may cause tool-slab interference. Focal regions are not manufacturable by one single continuous cutting motion. As it is suggested by this initial investigation, different cutting sequences are needed for various kinds of local shape features. The task is now to subdivide a slicing contour into a number of classified cutting features of table 1. Subdivision into Cc features and indication of the feature boundaries, following the scheme of table 1 are presented in figure 6.

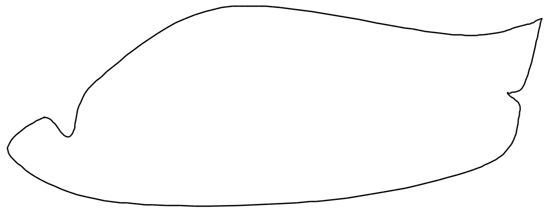

Figure 6a A typical slicing contour

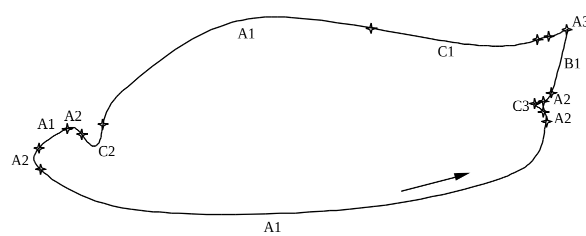

Figure 6b The slicing contour subdivided into curve features

Starting with the lower part of the contour in figure 6b, the Cc feature sequence for contour **i** clockwise is: $F_{cc}(i)$ = A1, A2, A1, A2, C2, A1, C1, A3, B1, A2, C3, A2
In order to make an estimation of the curvature and to subdivide the contour into Cc features the closed polyline is analysed in the following way. A first point of the polyline and next two points clockwise on the contour are chosen. Triplets of points are elaborated for the internal inclination of both connecting lines. For all the points on the contour the inclination of the next line with the previous connecting line is calculated.
In figure 7 P_1, …P_i….P_n are points of the polyline contour, from which point P_n is connected with point P_1 to close the contour. Line L_i and line L_{i+1} incline to each other at an angle $\_{i}$. So, $\_{i}$ is calculated from: $\_{i} = arctg(x_i-x_{i+1})/(y_i-y_{i+1}) - arctg(x_{i-1}-x_i)/(y_{i-1}-y_i)$. Sum of all calculated $\_{i}$'s is 2π.
The magnitude and sign of _ is an estimate of the curvature of the contour. When in a specific range of the polyline the magnitude and sign of _ are comparable then a Cc feature is detected. However, the analysis of the polyline for curvature is influenced by inaccuracy of calculated contour points from NURBS nominal shapes. The calculation method of an individual contour point is iterative, and each point will have a small random inaccuracy. Also, overall accuracy of the manufactured prototype must be considered. The curvature analysis therefor must be performed in a global way (curvature analysis over more than one point triplet). Or

the original NURBS representation is applied to analyse geometric properties of the contour curve. However, when analysing the curvature globally, there is a chance that a singularity in the shape is not detected properly. That will affect the quality of the physical model, because singularities characterise a shape in a dominant way. An algorithm, which allows a dependable curvature analysis, is needed. The contour curvature distribution is transferred into curve features (see table 1 and figure 6).

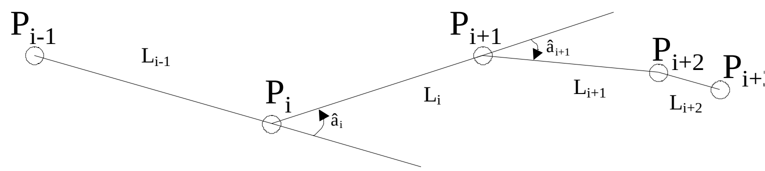

Figure 7 Polyline analysis

<u>Path planning (Pp) features</u>

Next, we consider the slab thickness and how to involve that information into the tool path generation. Mathematically we can calculate the slab thickness very accurate [7] but the foam slabs in store have standard thickness. For many reasons it is advisable to have a range of inter- or exchangeable foam slab thickness. Proposed are slab thicknesses ranging from 20 mm to 100 mm in steps of 20 mm. In restricted situations slabs of 10 mm are considered, but only supported or combined with thicker slabs during cutting, due to the fragility of the slab. The slab fixture or slab gripping of the FF-TLOM cutting equipment must be able to handle these compound slabs.

When this is accepted, then it is possible and very efficient to calculate slicing contours in advance without being involved in extensive matching calculations as described in [7], object segmenting is decided upon and an impression of the cutting efficiency is provided.

First a selection is made about the slicing orientation of the segment and a position for the first slicing contour, which must be favourable for a successful and efficient segmenting. The segmentation is optimised, and when needed, sliced in a premature contour distribution based on a grid of 20 mm. For each contour, subdivision into FF-TLOM related curve features is made. Brief analysis of the Cc features, inside one segment and related to the subsequent slicing contours according sort, amount and position is made and when necessary some initial decisions, e.g. about applying a different slicing orientation or even to start all over with a new segmentation orientation, are taken. At this moment, visualisation tools and manual intervention are needed, for comparison and decision making. But, afterwards when more knowledge and experience is available, the analysis and decision making will be automated in more extent. From contour maps of one segment also geometric information perpendicular to the contours is available and can be applied for early analysis of initial layer thickness for tool curve matching. This statement needs some explanation. From two neighbouring contours, both mapped on the same plane, the distance between both contours can be monitored.

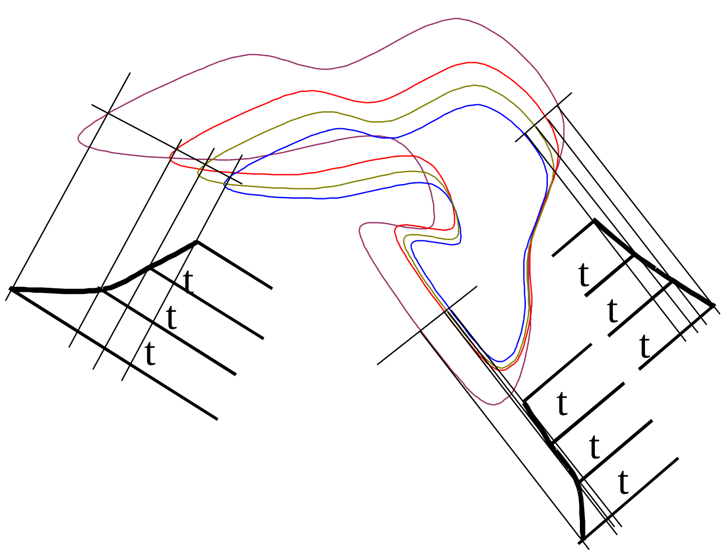

Figure 8 Contour map and curve reconstruction

When e.g. the distance becomes more than the considered layer height, there will be too much tool pitch involved. Also, sudden changes in pitch and yaw of the tool are detectable. In figure 8 a number of typical slicing contours are mapped on the same plane and a restricted number of cross-sectional polylines are reconstructed on troublesome positions. These lines provide also an indication about success of the tool curve matching.

Result of the activities up till now is that segments are defined out of a component and the segment is sliced in a standard pattern. The slicing contours are available and are classified into Cc features. An impression is available about the extent and magnitude of the Cc features. Problem areas are detected and treatment of the segments and layers is in concept known. Clustering of slicing contours is performed based on the reconstructed polyline information in order to fix standard slab height for manufacturing. In spite of the given fact that tool curve matching in a later stage of the preparation process can change this result.

Next step is the preparation of a layer from the Cc features of the available slicing contour in such a way that an efficient object manufacturing is assured. From the mapped inter contour distance an impression is obtained about the change in cutting tool pitch and the magnitude and boundaries of the FF-TLOM curve feature. A layer thickness from the stock range is chosen, so both top and base of the layer are fixed. The layer consists of an upper contour, a lower contour, both partitioned in Cc features, ($F_{Cc\ upper}$ & $F_{Cc\ lower}$) and the nominal shape of the object. The task is, given the Cc features of the upper and lower contour and the related boundaries to create Pp features. The boundary connections between upper and lower contour must be investigated thoroughly, because the Pp features are manufactured one by one in one continuous circumferential cutting motion.

Difficult tool motions can be expected when the upper and/or lower Cc features are of the level 2 or 3 (table 1). The upper and lower Cc features can be combined and again a classification is made based on table 1. For the regions we have combinations of large-large, large-medium, large-focal, medium-medium, medium-focal, and focal-focal. For the shape we have combinations of convex-convex, convex-straight, convex-concave, straight-straight, straight-concave, and concave-concave. In table 2 the combination of a "large-large" and "focal-focal" regions are presented. In total, we recognize 43 different Cc feature combinations. At a later moment, we have to reduce the number of combinations. As mentioned before the cutting strategy is a continuous constant speed process and the cutting tool movements are combined motions of pitch, yaw and roll.

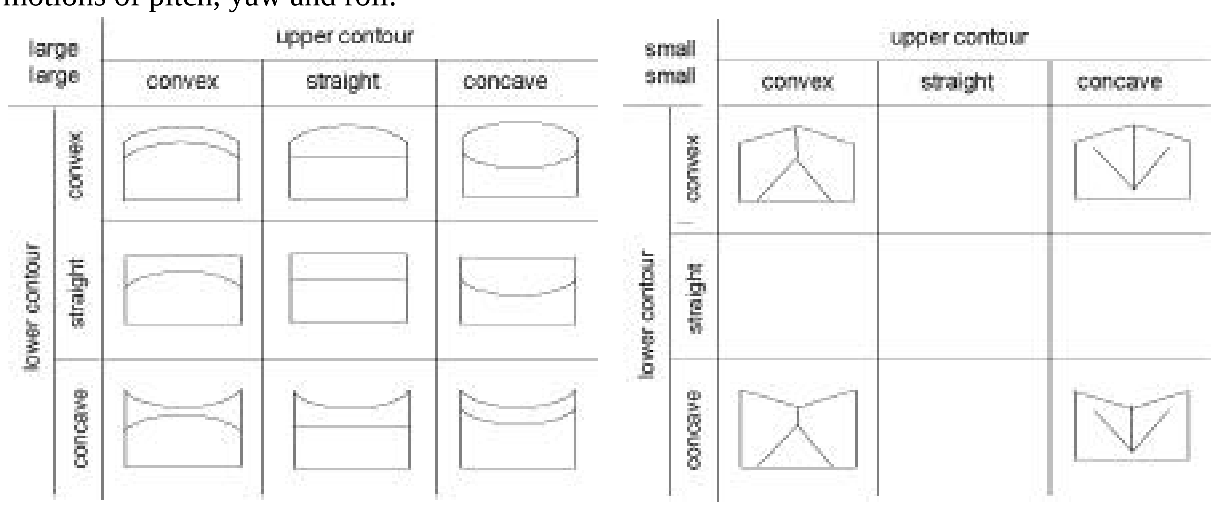

Table 2 Pp feature for a FF-TLOM layer (combination 'large-large' and 'focal-focal')

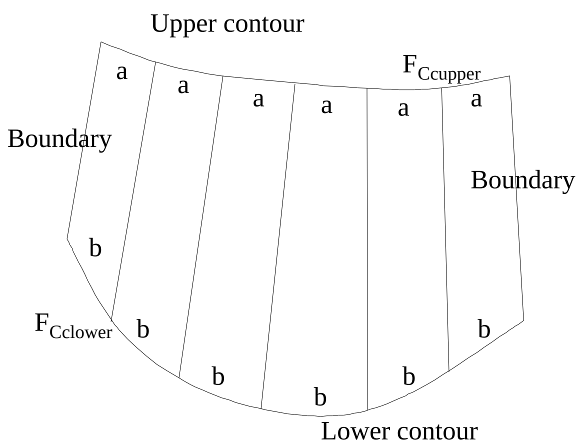

Figure 9 A FF-TLOM path planning feature

For the assumed straight cutting tool and for each type of feature a specific cutting sequence or cutting procedure can be developed. The cutter motion starts at one boundary and moves continuously towards the boundary at the other side. The points needed for an initial orientation of the cutting tool (setting of pitch and roll) have to be derived from the contour data in an accuracy, which is better than needed for an acceptable final prototype. In figure 9 sampling of such tool motion is presented. The individual tool positions fix the pitch and roll motion of the tool, leaving the yaw motion of the tool free to choose. The best way to define and fix the yaw is to calculate the local tangent at the upper contour and the lower contour. Calculate the mean value of both tangents and apply that value as yaw parameter. The tangent calculation can be biased by the same errors, which are described in the inclination calculation for feature recognition due to inaccurate point calculation. Taking the mean value of the tangents will minimise the mismatch of the cutting direction and the orientation of the cross section of the cutting blade (see figure 10). When the upper and lower tangent differ too much the number of contours can be decreased.

The orientation of the tool is fixed and next the position of the tool is chosen. The Tool Centre Point (TCP) of the tool is defined according to figure 4. At this point we have for each feature a set of tool positions related to a first order approximation. When we want to apply a higher order approximation it must be superimposed over the first order result.

An estimate of the total machining time can be calculated from the sum of cutting motion L(i) along the longest Cc feature for each Pp feature. In general

do i=1,n (if {[L_{upper}(i).gt.L_{lower}(i)] then $L_{total}=L_{total} + L_{upper}$ else $L_{total}=L_{total} + L_{lower}$})

Finally, the total free form cutting time is estimated by: $T_{cutting} = L_{total} / V_{cutmax}$.

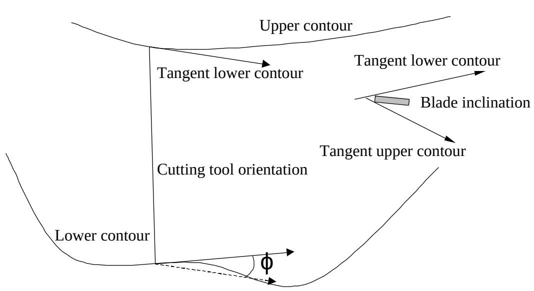

Figure 10 Yaw fixture from tangent calculation at both contours.

The higher order approximation and the related issues of the FF-TLOM technology are described in [7]. A library of tool curves are matched with the nominal shape contour. The nominal shape contour is defined by the plane defined by the lines between upper and lower contour (figure 9) and the calculated yaw. Successful matched tool curves (least bending energy curves) are gathered for each position. Than the cutting section of the blade in effect and the supporting blade points are known. The tool frame orientation and position need some corrections for an accurate cut.

Tool path generation

The tool path must be generated from an interpolation between the calculated single tool positions and sequence of tool shapes. Motion inversion must be avoided as much as possible. Regions of excessive jerk must be analysed and the motion must be smoothed to avoid damage of the cutting equipment. Much research is needed for understanding what optimal and magnitude smoothing is required. Also knowledge about the influence on tool motions is required for the continuous cutting at the transition from one Pp feature to the next. Another issue is the special way of cutting focal-focal PP feature. Continuous cutting is impossible and therefor the cutter has to leave the surface, set a new orientation and return to the surface for cutting continuation. Each of the Pp features is related with a defined pattern of effective tool motions, and. a tool path is generated from interconnected Pp features.

Conclusions

A straight forward tool path generation method is proposed, which can be applied for first order and is extendable for higher order approximation and different shaping technologies for the production of thick layers. The method is applied in this paper for the FF-TLOM technology. The preparation for manufacturing starts with standard analysis and standard methods and offers the opportunity, during the preparation stage, to decide about effectiveness of the manufacturing effort. The last part of the preparation process is the tool match and tool path generation based on heavy time-consuming calculations.

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