Enhanced B-Rep Graph-based Feature Sequences Recognition using Manufacturing Constraints

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Abstract
In this paper we propose and investigate the possibilities offered by a new approach to find milling sequences and chains to optimize the machining time. Optimized milling sequences helps the process planner in understanding and setting the optimal strategy to reduce the part's machining time. Most previous chaining approaches concerned 2.5D pocket recognition for automotive mechanical parts. We present a new approach adapted to complex parts with a multitude of 5-axes orientation, focusing on our restrictive chaining algorithm based on the previously extracted machining directions. In a latter phase, the output sequences are filtered whereas we account the manufacturing fixture and machine-tool constraints.

Keywords
Face sequencing, Chaining, Manufacturing fixture, Machining directions, Machining feature recognition

1 Introduction

Research conducted in the field of Computer Aided Process Planning software studied the recognition of manufacturing features which included inherently their chaining strategy. Then, the system studied how to sequence the milling of these machining features. Within our approach, developed in the scope of the USIQUICK Project [9], we treated the problem in a completely different manner. Instead of translating the part into a set of machining features and pursuing with the process plan, we go to the lowest level of the part geometry, enrich it with information and propose a chaining strategy to deduce the manufacturing sequence. For more information, please refer to [1, 2, 4, 11].

Within the scope of our article, we try to propose an approach to find milling sequences based on a restrictive chaining algorithm split into two main sections. The first would generate the Chaining Graph (CG). The second section is applied to "restrict" the chaining graph to machinable solutions. This restriction is made by including manufacturing fixture constraints and checking the proposed chaining falls in the machine rotational capabilities.

2 State of the Art

Three generic major steps can be highlighted in the literature survey on generative CAPP systems: (1) Feature recognition, (2) Operation planning and (3) Set-up planning. The former consists in identifying machining features on a part from the solid 3D model, the second deals with matching a machining operation to a feature, while the last groups the process operations into set-ups and sequence operations within each set-up.

Considering feature recognition, most approaches rely on the attributes and topology of elementary geometric elements (edges, vertex, volume…) to recognize them, taking the assumption that a preferred direction of tool axis is known. Indeed, most of the mechanical parts to machine are 2.5D parts; therefore the tool axis is constant during the machining and is easily extractable from the overall shape [10]. Techniques for 5-axis features (which are not easy to classify, therefore more difficult to recognize) are still confidential and not clearly explained [6].

To conclude, most approaches mainly focus on geometrical aspects to set the final geometry of extracted features. Few authors consider some manufacturing constraints other than generic rules affecting geometry. Gaines et al. [3] propose an approach to construct complex features considering existing tool shapes (tailored made) in the workshop. Raman et al. [8] overcome the "predefined features" limitation taking into account tool and process capabilities while interpreting the design. Lee et al. [7] propose some alternative 2.5D feature set considering various tool axis orientation for prismatic parts.

The proposed approach is quite innovative because it relies on the extraction of elementary faces (such as planes or cylinders) and their machinability attributes (such as their milling mode) to identify the possibility to mill them in a chain sequences. It has been developed to identify flank milling chain sequences of planes encountered on aircraft structural parts, but is not limited to this family of parts. Techniques to extract machinability attributes from planar surfaces in a 5-axis context are detailed in [5].

3 The Restrictive Chaining Approach

In the following we present the main guidelines for the restrictive chaining approach. The mechanical parts we consider are five axis parts with particular requirements (figure 1).

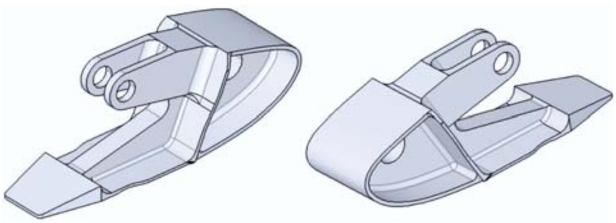

Fig. 1: Studied mechanical part

The general algorithm is essentially composed of two main phases: section 4 and section 5. The input would be a mechanical part. First, all the EMFs related to the current mechanical part are extracted. Once we obtain the EMFs, we study all the possible face sequences based on a 7 step sequential algorithm presented in section 4.

The last step would confirm the computed face sequences using the manufacturing constraints. A sequence is a continuous chain of faces that are potentially machinable along the same machining strategy. Machining direction sets construction, Accessibility checking step and Sub-sequence chains restriction constitutes the three different steps that outputs the final machining sequence. Different face sequences computed in the previous section might find themselves split unto two different sequences or might even be totally disqualified.

4 Face Sequence Extraction

This part of the general algorithm (section 4) aims to generate the total face sequences. The latter will be then reduced taking into account manufacturing constraints (section 5).

4.1 EMF Definition

EMFs, Elementary Machining Features, are nothing but the different faces of the CAD part completed with many technical attributes. These attributes enrich the face with some information, transforming it to a “smart face”. This latter concept means a face that knows how to be machined. The different Machinability Analysis conducted along the many computed attributes, enable the face to search in its surrounding which other faces to machine in the same manufacturing fixture, which machining mode will be used, what are the potential manufacturing tools to be used.

As told before, an EMF integrates a lot of attributes. We shall now introduce 4 essential attributes that the face is enriched with (over 15 attributes):

- *Face type*: this basic attribute refers to the face geometrical type. An EMF can be a planar face, a cylindrical face, a conical face, ruled face. An EMF face type is declared unspecified when it is not one of the previous face types.
- *Fillet identification*: it allows knowing if the face is a junction face between two others that perform certain functionality, or if the face is a stand alone face.
- *Machinability factor*: the different faces are tested for end and flank milling, and the attribute is added to the face. Some planar surfaces are suitable for both milling modes, it is then up to the chain sequence to force a certain machinability factor
- *Machining directions*: the face different machining directions are the main input used in the second phase of our algorithm. Based on trade rules and common sense of process planners, an automation to extract the potential machining directions is applied on the part and stored within the EMF object.

Finally, an EMF is an attributed face. From all the EMFs, we generate an attributed face adjacency graph called a ‘chaining graph’, where each node of the graph is an EMF and each link is an edge connecting two EMFs.

4.2 Chaining Links

The chaining links splits the junction types between different faces. The differentiation is made through the sharpness of the common edge between two different parts. The sharpness is the term used to describe on how the transition is made. A link can be Open (O), Closed(C), Tangent Open (TO) and Tangent Closed (TC) [KYP 80].

The chaining links are split into 6 categories, and a color attribute is given to each. This split results from the study of the 'interesting' links that might indicate a certain chain. Figure 2 presents the different chaining links.

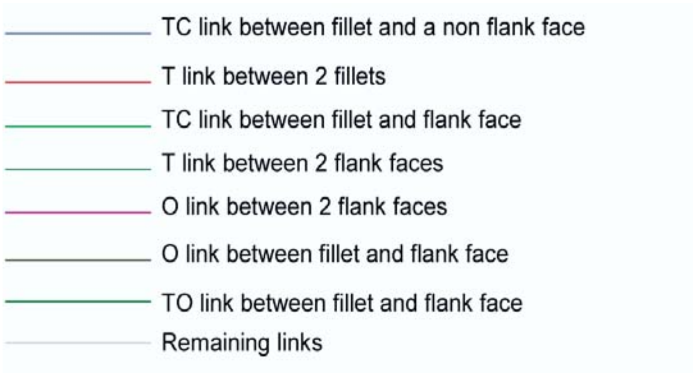

Fig. 2: Chaining link categories

Red links are a direct indication of the existence of chain sequences. We expect then from one side a flank milling chain and from the other a simultaneous end milling. Dark Green links forces a flank milling chain where the light green set the guidance.

4.3 Chaining Graph

The chaining links end up drawing the total part chaining graph with a clear forward proposition to the different sections that we'll be realized. The chaining graph is a normal part chaining graph which explicit the surrounding of the face. The addition is simply the links are colored respecting the chaining links previously presented. The different faces are split depending of their machining mode. If a face is to be flank milled then the face will be identified as {F} + {id} where id represents a different number for each face. The letter {C} will be used to represent fillets and the letter {B} to represent planar surfaces that will be end milled.

4.4 Chaining Algorithm

The algorithm relies heavily on the 'smart face' ability to understand its surrounding and to say "these surrounding faces belong to the same chain sequence as I". The algorithm is composed of the following steps:

1 **Fillet chains identification**
The first part is to split the fillet faces into 4 categories: Open fillets, Singular closed fillet, closed chain of closed fillets, and open chain of closed fillets. These 4 categories are identified through a dedicated algorithm.

2 **Pocket chains construction**
Based on the closed chain of closed fillets, pockets are identified. Usually closed fillet chains are linked to end milled faces from one side and three different types of 'flank milled' faces from the other side. The three different types can be regular pockets, open pockets and strip ones (figure 3 is cut in middle to show pocket natures).

3 **Open flank milling chains construction**
Based on the open chain of closed fillets, this set identifies regular flank milling chains where simultaneous machining is usually performed. Usually, these fillets are adjacent to an end milling EMF from the other side or series of end milling EMF in multiple depressions.

4 **Contouring chains construction**
The algorithm is based on the open fillets which junction in between free EMF. These open fillets often describe the contouring strategy to be used. It is to mention contouring chains recognition is not restrictedly based on open fillets.

5 **Flank milling ruled driven**
The remaining ruled surfaces still unaffected to any sequence can propagate the flank milling mode to their surrounding through the chaining links study (section 4.3). In Example a ruled surface linked through TC sharpness to a planar surface will create a flank milling sequence and so on.

6 **End milling chain**
Planar surfaces connected through tangent links are to be end milled together.

7 **Single closed fillet chain**
Single closed fillets are mainly combined with a close-by end milling and would not indicate any chain. However in the particular case of being next to a flank milled ruled surface it might be neglected.

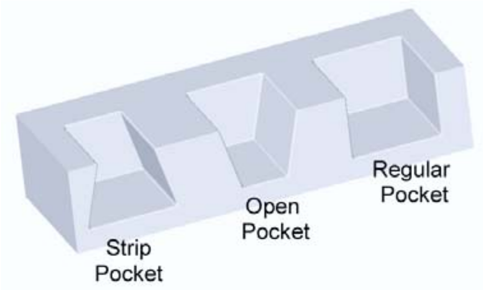

Fig. 3: Different pocket natures

By processing these steps, the majority of face chain sequences will be found. Tests were made on multiple parts and proved the proposed algorithm. Nevertheless it is not to forget that this chaining algorithm remains the approach of a machinability analysis, and the results are to be presented for the process planner to approve or to reject them. Sometimes, the same face belongs to two different sequences. That is often an indication that this face might be split and manufactured through two different chaining sequences.

4.5 Algorithm Execution

We propose to present how the algorithm proceeds in order to better explain the method to obtain the face chain sequences. We assume the EMF extraction is done. The figure 4(a) shows the different fillet categories: the red consists of the open chaining of closed fillets, the green of single closed fillets, red for open chain of closed fillets and orange for open fillets. Once step one of the algorithm is finished, we proceed to study the closed chain of closed fillets or the blue chain on figure 4(b). The chaining graph links the faces {F21, F22, F23, F24} all together. The junction fillets {C21, C22, C23, C24} are linked to {B21} from the other side which defines the global chaining. This pocket is similarly found from the other side of the part. Once we end up the closed chains we pass to step three and studying open chains. Figure 4(c) shows an open chain {C1, C2, C3, C4, C5, C6}. Due to space requirements, we won't show the next algorithm steps. However, the extraction process is the same.

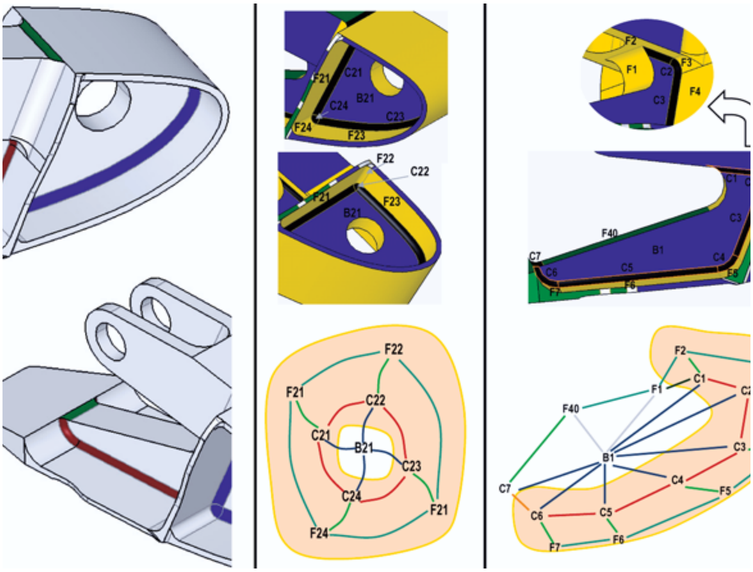

Fig. 4: Algorithm execution

5 Restrictions with Manufacturing Constraints

Feature recognition and machinability analysis are local analysis phases (feature-level), sometimes enhanced taking into account global constraints such as its surroundings topology (real visibility of the features considering the whole part volume; attributes of neighbor faces…). The results of these phases are alternatives elements, such as a combination {feature, operation}, that can be picked up to compose a process plan.

Set-up planning is the global analysis phase (part-level) that will combine these alternatives elements to generate a plan that is optimal considering a global objective function. The algorithm proposed take part within the machinability analysis: it is clustering elementary elements into chain sequences in order to ease the set-up planning activity reducing the number of elements to deal with. Although no decision relative to the generation of the plan itself has to be made, the feasibility of these chains (considering available information at the calculation time) have to be checked before displaying them to the planner. Given a machine-tool, the idea of this restriction is to propose the list of alternatives chaining sequences that are possible as long as the set-up orientation has not been defined.

5.1 Manufacturing Fixture Constraints

The global constraints considered in this paper are due to the limitation of the rotational axis of a machine-tool. In the configuration of figure 5, the joint design of the axis A limit its rotation from 0° to 20°. The parts are mounted on a cube, which limits the rotation around B axis from -90° to 90°.

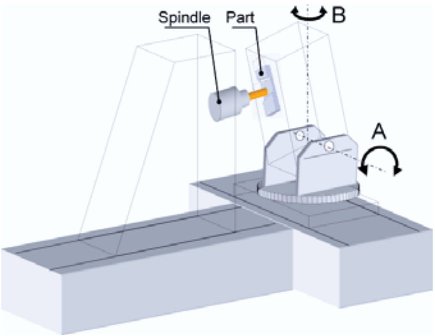

Fig. 5: Rotational Constraints

Considering the generalized pocket shown on figure 6, the difference of angles between opposite walls (30° and 25° in the perpendicular direction) overcome the possibility of rotation of the spindle about axis A. Therefore, the pocket chain construction will compute a flank-milling operation chaining the 4 flanks of the pocket but this operation will not be achievable on the considered machine-tool.

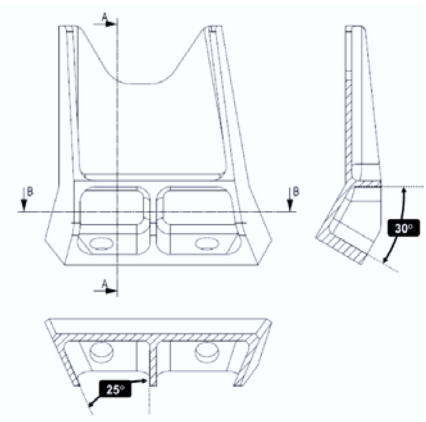

Fig. 6: Generalized Pocket

The main idea is to add an extra step to the algorithm of section 4 in order to restrict the theoretical chaining considering some constraints that are already known when starting the process plan, such as the machine-tool configuration. The objective of this extra step is to split the theoretical sequences considering the angles between the various flank-milling directions that are needed in the sequence.

5.2 Algorithm

The algorithm relies on an existing visibility based algorithm developed by Kang et al. [Kang 97]. A simplified version of this algorithm will be considered as a black box, taking a set of machining directions as in input in order to compute the minimum "spherical rectangle" as an output (fig. 7). The minimum spherical rectangle, defined by the two parameters, is a visibility-based model that represents the minimum rotations needed on A and B axis for the spindle to reach the considered machining directions.

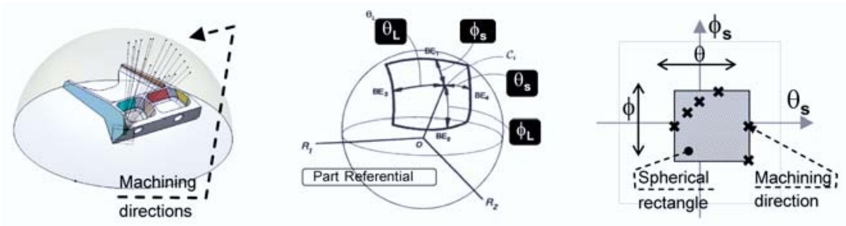

Fig. 7: Kang's algorithm

The spherical rectangle fits in the machine-tool rotational axis ranges if max[α, β] < max [A,B] and if min[α, β] < min [A, B]. The proposed algorithm to restrict a chaining sequence CS = {F1, Fi,…, Fn} associated to a set of machining direction DCS={machining directions} is presented below:

0. Initialize i=1
1. Check the feasibility of the theoretical chain CS
Compute the minimum spherical rectangle
(Kang's algorithm) with DCS
Check if the spherical rectangle fits in the machine-tool rotational axis ranges
→ If not *GOTO* 2 else CS is machinable
2. Define a subsequence CSi*
Select a face i till i=n / CSi* ={0}
3. Construct the Sub-Sequence of CSi*
j=i
The chain CSi* = CSi*+Fj
3A. Extract machining direction CSi*
Compute the minimum spherical rectangle of CSi*
Check if the spherical rectangle fits in the machine-tool rotational axis ranges
Yes → *GOTO* 3A with j=j+1
No → Substract the face Fj from CSi*, store the machinable
sub-sequence CSi* .
GOTO 2 with i=i+1

6 Results

From an initial chaining sequence, the presented algorithm may split it into sub-sequences that are locally achievable on the given machine-tool. Some faces may be present in several sub-sequences. The selection of the right sub-sequence(s) between the computed set will be made during the set-up planning phase, considering global constraints from feature interactions, tolerances and fixture possibilities.

Depending on the wishes of the planner and the process planning strategy of the sector, the identification of the "larger" 5-axis chaining sequences could ease the set-up planning orientation or the decision about the number of required set-ups.

7 Conclusion

This article presented an inherent manner to compute the machining sequences. The result allows the process planner to imagine all the potential machining chains he can apply to realize the part. This effort done in a post design – pre process planning - phase provides essentially a certain understanding of the design which can reduce the time needed for the process plan generation and thus the total cost. This effort is being realized with Dassault Systemes Component Application Architecture CAA ® & CATIA ® V5's API.

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