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Feature-based part decomposition and representation
for multi-axis DED processesLéo Pizzol^{a*}, Sylvain Lavernhe^a, Christophe Tournier^a, Nicolas Beraud^b^a Université Paris-Saclay, ENS Paris-Saclay, LURPA, 91190, Gif-sur-Yvette, France^b Univ. Grenoble Alpes, CNRS, Grenoble INP*, G-SCOP, 38000 Grenoble, France

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* Corresponding author. Tel.: +33 (0)1 81 87 56 51; E-mail address: leo.pizzol@ens-paris-saclay.fr**Abstract**

The development of Directed Energy Deposition technologies enables the production of complex parts in Additive Manufacturing. Such parts require process planning to determine the best production sequence. In machining, the process planning is based on feature decomposition and specific rules. Regarding AM, there is no consensual definition of manufacturing features, making process planning more challenging to develop. Therefore, the proposed works focus on defining features in DED and a graphical representation of features decomposed parts. This representation integrates topological links between features, feature characteristics, and specific rules to help develop process planning in DED.

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1. Introduction

Through the development of Directed Energy Deposition (DED) technologies, supportless parts with complex geometries could be produced by Additive Manufacturing (AM). Such parts require the development of specific process planning methods to ensure their producibility and optimise the production sequence.

In multi-axis DED, the production direction changes - discretely or continuously - during production. Therefore, considering trajectory and process planning, this technology could be related to multi-axis machining more than other AM technologies with a constant build direction, such as PBF-LB.

Process planning for machining - developed in the 90s [1] - is based on feature-based part decomposition and specific rules. Machining features are defined as the combination of

geometry, specifications, and a known process to produce this geometry [2]. Based on this definition, each feature is associated with a machining operation independent from other features. Therefore, the whole process planning is computed by ordering the different features in the production sequence. This order depends on various criteria, such as accessibility, geometrical specifications, etc.

Nomenclature

V	Volume of feature
S_f	Free surface of feature
S_c	Conduction surface of feature

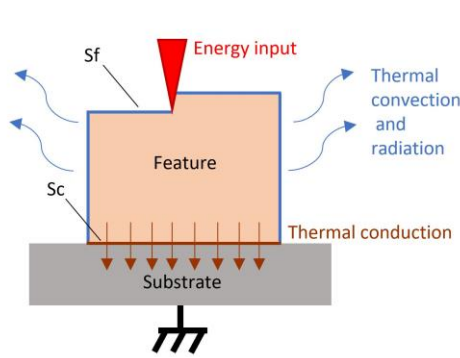


Fig. 1. Application of the first law of thermodynamics on a DED feature

The application of this method to multi-axis DED raised two main difficulties. First, the part must be divided into manufacturing features specifically defined for AM and DED. Second, rules and constraints specific to DED must be specified to guide process planning.

Thus, this paper focuses on developing a feature-based representation of the part using a graph that can be handled directly by an engineer or used by an algorithm to simulate process planning parameters. The purpose of this feature-based representation is to synthesise all the information related to process planning to determine the best production sequence for multi-feature parts.

The paper is organised as follows. The feature-based representation of the part itself is defined in the first section. Then, this geometrical representation is completed with process planning constraints to define the complete graph. Conclusion and future works present the actual state of the feature-surface graph, use cases and improvements.

2. Feature-based part representation

In the case of DED processes, there is no agreed definition of manufacturing features. The ISO standard does not consider the concept of AM features [3], and few works focus on this problem [4,5]. Therefore, this graph is designed to remain relevant with any feature definition or geometrical decomposition of the part.

2.1. Feature thermal behaviour estimation

The feature's thermal behaviour significantly impacts the production and is linked to several critical characteristics: microstructure, porosity, penetration, residual stress, etc. [6]. The thermal behaviour of a feature is directly related to its geometry. For instance, with the same production parameters, thin geometries act as cooling fins, thus dissipating more energy than massive geometries. Therefore, it is possible to estimate the global thermal behaviour of a feature based on its geometry and thus integrate it into the feature-surface graph to compute an estimation of the global thermal behaviour of the whole part. This estimation won't be developed in this article.

Based on the first law of thermodynamics, three thermal exchanges are considered (Fig. 1). Thus, each feature is associated with three geometrical parameters corresponding to

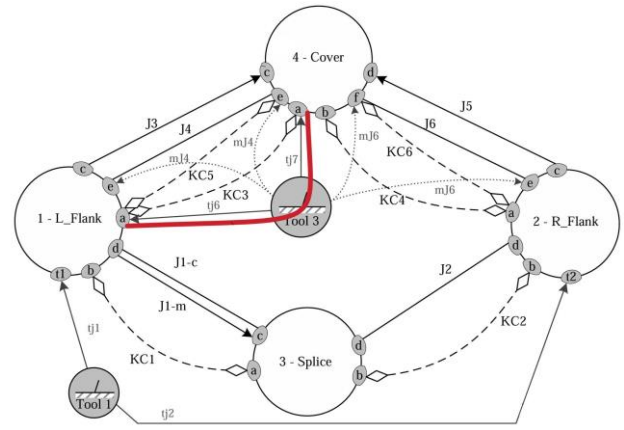


Fig. 2. Assembly-Oriented Graph [8]

those exchanges: the volume V , the free-surface area S_f and the conduction surface area S_c . The volume of the feature is representative of its thermal capacity. Moreover, the volume is equal to the amount of melted metal added to the feature during the production, thus representing the energy input. The free surface is representative of the thermal exchange between the feature and the surrounding environment by radiation and convective heat transfer. The free-surface S_f corresponds to the area of the feature in contact with the surrounding environment. The conduction surface S_c is representative of the thermal exchange between the feature and the rest of the part by conduction. This surface corresponds to the area of the feature shared with other features. Contrary to the energy dissipated through the free-surface, the energy transferred through this surface remains in the part, thus still impacting the production. The purpose of the three geometrical parameters is not to compute the precise temperature of the part but to be used to estimate the global thermal behaviour of the feature. This estimation will allow the optimisation of the production sequence regarding a targeted thermal behaviour; thus, those parameters are directly represented on the feature-based graph.

2.2. Feature-surface graph

To represent feature-based part decomposition, a feature-surface graph is created to include the different features of the parts and their surfaces. This graph is inspired by the Contact Graph or Assembly-Oriented Graph used for process planning in assembly presented in Fig. 2 [7,8]. In this case, each component is represented by a circle. The different contact surfaces of interest of the component are represented by ellipses at the border of the component circle. Several types of links can then be defined between those surfaces (contacts, distances, accessibility, geometrical specification, etc.) using different edge representations. This graph is relevant for an AM feature-based part representation, where features correspond to volumes, and contacts between features are directly related to the feature's surfaces and their thermal characteristics. Moreover, the variety of edge representations enables the integration of numerous links and constraints between features.

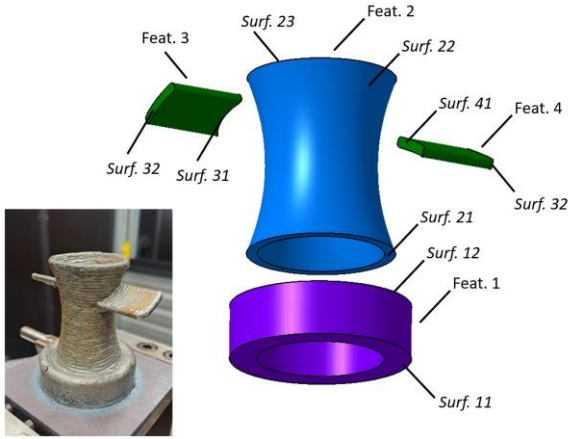


Fig. 3. Part example with the corresponding feature decomposition

2.3. Feature decomposition and part representation

Without an agreed definition of DED features, the example that will illustrate the construction of the Feature-surface graph has been chosen to show no ambiguity in its decomposition into features. This part is presented in Fig. 3 and has been produced with a multi-axis Wire Laser Additive Manufacturing (WLAM) process. We assume that it contains four features:

- The feature 1 is a thick square torus.
- The feature 2 is a single-bead tube.
- The features 3 and 4 are two single-bead thin walls.

Each feature is associated with several parameters to describe the feature itself with intrinsic parameters or its possible interaction with other features through extrinsic parameters. The intrinsic parameters are its volume V and its free-surface S_f , as presented above. Those parameters are directly written on the circle of the corresponding features (Fig. 4). The extrinsic parameters correspond to the surfaces of interest of the feature and are represented by ellipses placed at the border of the corresponding feature (Fig. 4). Those surfaces could be surfaces in contact with other features or starting surfaces to build the feature.

In some configurations, a feature could be buildable if the production starts with a certain surface and is unbuildable with another one. This could be linked to the poor capability of the DED process to produce parts with overhang [9], accessibility difficulties, machine configuration or process planning choices. A starting surface is thus defined as a surface that enables the production of the whole feature used as a substrate. For example, feature 1 of the Fig. 3 part can easily be produced when linked to the substrate through

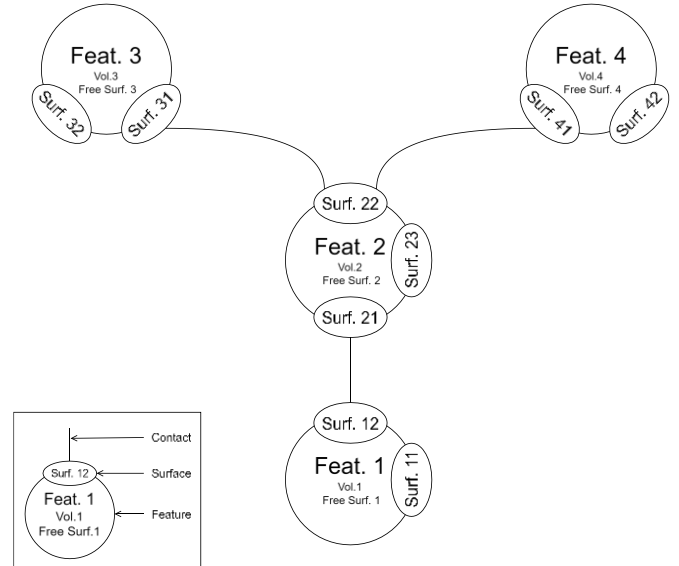


Fig. 4. Topological feature-surface graph of Fig.3 example

surfaces 21 (lower surface) or 23 (upper surface). However, this feature is almost impossible to produce if the substrate is in contact with the surface 22. Therefore, this feature has three surfaces of interest:

- Surf. 21, the lower surface of the tube that is a starting surface for this feature and in contact with feature 1
- Surf. 23, the upper surface of the tube that is also a starting surface for this feature
- Surf. 22, the exterior surface of the tube that is not a starting surface but is in contact with features 3 and 4
- The inner surface of the tube is not considered a starting surface nor in contact with other features; thus, it is not considered a surface of interest.

Once all features are represented with their surfaces of interest, undirected edges are drawn between surfaces to represent the topological links between the different features in contact, resulting in the graph presented in Fig. 4. For each edge, the last geometrical parameter of the feature definition, the conduction surface area between two features S_c , can be easily identified as it is the smallest of the two connected surfaces.

At this point, the feature-surface graph is a purely geometrical feature-based representation of the part without information related to the process, except the feature decomposition itself. Based on this first representation of the part, this graph can evolve to integrate information directly linked to the part's process planning.

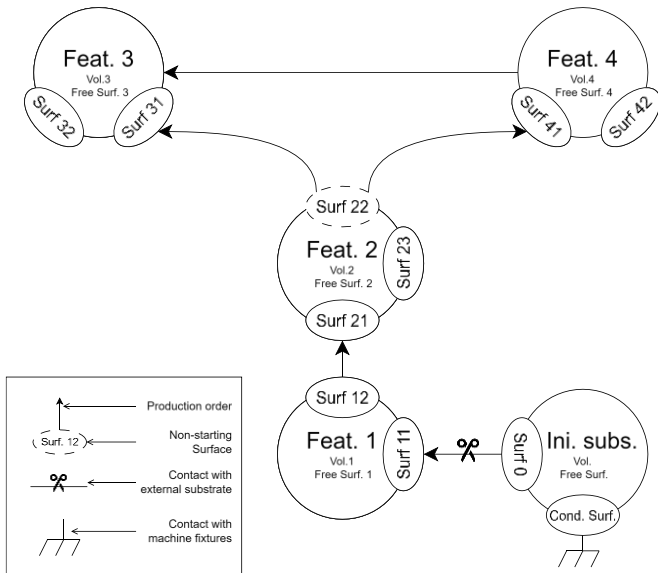


Fig. 5. Complete feature-surface graph of Fig.3 example

3. Process planning representation

To serve process planning and determine the best production sequence, given different criteria, the feature-surface graph can model several effects related to the specificity of the DED process. In addition to the thermal behaviour estimation presented above, contact between features, starting surface, imposed build order, and global substrate are presented here. Contrary to the first graph, where the part geometry imposes the construction, the added elements correspond to process planning choices, thus depending on the process and context of the production. Other constraints could be added to the graph in the future following the development of DED process planning.

3.1. Contact between features

The contact between features have a significant impact on the possible production sequence for the part. Contrary to machining, where features could theoretically be produced in any order, in AM, a feature could be produced only if it is in contact with a feature already produced because AM production requires a substrate. This substrate constraint implies that the production sequence must be guided through the graph by topological links: a feature could be produced only if one of the features topologically linked to it has already been produced. On the feature-surface graph, those topological links are represented by the undirected edges between surfaces presented on Fig. 4.

3.2. Starting surfaces

As presented above, some surfaces can not be used as starting surfaces. This distinction depends both on the process and the part geometry and has a direct impact on the possible production sequences. Therefore, surfaces that can not be considered as starting surfaces for the corresponding features

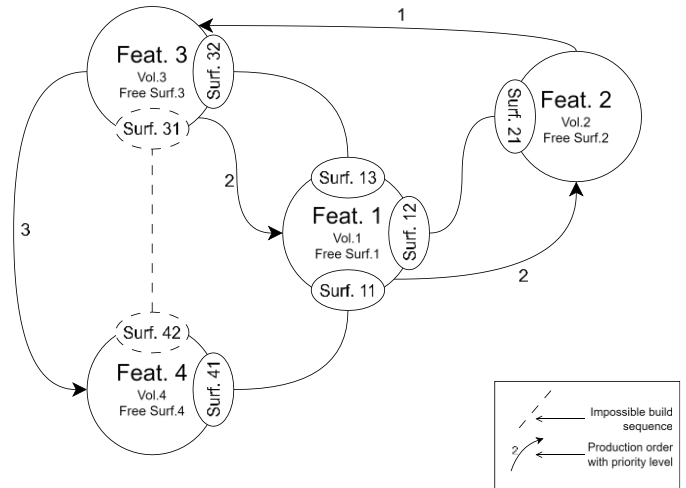


Fig. 6. Example of a feature-surface graph with an impossible build sequence and priority levels

must be identified on the graph. In this case (for example, surface 23 for feature 2), the corresponding ellipse will be drawn with a dotted line (Fig. 5). Therefore, a user could easily visualise the surfaces that can not be used to start the production without a complete vision of the geometry.

3.3. Directed edges

The undirected edges between surfaces of the topological graph can now be oriented based on the configuration of the two corresponding surfaces and the process capabilities. For example, feature 2 could easily be built on feature 1, but the opposite is more complicated or nearly impossible for most DED processes due to the critical overhang implied by the fact that surface 21 is smaller than surface 12.

In this case, the edge is oriented according to the production order from feature 1 to feature 2, which means that the production of feature 1 must be done first to enable the production of feature 2 based on surface 21. In the case of non-starting surfaces, if an edge is connected to one of those surfaces, it must be oriented from this non-starting surface to the other for the same reasons: the next feature to be produced requires a substrate and, therefore, cannot be based on a non-starting surface. If an edge is connected to two non-starting surfaces, the corresponding connection can not appear in the production sequence: whatever the first feature is to be produced; the second one can not be produced based on the previously built surface. The corresponding edge is drawn with a dotted line as it is irrelevant to the production sequence. However, as both features remain physically in contact, this edge stays relevant for thermal conduction. In this case, the only solution to produce the part - without redefining the feature decomposition - is to use another edge connecting the two features with at least one starting surface or to use edges that connect those two features to other features through starting surfaces. For example, in Fig. 6, features 1 and 2 are buildable only based on feature 3 and not on each other.

3.4. Feature order

Depending on the context, it is possible to impose that some features must be built before others. This could be due to accessibility problems, production configuration, or any other reason related to the production sequence. In the example, assuming that feature 4 must be produced before feature 3, the corresponding oriented edge is drawn from feature 4 to feature 3. This constraint is unrelated to any surface of interest, so this edge is directly connected to the features. Regarding several feature-feature edges, it is possible to ponder the edges to set priorities among the different constraints imposed on the production sequence. For example, in Fig. 6, the feature-feature edge labelled 1 must be respected before considering the edges labelled 2, and so on.

3.5. Initial substrate

The first feature in the production sequence is an exception to the substrate constraint presented above, as it requires a first substrate called the initial substrate to start the production of the whole part. This initial substrate could be removed from the part at the end of the AM process or be part of the final geometry. In the first case, the initial substrate is a new feature added to the part (like the metallic plate in Fig. 3). In the second case, one of the part's features is considered the initial substrate and has been previously built with another process. In both cases, the position of the initial substrate imposes the first feature and the first surface of the production sequence. In the Fig. 5 example, the initial substrate can be placed on surfaces 32, 42, 22 and 11. However, the only position that respects all the oriented edges is the surface 11. In this case, the production starts with feature 1 based on surface 11. Then, following edges orientation, feature 2 is built, then feature 4 and finally feature 3.

The initial substrate itself can be represented in two different ways. If the substrate is an added element, it is represented similarly to DED features, with surfaces of interest, conduction surface and the same parameters (volume and free surface). The substrate conduction surface corresponds to all the surfaces directly in contact with the machine - represented with the symbol of a base frame - through clamping fixtures, flange, etc. To illustrate the fact that this type of initial substrate is removed from the part at the end of the AM process, the link between the substrate and the part is drawn with a scissor symbol. This configuration is presented in Fig. 5.

If the substrate is one of the part's features, its conduction surface is added to the corresponding feature, and the machine symbol is directly connected to it. This configuration is presented in Fig. 7.

3.6. Complete Feature-surface graph

The feature-based graph representation aims to evolve from the topological graph to the complete graph through the process planning of the part. The graph allows the user to visualise or compute all the buildable production sequences for a given part. It also allows easy identification of

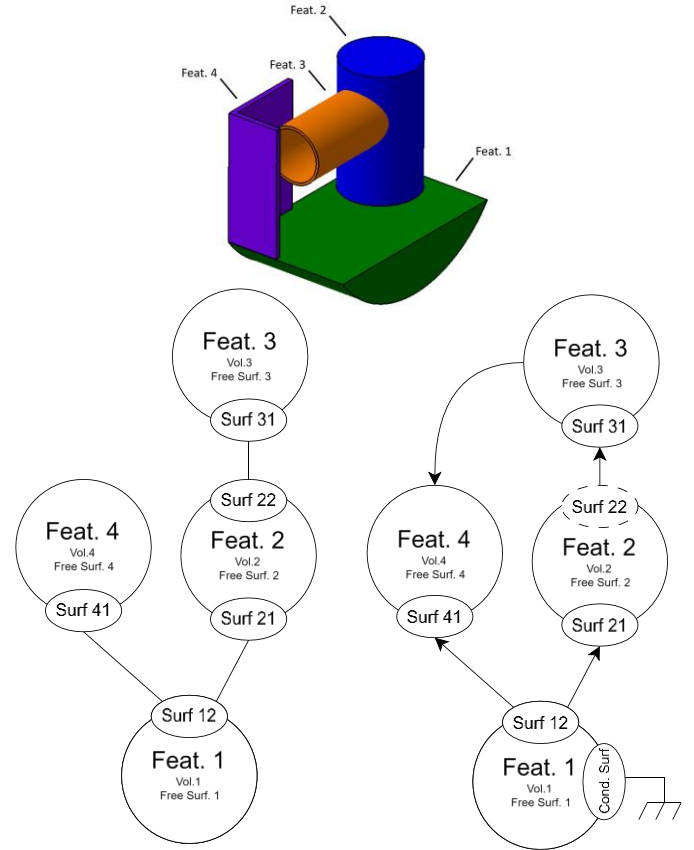


Fig. 7. Example of a multi-features part with the corresponding feature-surface graphs (topological and complete)

impossible configurations in the graph. Those configurations correspond to a set of constraints that can not be respected all at once (for example, if more than one feature must be produced before all the others or every feature must be produced after another one). This requires a new feature decomposition or a modification of constraints, both impacting the final production. Moreover, based on the three geometrical parameters presented above (V , S_f and S_c). This graph could be used to compute estimations of the global thermal behaviour of the part through thermal exchanges between the different features. This estimation adds new criteria to determine the best production sequence.

This graph is applied to a new part in Fig. 7. As for the first one, this part is designed to show no ambiguity in feature decomposition, with four identified features. Based only on the topological graph, eight production sequences are possible regarding the substrate constraint (1234, 1243, 1423, 2134, 2143, 2314, 3214, 4123). Then, several constraints are added to the graph: non-starting surface, directed edges, and an accessibility problem that imposed that feature 4 must be produced after feature 3. At this point, only one production sequence remains possible (1234). Therefore, feature 1 is the first one in the production sequence, and it has been chosen as the initial substrate of the part.

4. Conclusion

Inspired by machining, this article proposes a feature-based part representation of DED process planning. A feature-

surface graph is built to describe the different features of the part and the topological links that connect surfaces in contact. Moreover, geometrical parameters directly related to the thermal behaviour of the feature are integrated into the graph to enable the computation of thermal behaviour estimation of the production sequence. The feature-surface graph resulting from the part decomposition is completed by several parameters linked to the production sequence: starting surfaces, imposed build order and initial substrate. This graph is a tool to summarise all information related to process planning and help the user to visualise or compute all the buildable production sequences, dead-ends or impossible configurations.

5. Perspectives and future works

The feature-surface graph presented in this article aims to evolve with the development of DED process planning and to be completed with new elements and constraints to determine the best production sequence. Considering the estimation of features' thermal behaviour, the next evolution of the graph could be the representation of this behaviour directly on the graph, using colours or reshaping features' circles to correspond to the geometrical parameters. Moreover, this graph will be used to compute estimations of the thermal behaviour of the entire part for each production order to optimise the full process planning according to thermal criteria.

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