Title:
Validation of Feature Recognition on Manufacturability Analysis for Additive Manufacturing

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Keywords:
Manufacturability Analysis, Feature Recognition, Heat Kernel Signature, Additive Manufacturing

DOI: 10.14733/cadconfP.2016.445-450

Introduction:

By using binding materials in a layer by layer approach, the additive manufacturing (AM) process is useful for testing and prototyping or obtaining end-use products. This breakthrough in manufacturing technology makes the fabrication of complex shapes and intricate geometrical features possible and has the potential to significantly simplify the production of complex solid models directly from CAD data. It provides designers not only the freedom to their unruly imagination, but it also allows distributed and decentralized manufacturing and it is easier than tradition manufacturing to be run. Therefore, AM technology is introduced to various fields such as industrial, scientific, education, medical, archaeological, artistic or daily use. However, although AM expands the design space compared with conventional manufacturing, it does not remove all manufacturing restrictions. Designers might be unaware of specific manufacturing restrictions or rules of AM processes, which sometimes would cause 'non-manufacturable' designs. This is a popular problem, which can be time-consuming and therefore costly, especially in cases where the designs were accomplished without professional design-for-additive-manufacturing training. In order to minimize these types of problems and reduce the time consumption of design, an automated manufacturability analysis (MA) system is needed to provide designers with a preliminary tool classifying, based on available resources, their designs into manufacturable or non-manufacturable domains.

Although the development of AM technology is robust, hardly any attempt has been made to automated MA systems for AM. Existing software to analyze design models and generate input files for 3D printer mostly accompany a specific printer and intent to implement model cleanup, build direction optimization, and tool path generation [5]. Although these software suites are able to deal with some types of geometric errors such as duplicate vertices, self-intersections, none of these tools can identify specific problems of solid models due to these feature restrictions. In this paper, we propose a novel feature-based method for MA in AM by using Heat Kernel Signature to recognize the detailed information of design features.

Manufacturability Analysis:

Manufacturability is defined as a property of a design that dictates whether or not the design can be validated in a given production environment. Manufacturability analysis (MA) is a process which involves analyzing the design for potential manufacturability problems and estimating its manufacturing cost [1]. In a given condition of design and manufacturing resource, the first step of MA is to determine whether the design is manufacturable or not. And it is evident that whether a design is manufacturable is mostly determined by the geometric constrains imposed by manufacturing processes, and the purpose of MA is to minimize constraint violations in design.

Although additive manufacturing removes some common constraints for traditional manufacturing, there are still many manufacturing restrictions that need to be taken into consideration when designing parts for additive manufacturing. Therefore, it is reasonable to identify or describe these manufacturing restrictions and establish the design approaches considering these restrictions in the very early stages of the design phase to avoid the waste of resources. This paper will focus on the geometrical constraints, which are mainly due to unique characteristics of AM processes, and identified as follows:

1. Unsupported structure: For example, fused filament fabrication technology cannot extrude material above open air, so it requires external support structures for overhang, bridge and horizontal hole.
2. Minimum feature size: In some AM processes, thin wall or small size structures are subject to significant thermal dissipation, which may cause various defects, such as un-melted powder inclusions, internal voids, cracks and shape irregularities. Therefore, it is necessary to specify a minimum dimension for thin wall, holes, and beams features.
3. Maximum aspect ratio: Fused filament fabrication features cannot have a vertical aspect ratio exceeding a maximum value. Continual the recoating process will eventually result in the feature's bending.
4. Minimum spacing: For example, in powder melting processes, if two surfaces are too close to each other, heat from one side may influence the properties of the other side. Therefore, it is necessary to specify a minimum spacing between two different surfaces.
5. Minimum self-supporting angle: For fused filament fabrication features, it is necessary to set a minimum inclination angle to ensure that angled faces will not collapse without support material.

Feature Recognition:

Features are characteristics of functional interest on an object. According to different interests, they can be assigned to different disciplines. Design feature represent the intent of how a part conceived, and manufacturing feature describes how manufacturing operations process a part. The features we want to identify usually are CAD features, which can be considered as a medium of communication between the design feature and manufacturing feature.

Feature recognition is a critical sub-discipline of CAD/CAM that focuses on the design and implementation of algorithms for detecting manufacturing information from solid models produced by CAD systems [3]. Automatic feature recognition has been an active research area for decades. Many different techniques have been proposed. The basic problem that feature recognition technology tries to solve is identifying high-level information from the low-level geometric entities, such as a collection of faces, edges, vertices and the connectivity relationships in a CAD model and interpreting such high-level hints as a set of features. An ideal feature recognition system should be able to recognize all kinds of features with practical computation and provide sufficient manufacturing information for post-processing, such as manufacturing analysis, design optimization and downstream production plan.

Feature Recognition based on Heat Kernel Signature

Heat kernel signature is a concise and efficient pointwise shape descriptor developed in computer vison field in recent years. It inherits important properties from the heat kernel, which can fully describe the shape of a surface. Heat kernel signature is directly related to the Gaussian curvature on a surface, also closely related to diffusion maps and diffusion distances, which means it can describe not only the shape but also the positon of a point on a given domain. In other words, heat kernel signature is able to present the topologic and geometric characteristic of a feature. In this paper, we will illustrate a novel feature recognition technique based on heat kernel signature and apply it to manufacturability analysis for AM.

Algorithm

The following paragraph describes the approach adopted to recognize solid model features. For more detailed algorithm, readers are directed e.g. to [2]. The application presented is developed in Python and uses the MayaVi visualization engine. The input data is a triangular mesh with coordinates and vertices listed in a text file, and bears resemblance to an STL file. The mesh can be generated through a variety of software, including any finite element analysis software. There is one thing need to be noticed that HKS is also affected by position, therefore the mesh has to be refined for sufficient vertices at each face, even for the planes.

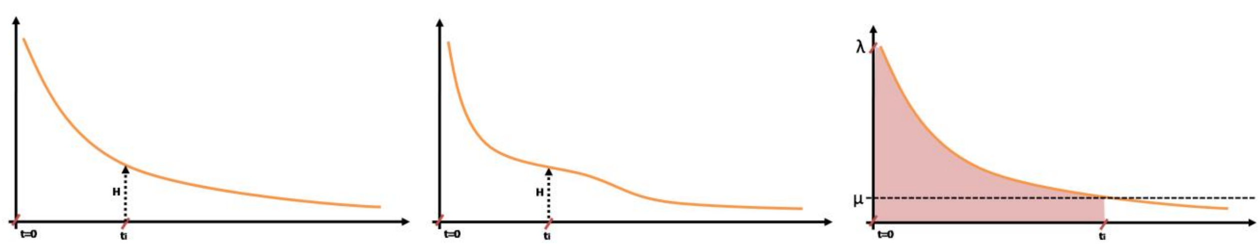

Fig. 1 : (a) Heat loss process at typical point, (b) Heat loss at point in resistance areas (typically bottom of a pocket), (c) Heat retention value shown in red [2].

Proceedings of CAD'17, Okayama, Japan, August 10-12, 2017, 445-450

The basic idea of HKS is to estimate the heat losses a source endures through time. The rate, at which a source diffuses heat, is deemed an indicator on the topological and geometric entities of a point on a given domain. In order to obtain the rate, the heat diffusion equation is solved, and the solution is the heat kernel, which represents the quantity of heat received by a point after a unit of heat is applied at a certain reference point at the initial time. We define the incremental value of an interval where the heat value on a node persists above a preset threshold as heat persistence value. It can be computed as the integral of the heat function as the area below the heat curve (shown in Figure 1(c)).

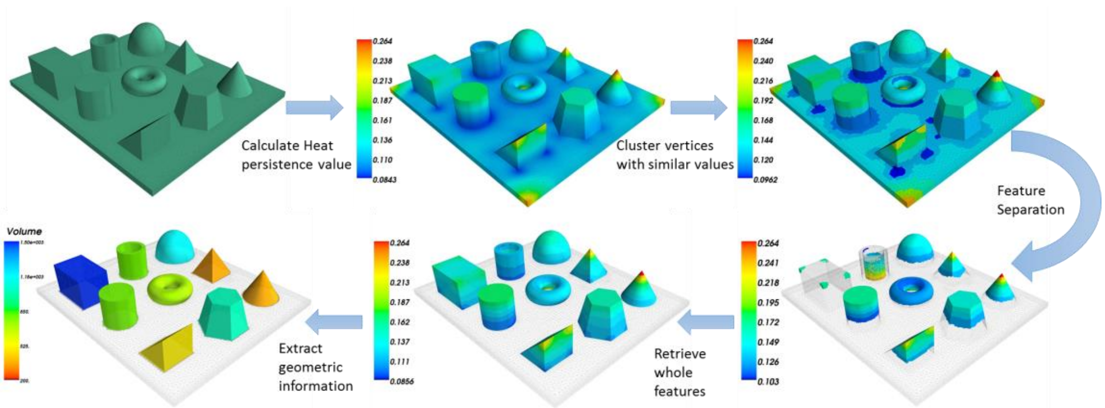

Fig. 2 : Flowchart of feature recognition process.

Using the heat persistence value and a percentage similarity, the vertices can be clustered into different sets in order to predict a mass distribution pattern and to prepare the potential shape recognition. As shown in Figure 2, these potential features will be separated through a multiscale clustering method. Specifically, using the connectivity of clusters and points, the tip clusters are identified first. Then tip clusters are merged based on similarity and inclusivity for similar subsets at incremented persistence similarity subsets. By extending identified subsets to the faces which they belong to, we can complete the features as a collection of faces, which are detected according to geometric reasoning of vertices. The information of faces and which face a specific vertex belongs to can be retrieved by the modified Laplacian, in other words, variations of curvature.

Validation on NIST Standard Test Part

In order to show the feasibility of our method, we validate it on a standard test artifact from National Institute of Standards and Technology (NIST). This artifact is designed for quantitatively evaluate the capability and test the limitations of an AM system [4]. As shown in Figure 3, it has multiple features in a variety of size, locations and orientations, which potentially could be features of “real-world” parts. Every feature serves a specific purpose, and the designer intents to test as many manufacturing scenarios as possible. Therefore, these features are also perfectly suitable for testing the developed algorithm.

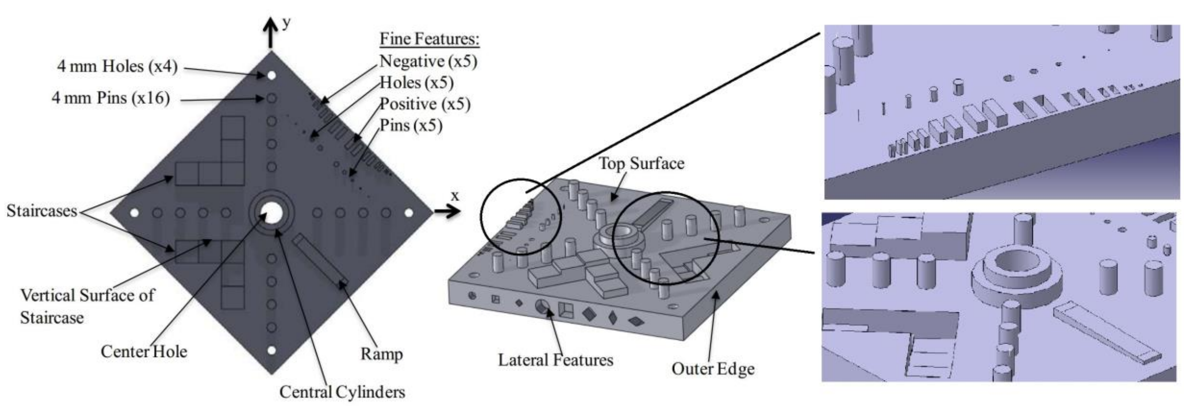

Fig. 3: Solid model of the NIST test artifact showing a top view (a) and an oblique view (b) with annotations of important features [4]. (c) Zoomed details of solid model.

The input mesh that was used is shown in Figure 4(a), and in Figure 4(b), the result of feature recognition is shown, indicating that 64 features in total are successfully recognized as marked in different colors. Even the smallest feature in size 0.25mm was well recognized. In Figure 5 and 6, the color of features is marked by the heat persistent value of vertex that used for clustering. As introduced in previous part, features are recognized based on shapes, therefore, the independence and completeness of a feature wouldn't be affected by size and location. Results of two shuffled versions of the NIST part are shown in Figure 6, in which is the features' locations are reorganized.

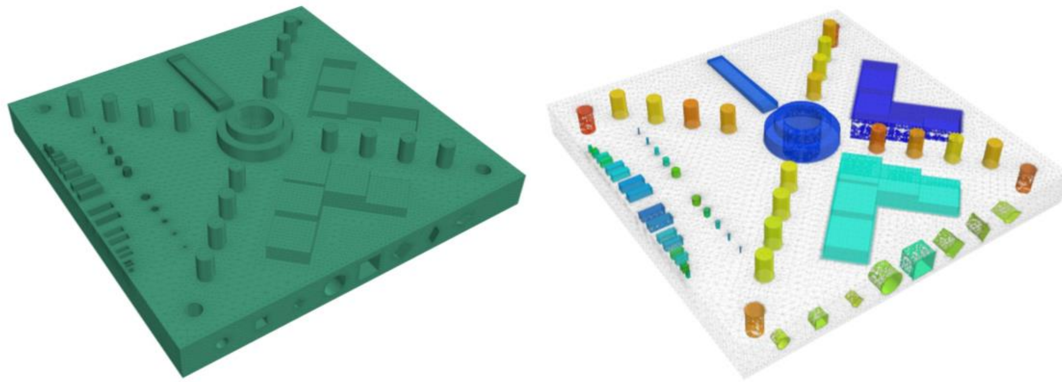

Fig. 4: (a) Input mesh of NIST standard test artifact, (b) 64 recognized features shown in color.

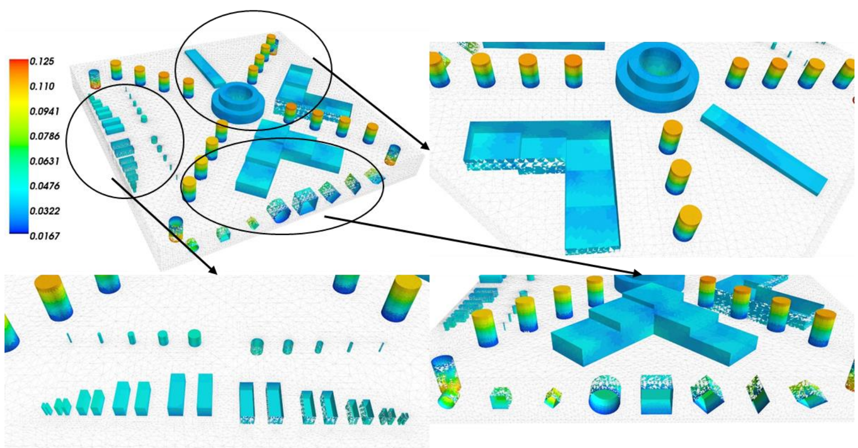

Fig. 5: Enlarged detail for the features of NIST standard test artifact.

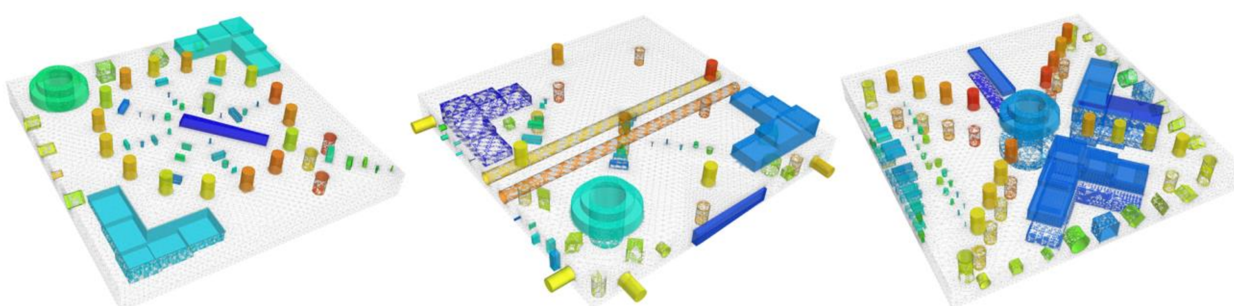

Fig. 6: (a) & (b) All the features' locations are changed randomly, (c) all features are mirrored to the other side.

Case demonstrations for Key geometric constraints of AM

In previous sections, the workings of the proposed methodology to recognize features in the part was introduced. Based on the successful recognition of features, detailed information for the features can be extracted and some desired comparisons or visual displays can be displayed. In order to validate feature recognition on these constraints, different sample parts were designed for visually demonstrating the results of the program. For all of these cases, the build direction in along the z direction was assumed.

1. Unsupported feature: As shown in Figure 7, after feature recognition to the three different types of unsupported features, each one is sliced layer by layer in the longitude and latitude direction, which can be found by the singular value decomposition of the vertex distribution in the feature. Thereafter, by analyzing the shape and position of these cross-sections, the corresponding vertices are marked in red color in the last figure.
2. Minimum feature size: In Figure 8, multiple cylindrical protrusions in different length and diameters are built. After feature recognition, three orthogonal axes can be found for each feature by using singular value decomposition. Then the minimum dimension is calculated by projecting vertices to the third axis.

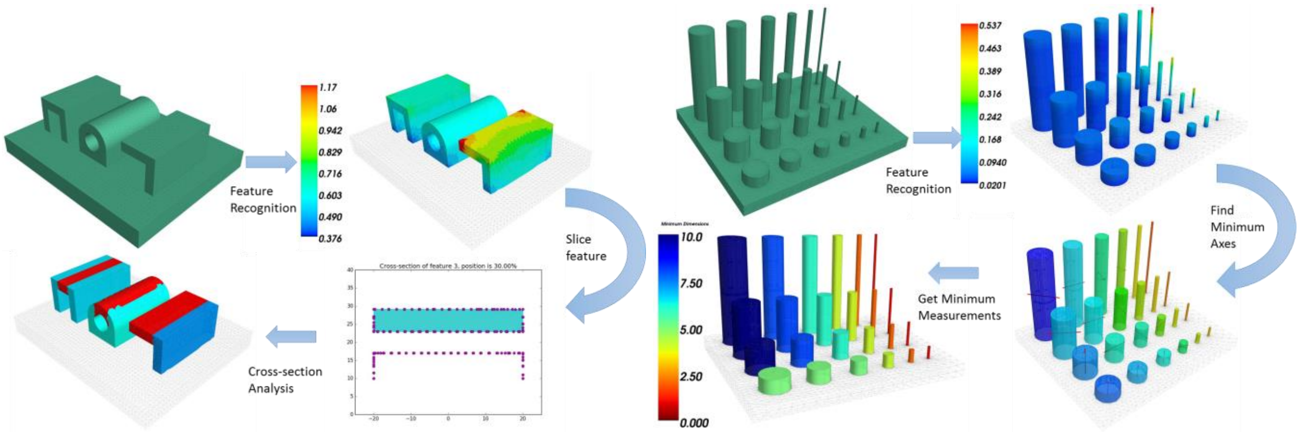

Fig. 7: (a) Three types of unsupported features, (b) Cylindrical features with different heights and diameters.

3. Maximum vertical aspect ratio: In Figure 9(a), cubic protrusions in different length, height, thickness are used for simple demonstration. After feature recognition, the minimum direction and measurement in XY plane can be found by singular value decomposition for each feature. Then the vertical aspect ratio is determined by comparing the height to the minimum measurement. In the last figure, the features are shown in different color indicating the maximum aspect ratio.

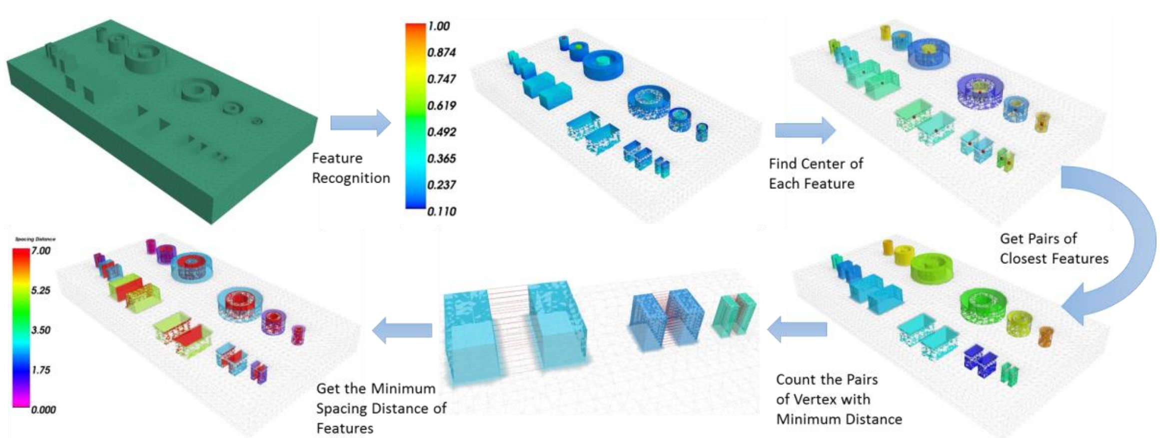

Fig. 8: Pairs of protrusions and pockets with different size and spacing distances.

4. Minimum spacing: In Figure 8, multiple protrusions and pockets are created in different size and spacing distances. First, the center of each feature is found, so features can be divided into pairs that are closest to each other. Then by looping over all the vertices in features, the pairs of vertices with the minimum spacing between the two features are obtained. Finally, the faces which these vertices belong to are marked in red, and the features are shown in colors indicating the spacing distance in the last figure.
5. Minimum self-supporting angle: In Figure 9(b), three self-supporting features with different inclination angles are built. First, the longitude axes of each feature are found out by singular value decomposition. Then, by measuring the angle between axes and XY plane, the inclination angle of the feature is obtained. In the last figure, features are marked in colors indicating the different angles.

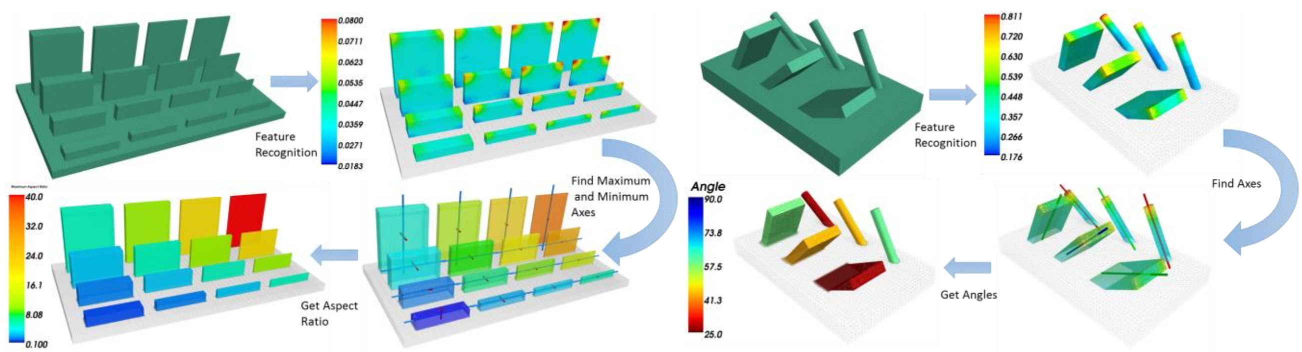

Fig. 9: (a) Cubic features with different lengths, heights, and thicknesses, (b) Self- supporting features with different inclination angles.

<u>Concluding remarks:</u>

In this paper, a new feature recognition method using Heat Kernel Signature is validated for manufacturability analysis of additive manufacturing. The algorithms are described and a NIST standard test artifact is used as an example to prove the feasibility of the method. Further, five key geometric constraints of AM processing are identified and reviewed. Several example part models are designed to demonstrate the feasibility of applying the proposed method for key constraints identification. Future research goals are to incorporate more sophisticated examples to solidify the proof, to continue to enhance our implementation to other restrictions of AM processing, and to extend our results and application to include more processing techniques and exploring for other possibilities.

Also, there is one important problem need to be solved that is how to separate the intersecting features. Although this problem has little influence for the application to AM, it is necessary for subtractive manufacturing (SM), since the manufacturability of SM involves tool approach directions and accessibility.

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