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Deviation Modeling and Shape transformation in Design for Additive Manufacturing

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Abstract

Additive Manufacturing (AM) technologies have gained extensive applications due to their capability to manufacture parts with complex shape, architected materials and multiple structure. However, the dimensional and geometrical accuracy of the resulting product remain a bottleneck for AM regarding quality assurance and control. Design for Additive Manufacturing (DfAM) aims at using different methodologies to help designer take into account the technological or geometrical specificities of AM, to maximize product performance during the design stage. As a main concern in DfAM, the consistency between the digital product and the final outcome should be effectively assessed. Therefore, the geometric deviations between designed model and real product should be modeled, in order to derive correction and compensation plans to increase geometrical accuracy, or to predict product performance more precisely. In this paper, a new deviation modeling method based on the STL file is proposed. A new shape transformation method is developed based on contour point displacement. In each slice, systematic deviations are represented by polar and radial functions and random deviations are modeled by translating the contour points with a given distance derived from the random field theory. The proposed method makes a good prediction of both repeatable and unexpected deviations of product shape, thus providing the designer with meaningful information for design improvement.

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1. Introduction

Additive Manufacturing (AM), also known as 3D printing, has gained extraordinary popularity and research interest in the past decades, due to its capability to manufacture parts with complex shape, multiple structures and a wide variety of materials. New AM processes and machines have continuously being developed and refined to extend their application to a wider spectrum such as automotive, aerospace, engineering, medicine and biological systems [1].

The layer-wise additive characteristics distinguish AM from traditional manufacturing processes, therefore, the design issues regarding to design knowledge, tools, rules, processes and methodologies, are substantially different [1]. In this context, the concept of Design for Additive Manufacturing (DfAM) is proposed aiming at using different methodologies to help designer take into account the technological or geometrical specificities of AM, to maximize product performance during the design stage [2]. As one of the main aspects of DfAM, the geometrical validation is to effectively assess the consistency between the digital product and the final outcome [3]. Therefore, the modeling of geometric deviations between designed model and manufactured product becomes more important, based on which corresponding correction and compensation plans can be made on the deigned model to increase geometrical accuracy, or to predict product performance more precisely.

As indicated in [4], the AM process consists of a digital dataflow and a subsequent physical workflow. In the former dataflow, first the digital volume or facet models are created based on input 2D images, CAD models, or point clouds obtained from reverse engineering. The models are then repaired to remove errors, and sliced to provide layer information that instructs the machine in the building process. Support structures are also generated if necessary, to ensure the quality and stability of the final product. In the physical workflow, the AM machine fabricates the product from raw

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material according to the instructions, after which post-processing procedures like support removal, cleaning, heat treatment and NC machining are executed to ensure the final product quality.

Geometric deviations may arise in both of the abovementioned stages. The facet model, which is commonly represented by the Stereolithography (STL) file, is transformed from the CAD model through triangular approximation, thus chordal deviations are introduced as the Euclidean distance between the STL facet and the CAD surface. In the layer-by-layer building process, additional deviations are introduced due to the "staircase effect". Moreover, machine errors, process parameter settings and material shrinkage will also bring about deviations that affect the geometric consistency between nominal model and final product. Effective modeling and control of these deviations is obviously critical for an optimal design for AM.

In this paper, a new deviation modeling method based on the STL file is proposed. A shape transformation method is developed based on contour point displacement. The proposed method makes a good prediction of both repeatable and unexpected deviations of product shape, thus providing the designer with meaningful information for design improvement. The paper is structured as follows: in Section 2, existing literature regarding DfAM and shape deviation modeling are reviewed. Different deviation models for AM are explained and compared; in Section 3, the new deviation modeling and shape transformation method is proposed and a case study is given in Section 4; conclusion and future research focus are drawn in Section 5.

2. Literature review

In this section, existing researches on DfAM and shape deviation modeling will be reviewed. A comprehensive overview of current shape deviation modeling approaches for AM will be presented.

2.1. Design for Additive Manufacturing

In spite of the short history of AM technologies, DfAM has gained much research attention and methodological maturity. An early definition of DfAM can be found in [5], based on the concept of Design for Manufacturing and the specificities of AM, DfAM is defined as "Synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other lifecycle objectives".

In both [2] and [3], a taxonomy is proposed that classifies the current DfAM methods into DfAM for design marketing and DfAM for design assessment. DfAM for design marketing is aimed at guiding designers in the design process by developing intermediate representations (IRs) that consist in guidelines or design features. While DfAM for design assessment focuses on employing acceptability criteria, such as cost, time and manufacturability, to evaluate IRs in the design stage. DfAM for design assessment is further classified into opportunistic DfAM, restrictive DfAM and dual DfAM according to their different ways to assist designers [2], among which restrictive DfAM methods aim to reach a consistency between the nominal geometric model and the skin model [6] that includes geometric deviations introduced in manufacturing processes, by taking into account the limitations of AM. The focus of this paper right belongs to the restrictive DfAM, since deviation modeling can effectively assist design optimization to ensure the geometric consistency.

2.2. Shape deviation modeling

The modeling of geometric deviations in traditional manufacturing processes has been extensively investigated in researches on geometric dimensioning and tolerancing (GD&T), and especially Computer Aided Tolerancing (CAT). Multiple models have been proposed and some of them are already adopted in commercial CAT tools. However, these models tend to represent deviations as rotational and translational feature defects of the nominal model, while ignoring the predictable and observable form deviations of the product shape that may reflect the influence of actual working condition and environment. With this regard, the concept of Skin Model Shapes (SMS) has emerged as a computational model for geometrical variations management [7]. It considers geometric deviations that are expected, predicted or already observed in real manufacturing processes, and incorporates the deviations directly in the shape model based on a discrete geometry framework. The main contributions of the SMS have been highlighted recently in different applications, such as assembly, contact modeling, tolerance analysis, and motion tolerancing [8]. The promising application of SMS in shape deviation modeling of the AM has also been envisioned [9].

While in the context of AM, deviation models have been proposed mainly to discover the effects of process parameters, input file quality or thermal shrinkage on the geometrical accuracy of the final product, thus correction or compensation plans can be made to ensure the surface quality. Main approaches can be classified into two categories. One category focuses on the modification of input files for AM machines. In [10] and [11], Vertex Translation Algorithm and Surface-based Modification Algorithm are proposed to modify the STL facets locally based on criteria like chordal error, cusp height and form error, so as to decrease the approximation deviation introduced in translation from CAD model to STL file. A variety of adaptive slicing approaches are proposed to minimize the deviation induced by staircase effect, and at the same time to reduce build time [12,13]. These approaches are applicable in the early design stage when the AM process hasn't been executed yet and only digital models are available. Later, Sushmit et al. [14] propose an Artificial Neural Network based method that learns from the deviations in measured surface data and uses the trained network to modify STL file to compensate for the deviations. However, these methods cannot provide a quantitative formulation of geometric deviations and an adaptive criterion for modification can hardly be reached. The other category aims at deriving closed-form parametric expression of deviations caused by shape shrinkage in certain AM processes and accordingly making optimal compensation of the design model to neutralize the deviations. Since AM is a layer-wise building process, the shrinkage deviations occur