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Using a virtual skeleton to increase printability of topology optimized design for industry-class applications

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A R T I C L E   I N F O

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A B S T R A C T

This article broadens the scheme previously developed to associate topology optimization with additive manufacturing through the use of a virtual skeleton, consisting in solving the same physical problem with a discrete approach and then with a continuum one. This procedure for 3D designs is applied to various domain geometries, to demonstrate its pertinence on high-resolution industrial cases. An algorithm searching for the best printing direction, exploring the solid angle, is also described and validated; the surface-shaped presentation of the result allows immediate understanding of the influence of the discrete problem parameters, while its running time is much lower than a unique continuum optimization simulation, which proves the attractiveness of the method. In the three examples studied, the procedure outputs exhibit greater printability than the ones produced by traditional methods in each of the printing direction tested, albeit responsibility is left to the final user to choose his best trade-off. Furthermore, the unprintable zones are readily displayed to be either reworked or supported. Explanations about increase of convergence likelihood on discrete structures despite the geometry complexity of an industrial application are also provided and demonstrated.

1. Introduction

The first additive manufacturing (AM) device was patented in the 1980s [1] and intended for stereolithography. The name has remained in the file extension used – STL, but the breakthrough has evolved and now, a wide range of materials can be used by this technology [2–5], in an extensive variety of application fields [6–10]. Although AM aggregates several methods and techniques, most of the academic works on the topic today concern the 3D printing approach [11]. Research is mainly directed toward finding new materials and their related printing processes and simulations. This modus operandi allows the production of almost free-form structures, hence is indicated to manufacture complex designs, such as the ones outputted by topology optimization (TO) algorithms.

TO aims at apportioning a minimal amount of material an optimal manner in a given design domain. Since the seminal paper from Bendsøe and Kikuchi [12], this field has developed from a load-bearing application to diverse engineering and science fields [7–9], generating various formulations and approaches [6]. Due to the freedom of the output topology, optimal designs are in general too complex to be built by conventional manufacturing processes. Consequently, it seems that AM

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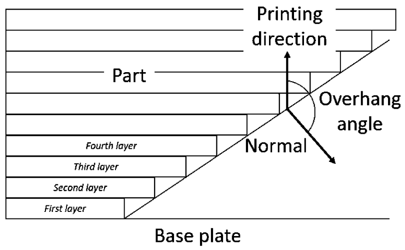

Fig. 1. Location of the overhang angle.

technologies are a perfect match to deal with TO designs. However, one still needs to consider the 3D printing limitations, such as the overhangs.

An overhang is the angle formed between the surface normal of a design and the building direction – or the baseplate modulo π – from which printing is performed with less precision, if possible at all. The location of this angle is illustrated in Fig. 1. Its value varies according to the materials and technologies used. No matter which material is used, although for different physical reasons, hanging elements without supports cannot be produced, or at least with poor precision or surface finish. Those problems result from the layer-fashioned manufacturing as depicted in Fig. 1. The greater the overhang angle, the more pronounced the stair-like shape appear. This issue is known as the *staircase effect*. Along with a *warping effect* due to the heat removal inefficiency in the structure, it constitutes the most challenging reason explaining the need for support addition during manufacturing. Both effects can be minimized by determining the best printing direction; this lead has been explored extensively [13–15], especially for stereolithography. All along this article, particularly for the numerical experiments and without any loss of generality, the maximum overhang angle will be assumed to be 45° – or 135° if taken from the printing direction [16]. Features with greater overhang than that value will be assumed to need support components.

To the authors' best knowledge, the first to deal with overhangs were Brackett et al. [17], who proposed an algorithm to localize them and suggested a way to implement an overhang constraint. Then, Leary et al. [18] introduced the idea of self-supporting topologies, where the supports would be part of the design. The actual implementation consisted in modifying the final design so as to make it printable, modifying at the same time the total amount of material. Subsequently, most of the research publications aimed at obtaining self-supported designs. Several approaches emerged.

Filtering is one of the most popular techniques to integrate supports to a part. The main advantage is that the formulation does not change, then no constraints are added. This approach degrades only slightly the solution optimality. On the other hand, a computational burden, in general small, is added. The works from Guest and Gaynor [19,20] introduce a filter that scans the way each element is supported and penalizes the ones which are not, at each iteration. Langelaar [21,22] then uses the concept to implement a filter that imitates the printing process. Van de Ven et al. [23] developed another filter, which mimics the propagation of a wave and penalizes the zones where the wave arrives late.

Other researchers choose to enforce the overhang limitation explicitly through a change of the formulation or approach. Guo et al. [24] propose a method named "Method of Moving Components" (MMC) together with its companion, the Method of Moving Voids (MMV), that uses predefined geometries whose dimension and location are optimized and projected onto a continuum design domain to form the final structure. Amir and Mass [25] choose to simulate the physical limitation of the fused deposition of plastic by adding an artificial self-weight of the material, at each iteration and for a group of layers. The idea is to force the design to be self-supported. Allaire et al. employ the same idea with the level-set approach [26], along with a second formulation that considers a direct constraint on the angle. Finally, the authors recently suggested a method laying on the use of a virtual truss skeleton to privilege specific locations known as efficient [27].

From another point of view, some studies target the supports themselves. Mirzendehdel and Suresh [28] propose to optimize simultaneously the topology and the supports, without any direct claim regarding the overhangs. The support volume is constrained, but while forced to be zero on the examples given, all the holes are removed from the topology. A recent publication from Qian [29] uses edge detectors to control the undercut and the minimal overhang angle without motivation regarding compliance.

The work presented in this article extends the technique published in [27], where focus was on the underlying formulation and 2D implementation. The important increase in the number of variables implies the use of appropriate tools and the correct implementation of the concept. The optimization problem is defined by a discrete formulation: a coarse grid of nodes is constituted along with bars connecting them – this is called the *ground structure*, and the bar cross-sections are optimized to solve the problem. Then, the truss obtained is rastered and exported into a design space constituted by a regular grid of finite elements – this is the *fine grid*, where its location will be given artificial extra stiffness to privilege material deposition. It is worth noting that, at this stage, the truss is nothing more than an educated guess and "a piece of advice" for continuum optimization, depending on an influence parameter α. In this publication, we aim at proving that the high-resolution 3D implementation of the method is appropriate for industrial applications. In particular, one of the proposed extensions is a search for the best printing direction algorithm. Several printing directions are tested in the solid angle and the best one is selected to serve as a guide for the continuum optimization.

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