Spider Web-Inspired Additive Manufacturing: Unleashing the Potential of Lightweight Support Structures

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Abstract. This paper explores the methodology for the utilization of spider web-inspired additive manufacturing to enhance overhang support structures in 3D printing. Inspired by the strength and flexibility of spider silk, we propose an approach that reduces material consumption and postprocessing efforts. The methodology includes 3D printing spider webs, addressing key questions on silk production, web strength, and printing path generation. Experimental results demonstrate substantial weight reduction in printed objects, showcasing the efficiency of spider web-inspired support compared to traditional methods. The potential applications extend to hollow shell printing and efficient mass production.

1 Introduction

Support structures are a vital component of additive manufacturing processes. Originally developed for rapid prototyping, they were seen as a minor inconvenience due to the limited production runs and the focus on other benefits. However, as additive manufacturing has evolved into a fully-fledged manufacturing process, the importance of support structures has become more evident. The challenge lies in generating and removing support material, which leads to increased material consumption, higher energy usage, and additional manual postprocessing steps. These factors not only drive up costs but also introduce a level of manual intervention that goes against the automated nature of the process. Consequently, there is a strong economic incentive to minimize the costs associated with support structures in additive manufacturing [1].

To address this, numerous studies have been conducted to optimize support structures by reducing wasted support materials, streamlining print time, cutting energy costs, and exploring other factors [2, 3]. Various approaches have been explored, including optimizing part orientation, using sacrificial or soluble materials as supports, optimizing support structures, designing self-support structures, and utilizing support baths. Yang et al. [4] modified the commonly used body-centered cubic lattice and transformed its coordinates to

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construct the self-supporting infill for the mirror. Additionally, they employed a density-based topology optimization method to optimize the diameters of all struts in the lattice infill, further enhancing its mechanical properties. Zheng et al. [5] addressed this issue by proposing an algorithm that integrates overhang constraints into the topology optimization framework, enabling the design of self-supporting porous structures. Zhang et al. [6] applied multi-axis 3D printing, which employed a general slicing framework called S^3 slicer, enabling the fabrication of complex structures without the need for additional supports. Zhao et al. [7] combined direct ink writing with near-infrared induced up-conversion particles-assisted photopolymerization. This unique combination can achieve the printing of unsupported multiscale and large-span ceramics.

Spider webs are intricate structures made by spiders using silk, a special material produced by glands in their abdomen. These webs serve multiple functions. They act as hunting tools, efficiently capturing prey. Spider silk is incredibly strong and sticky, allowing the webs to entangle and immobilize insects. During PLA part printing by fused deposition modeling, a similar phenomenon occurs where the production of silklike material is observed when the printing temperature for PLA is set high. When the printing temperature of PLA is increased, the material becomes more viscous and flows more easily. This increased flowability can result in the formation of excess material along the walls of the printed object, leading to the production of silklike strands. Therefore, an intriguing idea is to mimic the structure of spider webs using spider silk in the context of 3D printing. By incorporating spider webs into the design of printed parts, we can utilize their inherent strength and flexibility to support overhangs and reduce the need for additional support structures. For constructing spider webs using 3D printing, Qin et al. [8] identified different pathways to achieve optimal material distribution in 3D-printed spider webs based on the loading conditions. Zheng & Schleicher [9] developed a ground-breaking strategy for 3D printing spider webs on top of preexisting objects using sprayed continuous fibers.

In this paper, we present a methodology for leveraging spider web-inspired additive manufacturing to improve overhang support structures in 3D printing. By harnessing the strength and flexibility of spider silk, our approach aims to minimize material consumption and post-processing efforts. Through the exploration of 3D printing techniques for spider webs, including considerations of silk production, web strength, and printing path generation, our experimental results demonstrate significant weight reduction in printed objects.

The remainder of this paper is organized as follows: Section 2 discusses the categorization of overhangs during 3D printing, providing a comprehensive understanding of different scenarios. Section 3 introduces the main methodology to fabricate these overhangs using the spider web-inspired method to achieve support-free or near-free printing. Section 4 presents experimental results demonstrating the suitability of these methods for various types of overhangs. Finally, Section 5 summarizes the findings, draws conclusions, and discusses future work.

2 Categories of Overhang

In this section, we categorize overhangs encountered in additive manufacturing processes based on their position and shape. Using the position as the criteria, overhangs can be classified into two main cases: innerhang and outerhang as demonstrated on the left column in Fig. 1. Innerhang refers to suspended material located between two entities, such as within the interior of a printed object. On the other hand, outerhang involves suspended material outside the main entity, protruding from its surface. Understanding the specific position of the overhang is crucial for developing tailored support strategies to address each case effectively.

Moreover, if the shape of the overhang is taken as the criteria, the overhangs can be divided into three groups: 1D, 2D, and 3D, which is shown on the right column in Fig. 1. A

1D overhang represents a linear or edge-like structure that extends beyond the main entity, requiring support to prevent drooping or deformation during printing. Examples of 1D overhangs include horizontal protrusions or edges that lack support beneath them. A 2D overhang refers to a surface or planar area that requires support beneath it to maintain structural integrity. These overhangs typically occur when printing layers that extend beyond the boundaries of the underlying support structure. Lastly, a 3D overhang represents a volumetric structure that extends in multiple directions, presenting intricate support considerations. These overhangs are often found in complex geometries with curved or irregular shapes, requiring carefully designed support structures to ensure successful printing.

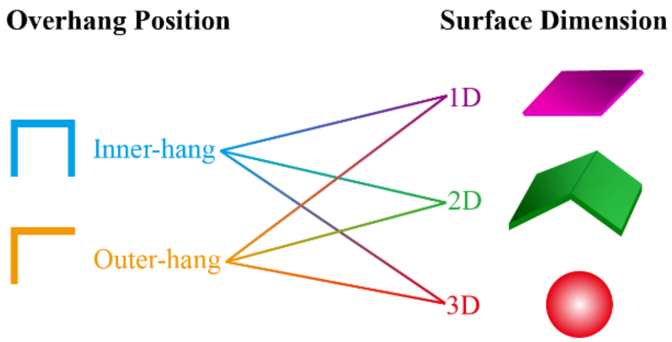

Fig. 1. The categories for overhangs.

3 Spider Web-Inspired Support Structure Design

In this section, we will explore the methodology for the design of the spider web-inspired support structure for the different scenarios discussed in Section 2.

The first scenario is the different overhang positions. In additive manufacturing, innerhang and outerhang overhangs present unique challenges that require tailored support strategies for successful printing. In the case of innerhang, suspended material is located between two pillars or entities, posing a risk of drooping or deformation during printing. To address this scenario, we propose a simple yet effective solution inspired by the structure of spider webs. By introducing a spider web-like structure between the two pillars, we create a natural support system that provides stability for the desired part to be printed on top as illustrated in Fig. 2. Leveraging the inherent strength and stability of spider webs, this approach ensures that the innerhang are adequately supported without the need for extensive additional support material. Just as spiders construct intricate webs to support their own weight and capture prey, we can harness the properties of spider webs to reinforce innerhang in additive manufacturing processes. Transitioning to the outerhang, where suspended material extends beyond the main entity or structure, we employ a strategy to transform it into an innerhang situation. By strategically introducing additional support pillars along the edges or periphery of the overhang as shown in Fig. 2, we create an innerhang configuration where the suspended material is positioned between two entities. Once the innerhang configuration is established through the placement of support pillars, the same spider web-inspired approach can be utilized. Incorporating a spider web between the support pillars creates a self-supporting structure that eliminates the need for excessive support material. This integration of spider web-like structures in the outerhang scenario enhances stability and structural integrity, simplifying the printing process while optimizing material usage and reducing post-processing efforts.

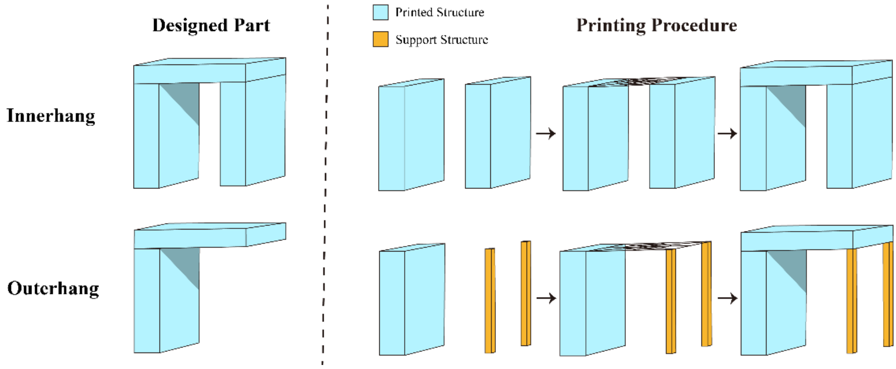

Fig. 2. Printing strategy for innerhang and outerhang.

The second scenario is the different overhang surface shape. Here, we discuss support strategies tailored to three categories of surface dimensions: 1D, 2D, and 3D, which is demonstrated in Fig. 3. The first category, 1D surface overhangs, involves linear extensions resembling flat surfaces. Remarkably, a spider-inspired support strategy offers a solution without the need for additional support structures. By strategically positioning two pillars or support points at either end of the overhang, a stable foundation for a spider web can be created. The spider web, delicately woven between these pillars, acts as a natural support system, ensuring stability during printing. In the case of 2D surface overhangs, where a flat, two-dimensional surface requires additional support, the spider-inspired approach proves effective once again. By placing support pillars along the edges of the overhang, a stable foundation is established for the construction of a spider web. These pillars serve as anchor points for the intricately woven spider web, providing essential structural support and preventing deformation during printing. Moving to 3D surface overhangs, where structural integrity during printing is paramount, a combination of regular support structures, pillars, and spider webs is employed. Identifying areas of the surface requiring support, characterized by significant overhang angles or unsupported sections, support pillars are strategically placed for stability. Spider webs are then intricately woven between these pillars, serving as additional reinforcement to prevent sagging or collapse of the regular support structures.

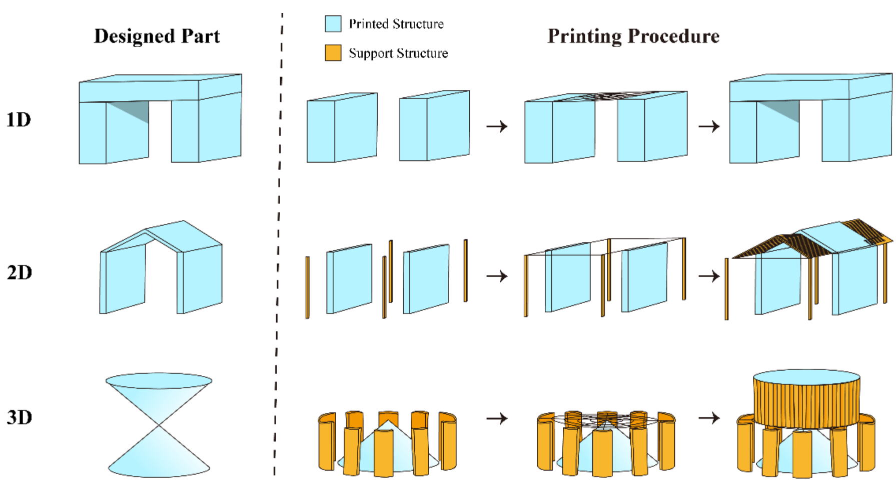

Fig. 3. Printing strategy for 1D, 2D, and 3D surfaces.

4 Experimental Demonstration

In this section, we present a series of case studies to validate the effectiveness and feasibility of our proposed spider-inspired support strategy across various scenarios in additive manufacturing. The results are illustrated in Fig. 4. The case studies include bridge (1D innerhang), house (1D innerhang & outerhang), tree (1D innerhang & outerhang), pavilion (2D innerhang & outerhang), and inverted cone (3D outerhang). These case studies demonstrate the versatility and effectiveness of our spider-inspired support strategy across a range of scenarios (different overhang positions: innerhang and outerhang; different overhang shapes: 1D, 2D, and 3D). From the part weights with different support methodologies for these five cases in Fig. 4, it can be concluded that the proposed support methodology can greatly reduce the material usage in additive manufacturing and also cut down on the manual postprocessing steps.

Fig. 4. Printing case studies for 1D, 2D, 3D, innerhang, and outerhang scenario.

5 Conclusions and Future Works

In this paper, we have introduced a methodological approach to enhance overhang support structures in 3D printing by drawing inspiration from spider web mechanics. By capitalizing on the durability and flexibility of spider silk, our proposed method aims to minimize material usage and post-printing processing requirements. Through the examination of various 3D printing techniques tailored for spider web replication, including investigations into silk production, web resilience, and printing path planning, our experimental findings demonstrate significant reductions in the weight of printed objects.

For future works, firstly, there is a need to identify the optimal conditions for producing spider silk and web structures using 3D printing techniques. This involves investigating the ideal printing parameters, such as temperature, speed, and material composition, to achieve the desired mechanical properties and structural integrity of the printed webs. Furthermore, there is room for further optimization of the web structure itself. By studying the optimal design of natural spider webs, we can explore ways to enhance their strength and load-bearing capabilities. Lastly, the development of dedicated software or tools to generate g-code from the designed part is necessary. This software should be capable of interpreting the optimized web structures and generating the machine instructions required for 3D printing. It should consider factors like material deposition, support attachment points, and coordination with other printing parameters to ensure the successful implementation of the proposed strategy.

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