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Multi-axis 3D printing of spiral parts without support structures

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Abstract

The recent developments in Additive Manufacturing (AM) have accelerated the spread of 3D printers all over the world. Fused filament fabrication (FFF) has become the prevalent technology for use in printing typical thermoplastics. Sometimes, the nature of layer-wise production brings about the necessity of using support structures, leading to (i) increased material consumption, (ii) reduced production speed, (iii) deterioration in the part quality, and (iv) extra post-processing. To eliminate these shortcomings of FFF, researchers proposed several methods, one of which is to benefit from particular multi-axis hardware. In this study, the capability of a multi-axis FFF machine in support-less printing is introduced. The quality of the produced part is compared with that of its identical counterpart printed on a conventional (i.e., 3-axis) FFF setup.

Keywords: Additive manufacturing; 3D printing, Multi-axis, Fused filament fabrication, support-free

1. Introduction

With the introduction of additive manufacturing (AM) and the spread of 3D printers over the last decade, many challenges that were difficult to overcome with conventional manufacturing techniques have been surpassed. Compared to the other traditional techniques, 3D printing provides ease of production in terms of both software and hardware. Notwithstanding the advantages introduced, the natural limitations coming along with 3D printing should not be overlooked.

Fused Filament Fabrication (FFF) has become one of the most prevalent applications of AM despite its weaknesses in production quality [1]. Sometimes, the nature of layer-wise production brings about the necessity of using support structures, causing (i) increased material consumption, (ii) reduced production speed, (iii) further deterioration in the part quality, and (iv) extra post-processing. Therefore, the need for support structure is regarded as another shortcoming of FFF [2].

Support structures become necessary in FFF when the upcoming layers cannot be sustained as an integral part of the previously deposited regions of the objects. That is a common drawback of standard (i.e., 3-axis) FFF applications, especially in the manufacture of the objects comprising overhang areas.

To alleviate the known problems originating from the use of support structures, researchers have investigated several methods to eliminate the entire structure or at least minimize them through optimization [2].

Regarding the standard FFF applications, typical approaches for minimizing the support structures embrace several well-known methods such as (i) shape corrections, (ii) build orientation optimization, (iii) object partitioning. For instance, Hu et al. [3] proposed insignificant modifications on the parts to reduce the number of unsupported faces. Nevertheless, this method would not be applicable for strict designs and unalterable shapes. For minimizing the consumption of support material for both interior and exterior of the object, Wang et al. [4] have worked on optimized build orientation together with the introduction of self-supporting and hollowed interior layers. In another study, Karasik et al. [5] proposed partitioning the objects, where each sub-part could be fabricated support-free and glued back together thereafter. However, both build orientation optimization and object partitioning have not offered a viable solution for all kinds of objects.

Support-free manufacturing on a regular 3-axis FFF setup turns out to be a challenging task that can partially be attained by the use of the aforementioned software solutions. In recent years, on the other hand, many flexible hardware facilities (e.g., gridded build plate with adjustable supporting pins [6], multi-axis manufacturing platforms [7]) have emerged for FFF technology, offering the promising potential to completely eliminate the need for support structures.

The development of various multi-axis FFF systems, including robotic arms [8] and the ones having extra Degrees of Freedom (DoF) on the extrusion tool or the printing base [9], has been accelerated in recent years.

In this paper, the capability of a 5-axis additive (and subtractive) manufacturing platform in support-less 3D printing is introduced. Sample objects printed by FFF technology on the developed multi-axis platform are to be presented. In the following section, the related literature is reviewed in brief. The third section covers the materials and method as well as the details of the software implementation for generating the multi-axis tool path for the manufactured sample. The remaining part of the paper presents the obtained results & discussions together with a short conclusion in the last section.

2. Background

Over the past decade, most research in the field of support-free FFF has emphasized the usefulness of multi-axis hardware.

Wulle et al. [10] have focused on the multi-axis tool path planning, highlighting the importance of a suitable printing head to avoid the risk of collision between the workpiece and the extruder while depositing along certain building directions. A long extruder head with a reasonably small diameter has been proposed to minimize the collision problem. Their findings have proved effective in eliminating the need for support while producing an L-shaped handle.

Wu et al. [7] have utilized a FFF setup composed of a 6-DoF robotic arm and a fixed nozzle. In this study, the objects were first decomposed into several segments, where each segment could successfully be fabricated without any support structures. However, it was noted that the robotic arm had to be operated at very low speeds to ensure positioning accuracy. In a similar study conducted by Dai et al. [11], a robotic arm has been employed to fabricate solid parts in the form of curved (i.e., non-planar) layers. They benefited from the convex hull of the objects to achieve collision-free FFF. Despite the support-less printing, extra post-processing was required for better surface quality. Wu et al. [12] have achieved further development and proposed a slicing algorithm for support-free 3D printing in a single pass, without the need for assembling separate components into a final model.

There are also studies for building thin-shell parts using multi-axis FFF systems without a need for supports. In one of these studies, P. M. Bhatt et al. [13] combined 3-DoF building platform and 3-DoF extrusion tool to have a multi-axis FFF system. Their main idea is to rotate the building platform and relocate the extruder whenever the highest support-free angle is reached.

Besides the robotic-base systems, an alternative multi-axis setup has been built by the modifications on conventional 3-axis FFF systems. Mingquian et al. [14] have investigated 5-axis printing by focusing on the intricate hollow objects. Nevertheless, the build volume is very limited in this setup.

3. Materials and method

The standard FFF 3D printers generally utilize three orthogonal translational movement axes (i.e., X, Y, Z). The slicing software generates both the tool path and any necessary support structure. Since the basic movements do not contain rotational motion, it is sufficient to slice the solid model along a single direction to generate the necessary tool path. In fact, this makes the standard FFF pipeline so simple that 3D printers have attracted attention from millions of users.

In case of additional rotational axes on the manufacturing platform, in-process alignment of Workpiece Coordinate System (i.e., build table) with respect to the material extrusion unit (i.e., nozzle) becomes possible. It brings extra flexibility in the tool path generation at the expense of the motion complexity. Hence, continuous alterations in the orientation may enable support-less FFF if the sequential layers are selected accordingly.

In order to demonstrate the apparent advantage of multi-axis FFF systems, a complex shape that cannot be printed without a support structure in a conventional 3-axis setup is selected.

The selected sample part has a hexagonal hollow cross-section swept along a complex and arbitrarily drawn helical guide curve. The cross-section is getting bigger while sweeping along the guide curve, as shown in Figure 1. The overall bounding box of the designed object is 75 mm x 75 mm x 100 mm.

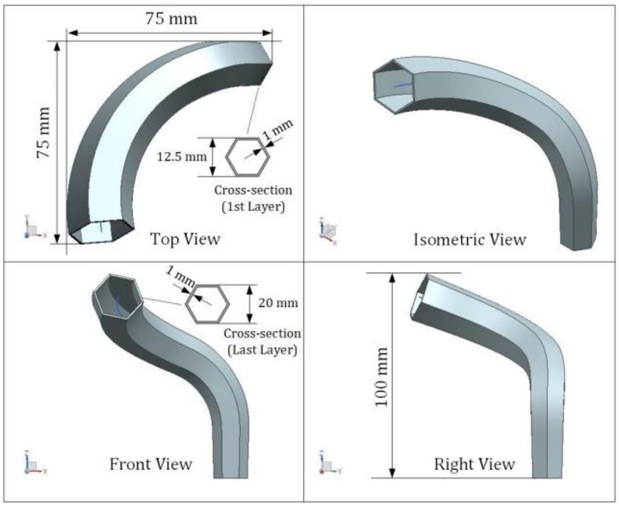

Fig 1. Alternative views of the produced sample part .

The object is created in CAD software (Rhinoceros) using its programmable environment (Grasshopper). The used environment allows the creation of the STL file of the object [15]. Besides, the programming for the extraction of the slices becomes simple using the guide curve & swept cross-section information.

To carry out support-free FFF, the slices are intentionally formed along the direction of the helical guide curve so that the normal vector of those layers is always parallel to the gravity.

The following procedure generates the slices and the continuous tool path:

1. Definition of the guide curve
2. Division of the guide curve into equally spaced arc lengths (i.e., layer thickness)
3. Identification of the slicing planes by using the TNB frames (i.e., Tangential, Normal, and Binormal vectors) at every division
4. Representation of the slices on each frame (See blue and black lines in Figure 2 for the outer and inner contours, respectively)
5. Listing the X, Y, Z coordinates on the contours in the purpose of positioning for every slice
6. Listing the unit normal vectors in the purpose of orientation for every slice (See red arrows in Figure 2)
7. Application of coordinate transformation using Homogenous Transformation Matrices (HTMs) defined for this platform [9]

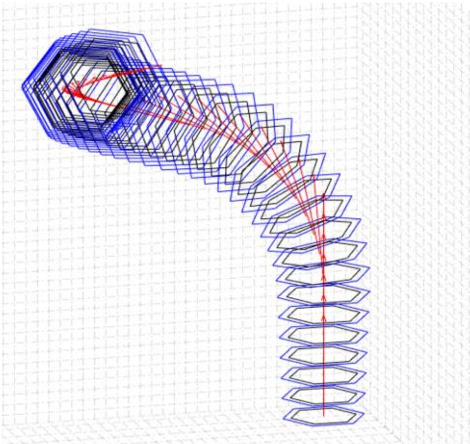

Fig 2. Illustration of some slices of the object.

After the tool path generation, the production tests are conducted on a five-axis manufacturing platform armed with two additional (fully rotatable & step motor driven) rotational axes.

The appearance of the manufacturing platform, identified as HYBRO, is shown in Figure 3. HYBRO is developed as a hybrid workstation containing additive (a modified ULTIMAKER print head) and subtractive (a spindle motor) manufacturing tools.

Purposefully, just the essential motion axes are utilized in five-axis FFF tests (i.e., X, Y, W, B, C).

The maximum build volume for a 3-axis FFF operation is 300 mm x 300 mm x 300 mm. The sticking of the part to the build plate is achieved by adhesive tape.

In the 5-axis production tests, some critical process parameters (such as layer thickness, feed, and amount of retraction) are selected as comparable to typical 3D printing processes, e.g., the layer thickness has become 0.2 mm in this multi-axis printing setting.

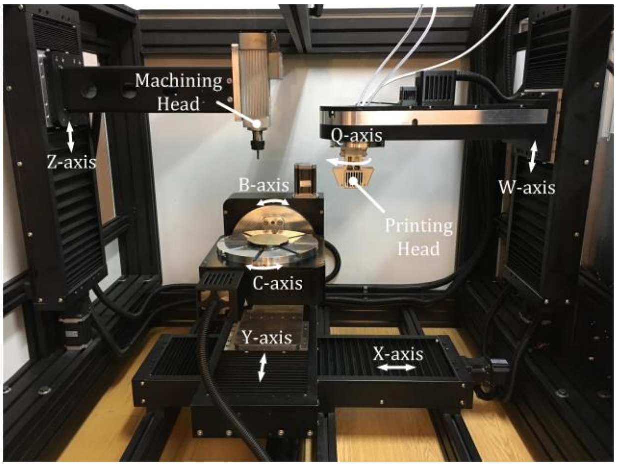

Fig 3. The developed multi-axis additive and subtractive manufacturing platform (HYBRO).

The fabricated object is a 2-shell thin structure without any infill. In this process, the extruded filament is Poly Lactic Acid (PLA), a typical thermoplastic material for FFF-based fabrication.

To compare the way of production on a 3-axis counterpart, the same part is also fabricated on AnyCubic i3 Mega with similar settings. This time, the production on the mentioned 3-axis FFF platform is carried out using the default settings of open-source slicing software. The slicing software, Cura, generated the tool path in the form of an NC-code, containing the necessary data for the unavoidable support structure as well. The layer thickness is identical (i.e., 0.2 mm) to provide a fair comparison between the 5-axis and the 3-axis case.

The critical process parameters for both 5-axis (on HYBRO) and 3-axis (on Anycubic) cases are summarized in Table 1.

Table 1. Critical Process Parameters.

	HYBRO	**Anycubic**
Used Material	PLA	
Process Temperature	205 °C	210 °C
Layer Thickness	0.2 mm	
Nozzle Diameter	0.4 mm	
Number of Shells	2	
Infill Ratio	0%	
Support Overhang Angle	N/A	60 °
Support density	N/A	8%
Retraction Distance	6 mm	
Retraction Speed	40 mm/s	
Consumed Material	~12 g	~23 g
Processing Time	80 min	161 min

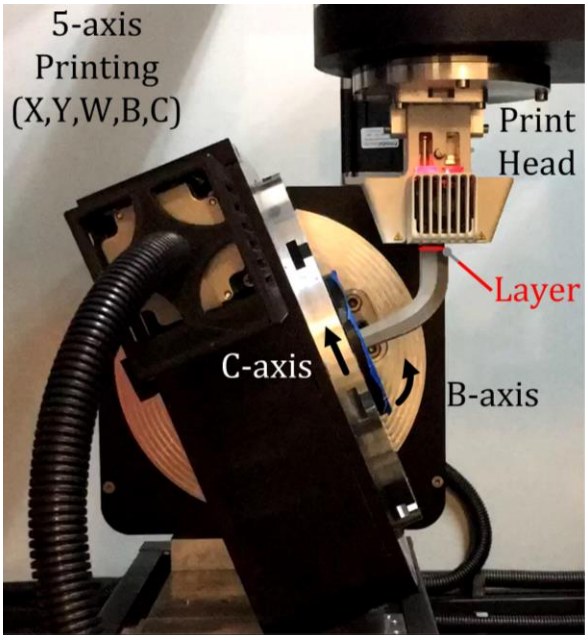

Fig 4. Production of the sample part on the developed 5-axis manufacturing platform.

With the defined process variables, the production of identical sample parts is carried out. Figure 4 and Figure 5 demonstrate an instant of production on HYBRO (5-axis) and Anycubic (3-axis), respectively.

The main difference between these cases is that the orientation of the WCS can continuously be altered to the predetermined arrangement by utilizing the B- and C-axis in the 5-axis FFF process.

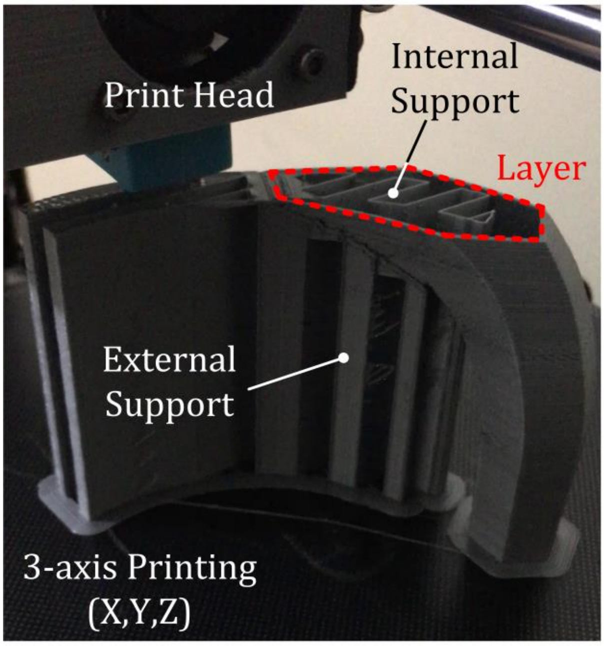

Fig 5. Production of the sample part on a regular 3-axis FFF platform.

4. Results and discussion

This section covers the significant results and the relevant remarks noticed in the production tests.

The sample part fabricated on the developed 5-axis manufacturing platform is shown in Figure 6a. Obviously, the final shape of the manufactured object reveals the promising potential of multi-axis systems in support-less FFF. The capability of in-process alterations on the orientation of the upcoming layers leads to the remarkable quality of the 2-shell hexagonal cross-section, as observed from the same figure.

The cross-section of a sample slice is shown with red color in Figure 6b. The stacking of those sequential layers (whose normal vectors were always oriented parallel to the gravity) results in a smooth surface shown in the detailed view.

In the case of the conventional 3-axis FFF, however, the only option is to utilize parallel layers to the build plate due to the absence of rotational axes (see Figure 5). Hence, the use of both internal & external support structures was inevitable to keep the overhanging layers in continuous contact with the previously deposited regions. The details of the sequential parallel layers can be viewed in Figure 6c. As can be inferred from the figure, the nature of the 3-axis FFF leads to the stair-stepping problem and the wastage of material for the support structure. Note that the printing time and material consumption are almost doubled in 3-axis FFF, as can be inferred from Table 1. Moreover, removing those supports is likely to induce accompanying problems such as permanent asperities on the contacting surfaces. Due to the shape complexity, support removal may become impossible in the inner sections (unless a soluble support material was not employed).

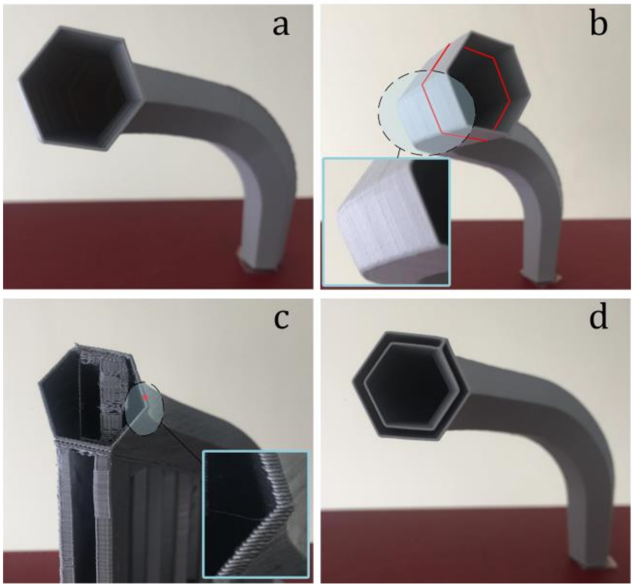

Fig 6. (a) The sample part produced on the 5-axis platform without support structure, (b) Another view of the same object with extra details, (c) The sample part produced on the 3-axis platform with support structures, (d) A modified part produced on the 5-axis platform without support structure.

In order to further promote the capability of the multi-axis FFF, a similar object with a more complex cross-section is also printed on the 5-axis platform. The modified hexagonal cross-section (i.e., two nested walls) is shown in Figure 6d. The production of the modified part on a 3-axis FFF platform would presumably require two internal support structures (in between the walls) and external support. This implies the inferiority of the conventional FFF hardware in printing intricate designs.

5. Conclusions

The need for support structure is one of the inherent weaknesses of the conventional FFF hardware. A possible remedy is to use multi-axis platforms and benefit from the flexibility they offer. In this study, the performance of a multi-axis FFF setup has proved efficient in support-free manufacturing of a complex sample part. In this work, the quality of the produced object is compared to its duplicate fabricated on a conventional FFF setup. The findings show the promising potential of multi-axis FFF to eliminate the support structure requirement completely. In future studies, quantitative comparisons are to be aimed to reveal the superiorities of the developed multi-axis platform over the existing ones.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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