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Use of a nozzle with a rectangular orifice on a hybrid FFF system

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Abstract

Fused Filament Fabrication (FFF) process has lower surface roughness quality, precision and it takes longer to fabricate compared to the conventional manufacturing operations and some additive manufacturing technologies. In order to overcome these issues, a rotary extruder head with a nozzle having a rectangular orifice has been utilized in this work. A new tool path planning for a rectangular nozzle is designed to increase the efficiency of the extrusion process by this nozzle. As a result, finer features (such as outer surfaces, edges, corners, etc.) can be 3D-printed with greater accuracy, and inner regions can be extruded in less time. The design algorithms for outer shells, inner regions, and infill paths are presented here to show the procedure of the tool path planning and examined for different test cases. Some modifications in the case of concave curves as the outer shells are also offered. Moreover, these test cases have been fabricated in our hybrid manufacturing system named HYBRO, which has five axes plus milling and rotary extruder heads to demonstrate this new strategy. The results demonstrate the smallest and the largest bead widths obtained with the same rectangular nozzle.

Keywords: Hybrid additive manufacturing, Nozzle with rectangular orifice, Process planning

1. Introduction

Fused Filament Fabrication (FFF) technology provides the opportunity to produce complex objects with sophisticated interior features. However, poor surface quality, low accuracy, and long production times are considerable drawbacks of FFF-based Additive Manufacturing (AM). In-process tuning of the width of the extruded beads has become a possible remedy to overcome the current difficulties. In this way, the smallest achievable bead width could be applicable in producing fine features of the objects, such as the skinny shells of the artifacts. By contrast, the largest achievable bead width is suitable for infill regions to decrease the built time. With the optimized selection concerning this trade-off relation, either the part quality or the production speed could be boosted.

In recent literature, the majority of the studies have focused on the modifications of the nozzle geometry to achieve variations in the bead width. The researchers have investigated unique nozzles with square-, rectangular-, and star-shaped orifices [1-4]. Other studies have concentrated on the extrusion parameters [5] and adaptive process planning [6].

In this work, a nozzle with a rectangular orifice to extrude variable bead widths between the size of the small and the large edge of the rectangle is investigated. In previous work, authors have introduced controlling the filament flow inside the rectangular nozzle [1]. The main focus is to attain controllable variations in the bead width of extruded material in a typical FFF process. First of all, an innovative tool path planning approach is essential for this novel extrusion method (i.e., variable bead width extrusion). This new process planning framework should also be easy to implement and computationally efficient.

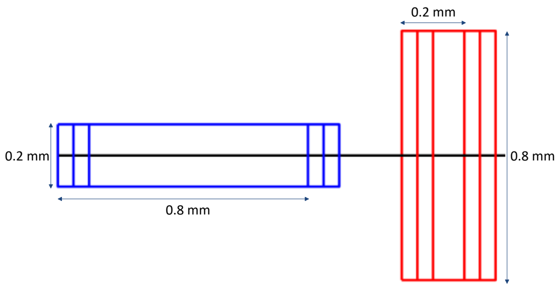
On the hardware side, the development of a compatible FFF setup is vital to carry out the necessary tests for the proof-of-the-concept. For this purpose, a multi-axis additive- and subtractive machine equipped with an additional rotational axis (for the rotation of the unique nozzle attached to the main 3D-printing head) is utilized. The machine setup, known as HYBRO, is capable of arranging the nozzle in any orientation and has a machining unit to modify the extruded beads/regions wherever necessary [7].

The key contributions of this work are summarized as follows: (i) proposing a new tool path planning approach for the unique nozzle with rectangular orifice, and (ii) presenting the remarkable findings obtained from the preliminary tests on the described machine setup.

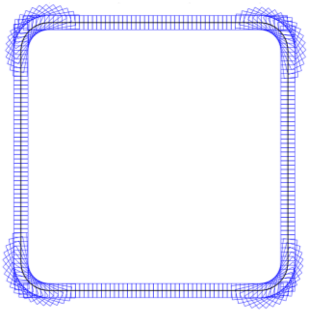
The rest of the paper is organized as follows. The new tool path planning method and the simulation results for various test cases are presented in Section 2. In the next section, a brief summary of the capabilities of the machine setup is presented. In Section 4, preliminary tests and the relevant results are provided. This paper is then concluded with critical remarks and the future works in Section 5.

2. Tool path planning approach

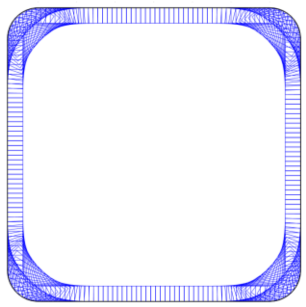
A variable bead-width extrusion system for FFF requires a new process planning approach different than the standard methods used for conventional nozzles having a circular orifice. Dynamic adjustment of polymer beads can be possible with the distinct shape of the nozzle and the accompanying rotational Degree of Freedom (DoF). Therefore, new strategies for this proposed extrusion system are developed to achieve planned bead width, i.e., the smallest possible width, the largest possible width, or any width in between. For example, Fig. 1(a) shows rectangles aligned by both small and large edges (three blue and red rectangles swept by small and big edges, respectively). The dimension of the rectangular orifice is selected as 0.2mm×0.8 mm.



(a)



(b)

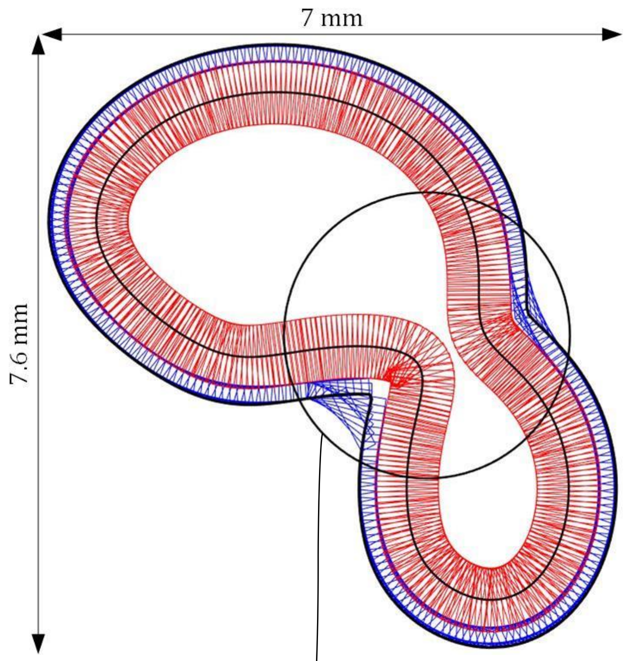


(c)

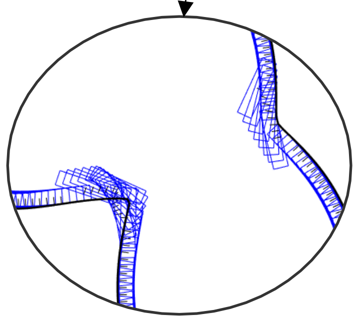
Fig 1. (a) Blue and red rectangles sweeping by the small and big edges, respectively, (b) forming the protrusion areas by sweeping the blue rectangles along the black curve to simulate the smallest bead width, (c) sweeping the blue rectangles, which are surrounded by the black curve to simulate the smallest bead width.

The first design strategy is presented to extrude the smallest bead width along an arbitrary 2D curve. If a rectangle is oriented along a 2D curve due to the curve's frames, some protrusion areas at the points of discontinuity occurred, as shown in Fig. 1(b). The primary purpose of this strategy is to orient the rectangles on a curve that those rectangles are located inside an envelope curve to remove protrusion areas at the discontinuity points during the contour. In other words, two corners of the large edge are always located on the curve where the rectangles themselves are located inside the main curve, as shown in Fig. 1(c). This strategy is resulted in removing the protrusion areas around the discontinuity points. The central points of rectangles and their angles with the horizontal axis are derived to generate G code commands at the end of the process.

Another strategy is based on the orientation of the rectangles by arbitrary angles to simulate arbitrary bead widths. Here, the largest bead width is simulated. In this method, the centroid points of the rectangles are oriented on the curve instead of their two corners in the previous method. In this way, simulating variable bead width can be achieved due to arbitrary angles. Fig. 2(a) shows 2D curves in black color, which are swept by the smallest and the largest bead widths for outer and inner curves, respectively (The blue and red rectangles are simulated the smallest and the largest bead widths, respectively).



(a)



(b)

Fig 2. Sweeping the rectangles to simulate (a) the smallest (blue rectangles) and the largest (red rectangles) bead widths, (b) by modifying rectangles located outside the concave curve.

However, the strategy for extruding the smallest bead width should be modified in the case of the concave curves. Some sections of the rectangles are located outside the concave curves, as shown in Fig. 2(a) (The blue rectangles outside the black curve). The center points of the rectangles are checked during the path. If they are located outside the main curve, the corresponding rectangles are rotated until their centroid points are located inside the concave curve, as shown in Fig. 2(b). Still, some small regions of the rectangles remain outside of the enveloped curve that can be ignored.

Furthermore, an additional method is about using a hybrid additive machine setup with a spindle head to remove the protruding areas. Thus, these areas should be specified and then machined. Fig. 3 shows the protruding areas (in red color), which can be machined by a machine tool (dotted regions). However, some negligible areas are still remained due to machine tool geometry constraints.

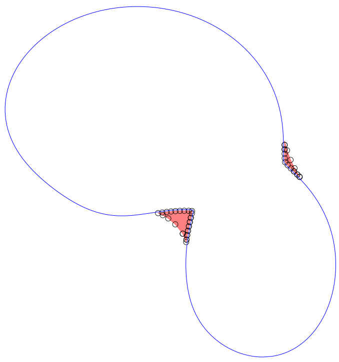


Fig 3. Machining the protruding areas (red regions) by machine tool (dotted regions).

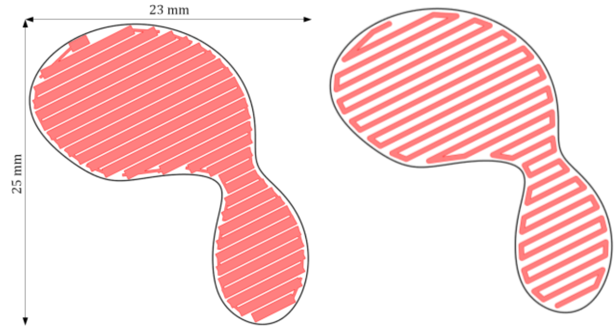
As shown in Fig. 1 and Fig. 2, discussed strategies and their simulated results are primarily used in curve contours as shells. However, the infill pattern for the rectangular nozzle may also be changed. By extruding the largest bead width inside the curves, build time can be decreased significantly.

Here hatched infill pattern is selected to simulate the infill strategy by sweeping rectangles. There is a comparison in Fig. 4 between a standard nozzle with a diameter of 0.4 mm and the nozzle with the rectangular orifice. The void area is decreased for the same number of lines using the largest bead width in the rectangular nozzle.

The infill density can be calculated by Eq. (1), where, A_{filled} and A_{total} are used for the filling and the total areas, respectively. The results of the infill density for the test cases in Fig. 4 are summarized in Table 1. It is evident that the infill density is increased more than twice for the rectangular nozzle in this example. In other words, the void area is decreased with the help of the rectangular nozzle.

So, the number of hatched lines decreases for the rectangular nozzle in the case of filling the same area by these two nozzles. It means the built time for the rectangular nozzle is decreased for filling the same area.

$$Infill\ density\ (\%) = \frac{A_{filled}}{A_{total}} \times 100 \qquad (1)$$



(a) (b)

Fig 4. Simulating the infill pattern due to (a) sweeping mostly by the largest edge of rectangle (b) circular nozzle.

Table 1. Comparison of the infill density for two types of extrusion method.

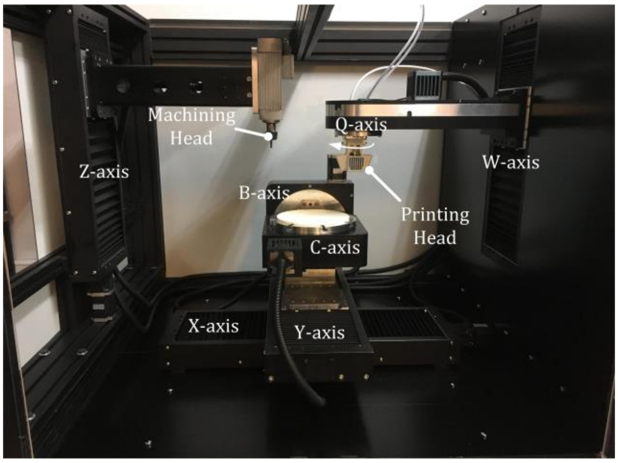
Nozzle type	**Rectangular Nozzle**	**Circular Nozzle**
Infill density (%)	72.89	39.66

3. Hybrid system (HYBRO)

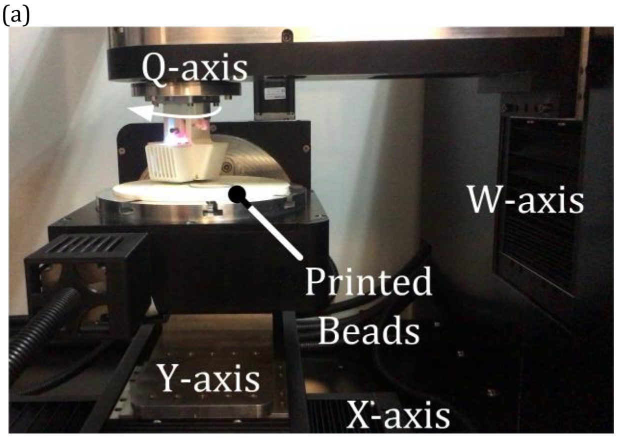
HYBRO, a multi-axis hybrid workstation, was built to enable FFF and CNC machining on a single setup. The purpose was to handle any manufacturing cases with the flexibility introduced.

The primary capabilities of the HYBRO are summarized as follows.

- 3D-print Head for AM: FFF technology is utilized with typical thermoplastics such as PLA or ABS. Dual extrusion is possible with the two nozzles accommodated on the 3D-print head.
- Machining Head for Subtractive Manufacturing: The collets (with the range of ∅3 mm – ∅16 mm) of the spindle motor are compatible with a number of machining and deburring tools
- 5-DoF for positioning/orientation: Workpiece Coordinate System (WCS) can be positioned/oriented with respect to the additive (i.e., X, Y, W, B, C) or subtractive tool (i.e., X, Y, Z, B, C)
- Extra rotational DoF for the 3D-Print Head: The unique nozzle (attached to the main print head) can be continuously oriented throughout the 3D printing process. A complete rotation could also be handled.



(a)



(b)

Fig 5. (a) HYBRO and (b) Detailed view of the rotational Q-axis.

Fig. 5(a) reveals the placement of the axes of HYBRO. In this configuration, there are 4 different translational (i.e., X,Y,Z,W) and 3 rotational motion (i.e., B,C,Q).

Since the main purpose of this study is to produce 2.5D beads with FFF technology, the motion axes X, Y, W are used for positioning, whereas the Q axis is used for orienting the nozzle while tracing on the 2D contour (see Fig. 5(b)).

4. Implementations in HYBRO

In this section, different experimental results have been obtained to demonstrate the extruding variable bead width. The PLA filament is used as an extrusion material. So, thin and thick shells have been extruded separately to measure their shell thicknesses. Also, a 2.5-D object consists of thin, thick shells, and the infilled area is printed as a test case. Fig. 6 shows the thicker shell inside the thinner shell and the 2.5-D object. The results demonstrate that the smallest and the largest beads have been extruded successfully. The widths of the smallest and the largest beads (thin and thick shells) are about 0.25 mm and 0.82 mm, respectively, as expected due to the tool path planning strategy. The width of the infill pattern is about 0.82 mm as the desired value. Layer thickness for the thin and thick shells is 0.1 mm, and it is set to 0.2 mm for the infill pattern. Also, the temperature of the extruder is set at 205 °C, and the print speed is 6 mm/sec.

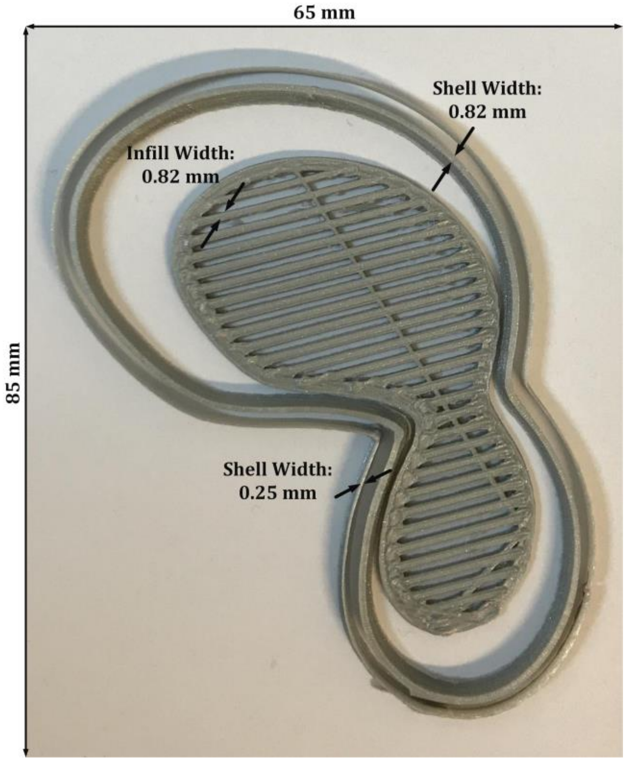


Fig 6. Extruded outer and inner shells plus a 2.5-D object.

5. Conclusions

In this paper, a new tool path planning algorithm is proposed for the nozzle with a rectangular orifice. Therefore, variable bead width can be extruded by these new extrusion methods. For example, the smallest and the largest shells can be extruded. Moreover, the largest bead width may be used for the infill area. Simulations and experimental results show that extruding the variable bead width is possible with proper tool path planning and the required machine setup.

As future works, 3D sophisticated parts will be designed and manufactured by this new tool path planning and HYBRO machine. Modified extrusion and milling strategies can also be examined in the near future.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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