Model guided DLP 3D printing for solid and hollow structure

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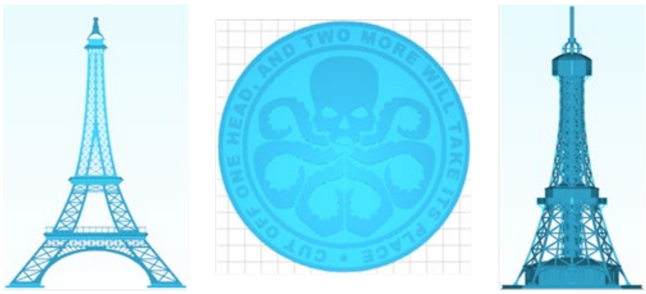
***Abstract*—Manufacturing speed is one of the biggest challenges in 3D printing. Continuous stereolithography printing can effectively improve the printing speed. However, the model it can print is limited to the hollow out structure or flake structure. In the real application scenario, the models are the composition of multiple kinds of structures such as solid structure, hollow out structure, or flake structure. The continuous stereolithography printing scheme will not work for such models. In order to define the problem, we first propose a concept of maximum fillable distance (MFD) for a set of resin material and printing settings. And for a specific kind of printing setting, the MFD of resin material at different platform moving speeds is estimated by experiments. Furthermore, combining analysis to the model slices, a printing control scheme to combining the continuous and layer-wise printing is generated automatically. Using the printing control scheme, two real models are successfully printed.**

Keywords—DLP 3D printing, large area, fast 3D printing, continuous 3D printing, layer-wise 3D printing, maximum fillable distance, model-guided

I. Introduction

In recent years, 3D printing has become a popular manufacturing technology, and it has been widely used in many fields such as mold manufacturing, medicine and health, and design [1-4]. There are many types of 3D printing technologies, such as selective laser melting (SLM) using metal materials, selective laser sintering (SLS) using nylon powder, stereolithography apparatus (SLA) and digital light processing (DLP) using resins, and fused deposition modeling (FDM) using plastomers [5]. DLP 3D printing [6] is one of the most popular mask projection 3D printing technologies, and it has the characteristics of high speed and high precision.

Manufacturing speed is one of the biggest challenges in 3D printing. Further, it obstructs the development and application of 3D printing technology. In recent years, some exciting works have been proposed for continuous printing in mask projecting 3D printers. These approaches can be classified into gas interface control-based schemes [7], liquid interface control-based schemes [8-9], and illumination control-based schemes [10-12].The system structure and the control scheme of liquid interface-based methods are comparatively simple, and it is more promising. However, the existed Liquid interface-based scheme can print only the models with the hollow out structure or flake structure (as shown in Fig. 1) because of the confliction of resin flowing, platform moving speed, and light intensity. In the real application scenarios, most models include the solid structure. Therefore a novel printing control scheme to effectively combining the continuous and layer-wise printing is needed.



(a) (b) (c)

Figure 1 The printability of models for continuous printing. (a) The model of hollow out structure----printable (b) The flake structure ---- printable. (c) The model of the combination of solid structure and hollow out structure ---- not printable.

In fact, the flowing speed of resin material under the fixed condition, including the liquid interface, the platform moving speed. On the other hand, the curing speed of resin is related to the platform moving speed and light intensity. In this paper, we first propose a concept of maximum fillable distance (MFD). And for a specific kind of resin material and a kind of DLPligh source with a light intensity of 20mW, the MFD of resin material at different platform moving speeds is estimated by experiments. Based on the estimated MFD, combining analysis to the model slices, a printing control scheme to combining the continuous and layer-wise printing is generated automatically. Using the printing control scheme, two real models are successfully printed.

The contributions of this paper are as follows:

1. A concept of maximum fillable distance (MFD) is proposed to evaluate the printability of resin under fixed conditions.

2. An 3D printer with a camera is designed to observe flowing of the resin material. Using the printer, the MFD of resin material could be estimated under the fixed condition,

including illumination intensity, platform moving speed, liquid interface, and so on.

3. Based on the estimated MFD, a model-guided printing control scheme is designed to effectively combine continuous and layer-wise printing. And two models are printed successfully.

II. Related Work

A. Gas Interface Control Based Schemes

In 2015, CLIP (continuous liquid interface production) systems appeared for the first time in Science [7]. The bot-tom film of the resin tank is an oxygen-permeable window through which oxygen is injected to form a "dead zone" between the curing part and the film. The photosensitive resin can polymerize above the "dead zone" instead of directly polymerizing on the film, so the resin can continuously flow into the dead zone to supplement and realize continuous printing. However, CLIP systems have the following limitations: because the inhibition of oxygen is only limited to prevent free radical polymerization, the choice of resin materials and exposure conditions is limited; the oxygen structure is complex, and the oxygen control may lead to poor surface curing; in addition, the maximum molding surface provided in this paper is not more than 10cm * 10cm.

This scheme changes the traditional way of DLP 3D printing and greatly improves the printing speed. However, because the inhibition of oxygen is limited to preventing free radical polymerization, the selection of resin and exposure conditions are limited. The introduction of oxygen will lead to poor surface curing of hundreds of microns or larger, and the oxygen structure is more complex.

B. Illumination Control Based Schemes

In 2019, The University of Michigan had developed an additive manufacturing (AM) system [10], using a molding head and pulling up the photopolymerizable resin and two illumination sources with different wavelengths. Through the patterned illumination from the bottom of the transparent glass window, the polymerization of the resin is initiated, and the second wavelength irradiation suppresses the polymerization reaction next to the glass window so as to achieve the purpose of eliminating adhesion and continuous operation. By adjusting the light intensity of each pixel, the surface topography can be patterned without phase translation. The printing speed of this scheme is fast, but the light source control is complex. The University of California, Berkeley has proposed a new computational axial lithography technology [11]. When rotating around the vertical axis, the pre-calculated sequence of light patterns is digitally projected into the resin container. When rotating, thousands of different projections can be illuminated in the resin. Over time, the accumulated light exposure area that passes through the polymerization threshold becomes solid, while the area that does not pass through the threshold remains uncured, thus printing the designed three-dimensional object at one time. This technology does not need to print layer by layer and directly form the whole 3D object by photopolymerization in a high viscosity resin container. They also use the oxygen suppression mechanism to ensure that the resin closest to the light source will not react before the object in the center of the container accumulates enough light intensity to become solid. The light source control is more complex and needs to be coordinated with the oxygen control.

In 2020, a team from Germany will be able to complete a 3D printing in a few seconds, with a printing accuracy of 25 microns and a printing speed of 55 cm3/s[12]. In this method, a liquid compound dual-color photoinitiator(dcpi) is used to apply two different wavelengths of rays in the resin. The first wavelength activates the molecule of the photoviscous initiator, and then the projector projects a second beam of light to project the slice image of the 3D object, triggering the polymerization and solidification of the resin material. This method has the advantages of no support, high precision, and fast printing speed. At the same time, the printing speed is limited by laser light source and resin material.

C. Liquid Interface Control Based Schemes

In 2018, inspired by the smooth water layer on the surface of the pitcher plant, Song Yanlin's team from the Institute of Chemistry, Chinese Academy of Sciences proposed a smooth and ultra-low viscosity manufacturing surface [8]. Crosslinked poly(dimethyl siloxane) (PDMS) is immersed in perfluorocarbon for 24 hours to prepare the ultra-low adhesive energy interface (S-PDMS). The forming interface controlled by liquid is formed. This interface overcomes the adhesion problem between the samples and the interface in the previous 3D printing curing process and enables the printing material to be continuously and rapidly formed with high precision so as to realize continuous and high-speed 3D printing. At the same time, the method overcomes the requirement of resin type and has universality. This strategy of controlling 3D structure forming through 2D interface properties provides a new idea for the development of fast 3D printing.

In 2019, Walker et al. of Northwestern University in the United States believed that a large amount of heat was generated during the curing of photosensitive resin and proposed active, flow cooling fluorinated oil for heat dissipation so as to further improve the speed [9].

This interface overcomes the adhesion problem between the sample and the interface in the previous 3D printing curing process and enables the printing material to be continuously and rapidly formed with high precision so as to realize continuous and high-speed 3D printing. At the same time, the method overcomes the requirement of resin type and has universality.

However, the liquid interface control-based schemes molding technology generally prints the hollow out structure model so that the resin material can fill the exposure area in time. However, in practical application, most models are not hollow out the structure and have a large exposure area. For this kind of area, the material is difficult to fill completely in time, so this technology is limited. How to realize the rapid printing of large-scale nonhollow structure models is of great significance for the promotion and application of 3D printing technology. Therefore, this is the focus of this paper.

III. Estimation Of Maximum fillable Distance Prepare

A. The designed 3D printer

The designed 3D printer is a bottom exposure device, as shown in Fig. 2, (a)The hardware design of the designed 3D printer; (b) A practical device. The system includes several components. The projector is placed on the placement units.

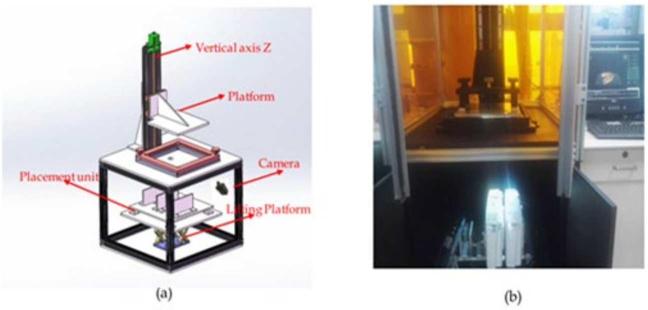


Figure 2. The designed 3D printer

The camera is used to capture the videos in the printing process. The liquid photopolymer resin to be cured is contained in a transparent tank. The object is printed on the platform. A layer of PDMS with fluorinated oil is stuck on the bottom of the tank. The oil is the key factor to form the liquid interface. Therefore, before printing starts, the PDMS should be soaked in the fluorinated oil for about 10 hours. The platform could be lifted along the vertical axis (z) so that the model could be printed continuously or layer by layer.

In the system, UV light beams that are controlled using the mask images from the projectors are projected onto the bottom of the tank. The printing material (resin) is then cured rapidly through the transparent tank. For continuous printing, the platform is lifted at a constant speed. And for the layer-wise printing, after each layer is cured, the platform is lifted vertically along the z-axis to a height such as 0.3mm, so that a small gap could be formed between the fabricated layer and the bottom of the tank, and the resin material could be filled quickly. Then the platform descends a distance so that a layer of resin with a fixed height such as 0.1mm could be formed. Then the light source is turned on, and the curing is implemented. To prevent the cured layer from adhering to the tank, a fluorinated ethylene propylene layer [13] is used to coat the bottom surface of the tank. This mask image projection and resin curing process are applied iteratively to print the model layer by layer.

In the process of continuous curing, the videos captured by the camera could present the resin flowing, the normal and abnormal curing. Some examples are shown in Figure 3.

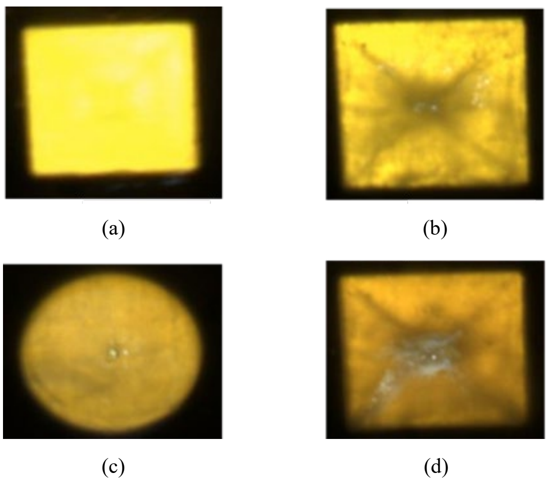


Figure 3 Illustration of normal and abnormal curing status. (a) The normal curing status. (b) A status of resin flowing for a square model. (c) A status of resin flowing for disk model. (d) The abnormal curing status (the white region means that the resin cannot be filled in time.)

From Fig. 3, we can see that the normal and abnormal curing status lack of resin could be discriminated from the videos. For the normal printing regions, because the resin material is similar yellow, the R and G component is much higher, and the B component is comparatively smaller. They are usually smaller than 100. For the abnormal region, the color is close to the white color, and the R, G, and B components are all higher. Therefore, it is easy to distinguish the abnormal and normal regions by using the B component.

B. Estimation of MFD

Under the fixed illumination intensity, whether the continuous printing is successful or not depends on the resin material flowing and filling. If the resin could fill the region for exposure, the printing will be successful. In order to measure the resin filling, we propose the concept of maximum fillable distance (MFD), the maximum distance that the resin material could fill at a specific platform lifting speed. Of course, the MFD is also related to the viscosity of the resin, the fluorinated oil, and so on.

In this paper, an experiment is designed to measure the MFD of the resin material we used.

First, we set the illumination intensity to the highest 20mw, and test the printability at speed of 0.04mm/s, 0.06mm/s, 0.08mm/s and 0.1mm/s. the experiments demonstrate that except 0.1mm/s, the other three speeds are printable. Conclusion 1: under the illumination of 20mw, the height of the platform moving should be smaller or equal to 0.08mm/s.

Furthermore, we test the MFD at the above three speeds. The model of 1cm*1cm, 2cm*2cm, 3cm*3cm are printed respectively. The printing process is monitored using the camera. And the video is an automated analysis, if there is a region whose B component is higher than 120, we think these regions are not fully filled, and the printing process is stopped. The height of the printed objects is measured. The results are shown in TABLE I.

Therefore, if we set the minimum continuously printing height as 1mm, the maximum successfully printed at printing speed 0.04mm/s is 2cm*2cm. Therefore, MFD is 1cm. So forth, MFD at printing speed 0.06mm/s is 1.5cm. MFD at speed 0.08mm/s is 2cm.

TABLE I THE PRINTABLE HEIGHT FOR DIFFERENT EXPOSURE AREA

Area of the model	**Platform moving speed**	**Maximum printable height**
1cm*1cm	0.04mm/s	3.482mm
1cm*1cm	0.06mm/s	3.642mm
1cm*1cm	0.08mm/s	4.030mm
2cm*2cm	0.04mm/s	1.163mm
2cm*2cm	0.06mm/s	1.457mm
2cm*2cm	0.08mm/s	1.792mm
3cm*3cm	0.04mm/s	0.658mm
3cm*3cm	0.06mm/s	1.297mm
3cm*3cm	0.08mm/s	1.433mm

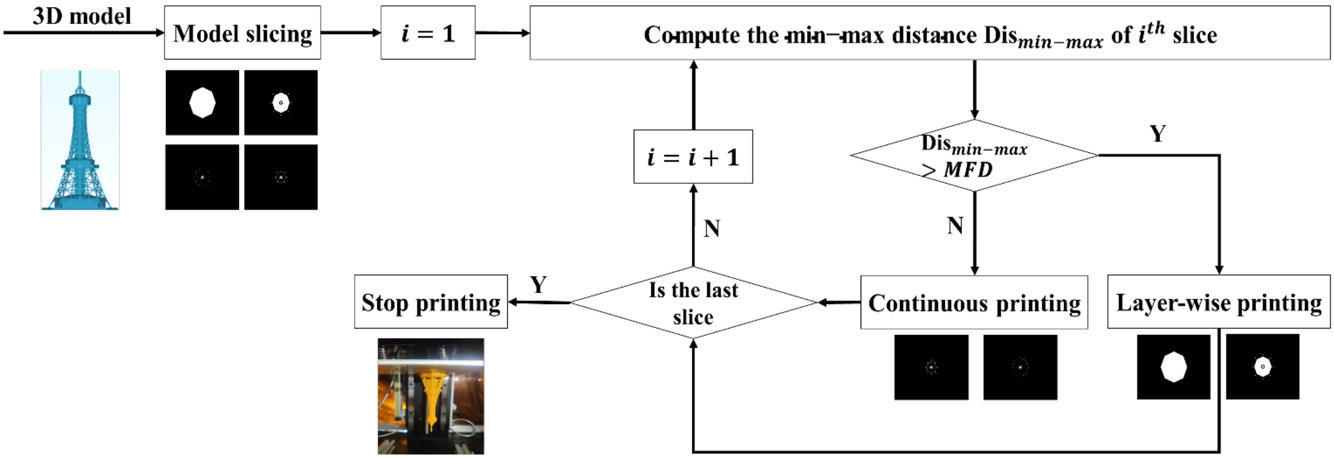


Figure 4 Model guided printing control scheme

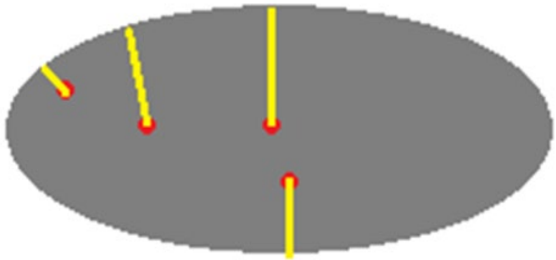


Figure 5 Illustration of minimum distance

IV. Model Guided Printing Control

Based on the MFD, the model-guided printing control scheme is designed as shown in Fig. 4. First, the continuous printing speed is selected.

The model is firstly sliced by layer-wise printing. Then the minimum-maximum distance DisMax-Min is computed of each slice. If the max-min distance is bigger than MFD at the selected speed, the layer-wise printing is conducted other continuous printed is conducted.

What's the max-min distance? We suppose that the resin flowing speed at the contour point is uniform. For the non-contour points, if the resin could flow and fill them, the corresponding region could be successfully cured. Otherwise, the region could not be successfully printed. For each non-contour point, we compute the minimum distance from it to the contour points, as shown in Fig. 5. Then the maximum of the minimum distance of all the noncontour points is thought the points, which need the longest time for fully filling

V. Experimental Results

A. *How does the Moving Speed Influence the Curing Quality*

We print the square with the size of 1cm*1cm*3mm, 2cm*2cm*3mm,3cm*3cm*3mm under the speed of 0.04mm/s, 0.06mm/s, and 0.08mm/s respectively, and measure the observe the videos of the print process, the printed objects are shown in Fig. 6

As is well known, the roughness represents the surface quality. The bigger roughness, the poorer printing quality.

From Figure 4 we can see that the surface quality of the printed reises as the size of the printed object increases at the same speed. As known from Section, the mix-min distance raises as the size increases. with the same size, the roughness descends as the moving speed increase. As shown in Section 3, MFD increase as the moving speed increase. The results confirms that the analysis in the former sections are meaningful.

B. *Printing Samples with the Proposed Scheme*

In this Section, two models in Fig. 7 are printed by combining the continuous printing at speed 0.06mm/s and layer-wise printing 0.1mm/slices.

The model tower is segmented into six parts. Part 1 is the base part, its dominantly hexagon solid structure. The width

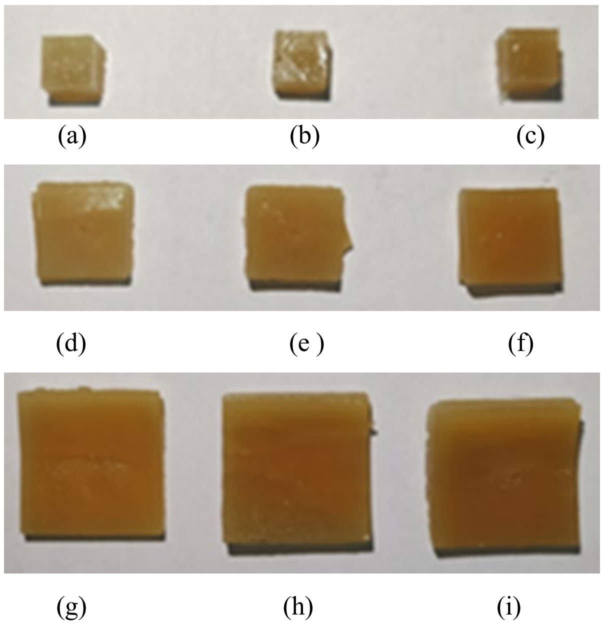
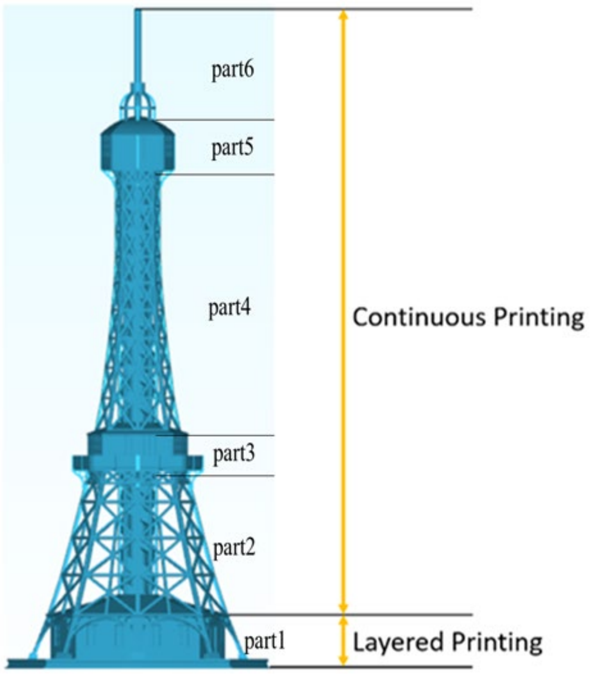
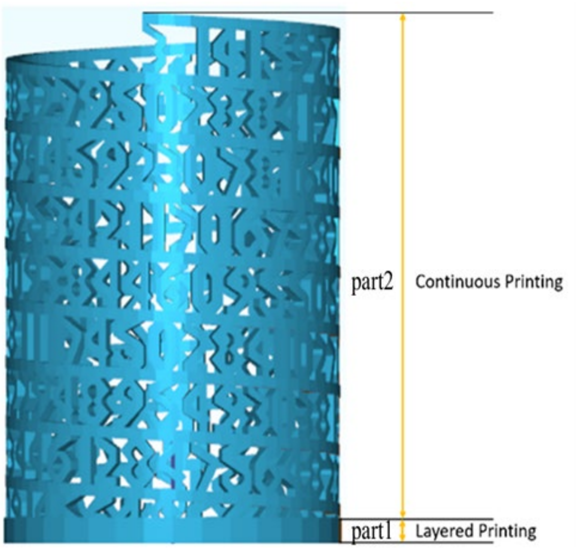


Figure 6 Roughness of the objects of different size printed at different speed. (a) 1cm*1cm*3mm at speed of 0.04mm/s, Ra=1.83um, Rz=11.84um; (b)1cm*1cm*3mm at speed of 0.06mm/s, Ra=0.87um, Rz=7.22um; (c)1cm*1cm*3mm at speed of 0.08mm/s, Ra=0.85um, Rz=6.81um; (d) 2cm*2cm*3mm at speed of 0.04mm/s, Ra=1.78um, Rz=12.70; (e) 2cm*2cm*3mm at speed of 0.06mm/s, Ra=1.38um, Rz=11.82um; (f)2cm*2cm*3mm at speed of 0.08m/s, Ra=1.12um, Rz=8.75um; (g)3m*3m*3mm at speed of 0.04mm/s, Ra=2.32um, Rz=13.21um; (h) 3m*3m*3mm at speed of 0.06m/s, Ra=2.13um, Rz=11.87um; (i) 3m*3m*3mm at speed of 0.08m/s, Ra=1.94um, Rz=9.65um

of the solid region is in the range of [3.0cm,4.2cm]. The max-min distance is in the range of [1.5cm,2.1cm], which are all bigger than the MDF at the corresponding speed. Therefore, layer-wise printed is conducted. This part is printed layer by layer. Part 2, part4, part 6 are all dominantly hollow out structures. They are continuously printed. Part 3 and part 5 are also the solid structure, but their max-width is 2cm and 1.1cm, respectively. And the max-min distances are smaller than 1.5cm. Therefore, they are also continuously printed. Model "π pen holder" is comparatively simple. It is partitioned into two-part. Part 1 is the bottom of the pen holder. It is a solid disk, its diameter is 4.5cm, and the max-min distance is 2.25cm, which is much bigger than the MFD. Therefore, it is printed layer by layer. Part 2 is a dominantly hollow-out structure, and it is printed continuously.

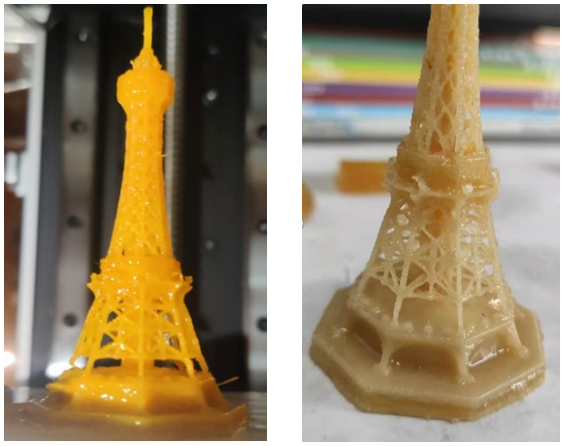


(a) Tower control parameters

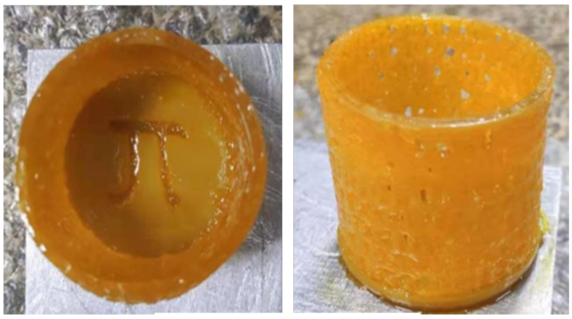


(b) "π" pen holder control parameters

Figure 7 Two models and printing plan. (a) Tower (b) π pen holder.



(a) Tower



(b) "π" pen holder

Figure 8 The printed objects for the models in Figure 7.

The height of the tower is 7.5 cm, the total printing time is 34 minutes 51 seconds. The height of the pen holder is 5.8 cm, its printing time is 23 minutes 13 seconds. The printing time is about 23.4% of the layer-wise printing. The printed objects are shown in Fig. 8. From Fig. 8, we can see that the layer-wise printed could guarantee the quality of a large area solid structure. Such as the base part of the tower and the bottom of the pen holder.

VI. Conclusion

In this paper, a novel model-guided printing control scheme is proposed. We first propose the concept of MFD to represent continuous printability. Then we design an experiment to estimate the MFD of a kind of resin material at a different speed. Finally, a model-guided printing control scheme is designed for practical printing. Two successfully printed objects demonstrate that the proposed scheme is helpful to realistic application.

However, the work in this paper is preliminary. We just obtain the MFD by experiments. In the future, we will further theoretically analyze the experimental results and draw the resin-flowing equation. Further, we need to introduce more factors that possibly influence the resin flowing and filling

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