Research on the Productivity of Desktop 3D Printer

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Abstract. At present, desktop 3D printer has got lots of attention in many fields. Compared with traditional machining, 3D printer makes the parts through the principle of layered manufacturing, which has lower production efficiency. To improve the productivity of a desktop 3D printer, this article provides a new way to optimize part build time, that is, the surface layer, the bottom and top outline are printed by nozzle of 0.4 mm, while the internal filling is performed by the nozzle of 1.2 mm. Last, through contrast experiment to the existing single nozzle process, the new process method, based on the unabated accuracy and strength of parts shortened the parts’ build time substantially, meanwhile ensured the surface roughness under the same premise. It could provide a new idea for the desktop 3D printing efficiency.

1. Introduction
After nearly 30 years' developing, 3D printing has penetrated into automobile manufacturing, aerospace, cultural entertainment, medical prosthetics, and other fields. But like any other technology, 3D printing as a new technology also exits limitations in the process of its formation as well as its development. Lu Bingheng pointed out that additive manufacturing technology in our country is mainly used in product researching, which has high cost, low efficiency in manufacturing and the accuracy can't be satisfied[1].

Fused deposition molding process used in the desktop 3D printer is widely used in rapid prototyping process. It forms by extruding the melt filament, which uses the principle of layered manufacturing. Because of its forming process characteristics, each lamella takes certain scanning time. In terms of technology, to improve the printing surface roughness is not difficult, only need to redesign the nozzle to decrease the nozzle’s diameter, and improve the precision of stepper motor at the same time. But the spinneret diameter's reducing may add the moving frequency of the nozzle. However, this lead to the consumed time increasing, greatly reducing the printing speed and the cost will increase. It is clear that to gain the build time and print surface roughness at the same time is too hard. So it has important practical value to study how to improve the working efficiency of FDM desktop 3D printer on the premise that the surface roughness is not abate.

To solve the problem of how to improve the efficiency of desktop 3D printer, many scholars carried out depth researches both at home and abroad and have put forward different solutions. Li Wei[2], Zhang Yong, etc.[3]through software simulation from optimizing filling path to reducing spare route to shorten the build time. Thrimurthulu [4] used real coded genetic algorithm (GA) to develop an analytical model to predict the optimum part orientation for surface roughness. This study revealed that the main factor affected build time was build orientation. Nancharaiah [5] examined the relation-ship between process parameters and build time using Taguchi’s design matrix L9 orthogonal array and ANOVA technique. It was pointed out that process parameters such as layer thickness and air gap could affect the build time significantly. Kumar and Regalla[6] applied 25 full factorial design
to analyze the influence of each process parameter, such as layer thickness, raster angle, orientation, contour width and part raster width on build time of FDM part. It was experimentally reported that the layer thickness and build orientation were important factors in the minimization of the build time. Luo Zhongming[7] by changing the size of the drops, in the case of guaranteeing accuracy influence as small as possible, improved the speed of the printing, so as to shorten the build time.

Throughout the domestic and foreign researches we can find that researchers mostly focus on optimizing process parameters, scanning path, and the support material to improve the efficiency, leaving improving the use of 3D printing equipment to achieve better purpose out of consideration. This paper presents a method to improve the efficiency of desktop 3D printers. Through comparing with the existing methods, it proved that this method improved the efficiency of desktop 3D printing on the premise that the surface roughness of parts guaranteed.

2. Theoretical basis
The FDM forming part is formed by the accumulation of the extrusion head, and the total time required for the forming comprises the boundary scan time, the filling time and the auxiliary time. That is:

\[
t_{\text{total}} = \sum_{i=1}^{N} \left( t_{\text{bound}} + t_{\text{fill}} + t_{\text{auxil}} \right)
\]

\[t_{\text{bound}}\] - Time used for each layer of scan boundary;
\[t_{\text{fill}}\] - Time used for each filling layer scan;
\[t_{\text{auxil}}\] - Each layer of extrusion head empty travel time, squeeze out the time used to change the layer;
\[N\] - The total number of layers of a part.

In the process of extrusion head scanning, the build time of each layer is decided by the scanning speed and the scanning path. That is:

\[
t = \frac{L}{V_f}
\]

Where, \[t\] is the build time of each layer, \[L\] respects scanning path, \[V_f\] stands for scanning speed.

In this paper, we take the cube as an example to calculate the theoretical build time by constructing the generation mechanism of time. If the side length of a part has \(b\) layer boundary contours, the filling path can be obtained at the boundary as

\[
L_{\text{bound}} = \sum_{i=1}^{b} A(a - (2b - 1)W_{\text{bound}})
\]

Where, \(a\) is the length of part, \(W_{\text{bound}}\) respects the width of boundary, \(b\) stands for the number of contours in the boundary. Thus, the time for each layer boundary filling can be got:

\[
t_{\text{bound}} = \frac{L_{\text{bound}}}{V_f} = \frac{\sum_{i=1}^{b} A(a - (2b - 1)W_{\text{bound}})}{V_f}
\]

The path of each section of the component is shown in Fig. 1.
In Fig. 1, $W_{\text{bound}}$ indicates the boundary wire width, $W_{\text{fill}}$ indicates the width of filling wire. If the filling scanning path respected as $L_{\text{fill}}$, the area of each layer of the fill area is $W_{\text{fill}} \cdot L_{\text{fill}} \cdot f$. $f$ stands for the filling ratio. At the same time, its area can be expressed as $(a - 2b \cdot W_{\text{bound}})^2 \cdot f$, so there is $W_{\text{fill}} \cdot L_{\text{fill}} \cdot f = (a - 2b \cdot W_{\text{bound}})^2 \cdot f$, so we can get the filling area of each layer with the time $t_{\text{fill}}$:

$$t_{\text{fill}} = \frac{L_{\text{fill}}}{V_r} = \frac{(a - 2b \cdot W_{\text{bound}})^2 \cdot f}{W_{\text{fill}} \cdot V_r}$$

(5)

The parts of each layer required for build time is the addition of each layer’ filling time, boundary time of each layer and the auxiliary time. That is:

$$t_{\text{each layer}} = \sum_{i=1}^{n} \frac{4[a - (2b - 1)W_{\text{bound}}]}{V_r} + \frac{(a - 2b \cdot W_{\text{bound}})^2 \cdot f}{W_{\text{fill}} \cdot V_r} + t_{\text{aux}}$$

(6)

Assuming that the parts have n layers, the total build time can be obtained by adding together the time of each layer. That is:

$$t_{\text{total}} = \sum_{a=1}^{n} \sum_{i=1}^{n} \frac{4[a - (2b - 1)W_{\text{bound}}]}{V_r} + \frac{(a - 2b \cdot W_{\text{bound}})^2 \cdot f}{W_{\text{fill}} \cdot V_r} + t_{\text{aux}}$$

(7)

The formula for calculating the wire width is:

$$\lambda = \frac{\pi d^2}{2h} \cdot \frac{V_e}{V_r}, B = \frac{\lambda^2 - h^2}{2\lambda}, \bar{W} = \frac{B^2 + h^2}{B}$$

(8)

Where, respects scanning speed, is extruding speed, and stands for the nozzle diameter. By Eq.7 and Eq.8, it can be known that the build time can be shortened by increasing the width of boundary.
wire or the width of filling wire, as well as improving the scanning speed. But increasing the width of the boundary wire or improving the scanning speed will lead to the surface roughness of the parts increasing[8]. The scanning speed depends on the extrusion speed[9]. If you want to improve the extrusion speed, a lot of improvement work is needed. In this view, the two methods are not that desirable. If the width of the boundary wire and the scanning speed is kept constant while increasing the filling wire width, it can not only guarantee the surface roughness not abate, but also improve the efficiency of the desktop 3D printer. According to Eq.7, increase the width of filling wire must increase the diameter of the nozzle, thus there requires a use of double nozzle processing equipment. The device can be used with larger diameter nozzle when works in the filling area, and changes to the smaller diameter nozzle when machining the boundary area.

3. Experimental analysis

3.1. Experimental environment

The equipment uses in this experiment was based on the prusa i3 and was independently developed and improved. It is named double X carriage 3D printer, whose nozzle diameter d equals 0.4mm. At the same time, it uses a modified prusa i3 double nozzles 3D and the nozzle diameter respectively is d1=0.4mm, d2=1.2mm. In both method, the deposition layer h is 0.3mm and the boundary contour number is 2. Wire extrusion speed \( V_e =24\text{mm/s} \), extrusion head scanning speed \( V_f =30\text{mm/s} \). The material used is PLA, the nozzle temperature is 200 centigrade, the filling rate f equals 100%, heating temperature is set to 60 centigrade and the diameter of PLA is 1.75mm. In order to facilitate the research, the parts used in the experiment are all solid cubes of different sizes. The double X carriage 3D printer is shown in Fig. 2.

![Fig.2 double X carriage 3D printer](image)

3.2. Experimental analysis

In the single nozzle method, the nozzle diameter d equals 0.4mm. So the boundary area and the filling area are completed both by the nozzle diameter 0.4mm. After optimizing, the double nozzle diameter changes to d1=0.4mm and d2=1.2mm. In this optimized method, the boundary region is completed by the nozzle diameter d1=0.4mm, while the filling area is completed by the nozzle diameter d2=1.2mm. Other hardware parameters are all consistent. The experiment was divided into double nozzles method and single nozzle method. In each experimental method, eleven groups of side length of 30mm to 130mm solid cube were chose as the research objects. Build time of the two methods were obtained through the printing experiment. Related data is shown in Table 1.
Table 1: Contrast data under two kinds of processing methods

| Parameter | Length a/mm | Time of single nozzle \( t_{\text{single}} \)/min | Time of double nozzles \( t_{\text{double}} \)/min | Time difference \( t \)/min | \( V_{\text{fill}}/V_{\text{total}} \) | Efficiency enhancement factor \( t_{\text{single}}/t_{\text{double}} \) |
|-----------|-------------|---------------------------------|---------------------------------|-----------------|----------------|-------------------------------|
| 30        | 92          | 37                              | 55                              | 0.813           | 2.49            |
| 40        | 209         | 72                              | 137                             | 0.87            | 2.9             |
| 50        | 402         | 126                             | 276                             | 0.885           | 3.19            |
| 60        | 686         | 200                             | 486                             | 0.903           | 3.43            |
| 70        | 1080        | 299                             | 781                             | 0.916           | 3.16            |
| 80        | 1610        | 429                             | 1181                            | 0.926           | 3.75            |
| 90        | 2282        | 589                             | 1693                            | 0.934           | 3.87            |
| 100       | 3120        | 785                             | 2335                            | 0.941           | 3.97            |
| 110       | 4134        | 1023                            | 3131                            | 0.946           | 4.06            |
| 120       | 5380        | 1301                            | 4079                            | 0.950           | 4.14            |
| 130       | 6828        | 1627                            | 5201                            | 0.954           | 4.2             |

The surface roughness of parts is proportional to the boundary wire width \( W \). The smaller the \( W \) is, the smoother the surface of the component, but the larger of the build time it costs. In the double nozzle method, it only changes the width of the filling wire, while the boundary wire width is the same as that of the single nozzle. Therefore, the double nozzle method does not reduce the surface roughness of the parts. From Table 1 we can found that with the increase of the side length, the time required in the two methods both increase, but the double nozzle print saves more time. The nature the double nozzle method let time shortens is that it increases the filling wire width, thereby reducing the filling area path, this is the real reason. When the ratio of the filling volume to the total volume is larger, the more time is saved, the more efficiency it improves.

4. Conclusion
In this paper, a double nozzle method with two different diameter nozzles is put forward, that is, the boundary uses smaller diameter nozzle and larger diameter nozzle is used in filling area. Through comparing with the existing method of single nozzle we find that, this double nozzle method improves the efficiency of desktop 3D printer on the premise of the surface roughness not weaken. Meanwhile, the larger side length of the parts, the more significant efficiency it improves.

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References
[1] B.L. Sun. The Advantages and Limitations of 3D Printing Technology [J]. Techniques of Automation & Applications. 2013, 32(6) (in Chinese).
[2] W. Li, C.S. Ye and S.H. Huang. Filling Path Optimization of FDM System for Fused Extrusion [J]. New Technology & Technology. 2005 (in Chinese).
[3] Y. Zhang, T.R. Zhou and X.H. Zhong. Optimization and Simulation on Filling Path in FDM Rapid Prototyping Process [J]. Forging & Stamping Technology. 2008, 33(2): 124-127 (in Chinese).
[4] Thrimurthulu K, Pandey PM, Reddy NV (2004) Optimum Part Deposition Orientation in Fused Deposition Modeling. Int J Mach Tools Manuf 44(6):585-594. (in Chinese).
[5] Nancharaiah T (2011) Optimization of Process Parameters in FDM Process Using Design of Experiments. Int J Emerg Technol 2(1):100-102.
[6] Kumar GP, Regalla SP (2012) Optimization of Support Material and Build Time in Fused Deposition Modeling (FDM). Appl Mech Mater 110:2245-2251.
[7] Z.M. Luo. Research on Algorithm and Application of 3D Printing [D]. Beijing: Beijing Institute
Of Graphic Communication, 2014 (in Chinese).

[8] C.Y. Mu, Y. Chai and M. Lu. Surface Quality Experimental Research of Modeling Parts Based on FDM[J]. Journal of Shenyang Jianzhu University (Natural Science), 2015, 31(3): 551-561 (in Chinese).

[9] L. Pei, R.D. Wu, and R.J. Zhang. Finite Element Analysis of Scanning Speed Influence on Melted Extrusion Manufacturing[J]. China Mechanical Engineering, 2003, 14(8): 687-689 (in Chinese).