# The influence and improvement of scanning speed to the line width in fused deposition manufacturing

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**Abstract**

During the process of fused deposition manufacturing, the extruding speed and the scanning speed of nozzle don't match in some path of large change in direction may lead the extrusion of material more or less than demand too much which causes accumulation of material or the lack of line width. The method of controlling FDM's forming accuracy which is under the restrictions of the mechanical structure of the work platform is studied. By adjusting the extruding speed and measuring the line width on the work platform the width of forming line in process can be controlled in allowed range. The experiment results indicate that through controlling the speed of extruding motor the extrusion of material is controlled efficiently and the accuracy of molding is improved.

*Keywords:* movement theory of nozzle, scanning speed, extruding motor controlling, measure of line-width

## 1 Introduction

The Fused deposition manufacturing (FDM) is one of the rapid prototyping manufacturing technology and is today the second most common commercial layered manufacturing system [1]. The FDM without the need of laser is lower cost and has a simpler structure compared to SLA, LOM, SLS and other rapid prototyping manufacturing technology. So the maintenance is more convenient, too. But the accuracy of line width is the constraint to the FDM's further improvement [2].

## 2 Theory of scanning speed

The manufacturing accuracy of the FDM is influenced by many factors including the temperature of the nozzle, material viscosity, the contraction size of material's solidification [3], the accuracy of the equipment, the performance of software system and so on. Besides, the manufacturing is also restricted by working platform. The movement of the FDM mainly depends on the three motors of $X$ axis, $Y$ axis and $Z$ axis. The $Z$ axis motor controls the height while the $X$ and $Y$ axes motors controls the nozzle's movement in horizontal direction. That means the nozzle's horizontal scanning speed is composed of motors speed of $X$ and $Y$ axes. As shown in Figure 1.

It's hard to form when the scanning speed is faster than the extruding speed which causes the line broken due to the lack of the material. Instead, when the scanning speed is slower than the extruding speed will lead to the extrusion of the material too much and it causes the material on the working platform spreading non-uniform, which will affect the model's quality [4]. The set scanning speed of the nozzle matches the appropriate extruding speed can make the line width of the material on the working platform in a stable range.

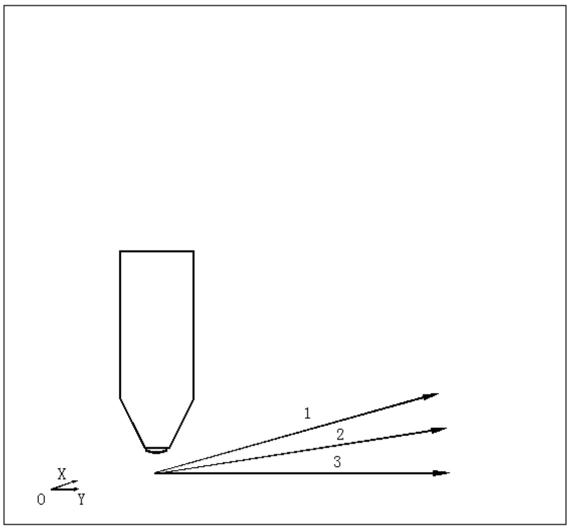


FIGURE 1 The velocity of the nozzle 1. The speed of the $X$ axis 2. The actual speed of the nozzle 3. The speed of the $Y$ axis

However, in some path, such as right-angled path, the scanning speed will change substantially while the extruding speed doesn't change which may cause accumulation of the material on the working platform. Although the scanning speed that is set by PC in different paths, which the PC cannot tell the difference, the motor speed of X and Y axes will change anyway. The most paths during FDM's working process are the straight line path, the right-angled path and the curved path. Here is an experiment between the line width and them. The right-angled path takes the bevel width, which is the critical point of the velocity's change, as the line width. The motor

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speed of $X$ and $Y$ axes don't change when it comes the straight line path. The Table 1 shows the line width of straight line path doesn't change much. The line width in curved path is wider than it in straight line path but the difference between them is not big in generally even the motor speed of X and Y axes are changing all the time. The scanning speed couldn't keep the same when its direction is about to change 90 degree. Because the scanning speed is composed of 2 phase motors' speed and the change in direction of the nozzle need both change of the two motors substantially in a very short time.

TABLE 1 The line-width in different trajectory (mm)

| | **straight line path** | **the curved path** | **right-angled path** |
|---|---|---|---|
| $d$ | 0.65 | 0.7 | 1.10 |
| | 0.62 | 0.69 | 1.05 |
| | 0.61 | 0.72 | 1.07 |
| | 0.59 | 0.71 | 0.99 |
| | 0.62 | 0.75 | 1.08 |
| | 0.63 | 0.7 | 1.09 |
| $\bar{d}$ | 0.62 | 0.71 | 1.06 |

Nozzle's temperature: 200°C the scanning speed: 10mm/s material: Polyurethane

The change of the shaft's speed is accomplished by changing the speed of the servo motor. In normal case, the starting of the no-load servo motor is very quick and the time of it can be ignored compared to the while working process. Even it may cost longer when it is loaded. The right-angled path is done by the nozzle instantly which makes time of the servo motor's acceleration not be ignored and it can be proved by Table 1.The acceleration of the servo motor in the starting and stopping stays the same, which is showed by Figure 2, thus, the relation between the velocity of servo motor and the velocity of the shaft can be calculated. The rotation of the shaft driven by servo motor makes the nozzle move in the direction of X(Y) axis. According to relation between the spiral and the helical pitch in mechanical transmission, the equation can be got as follows:

$$L = M \times P_h . \tag{1}$$

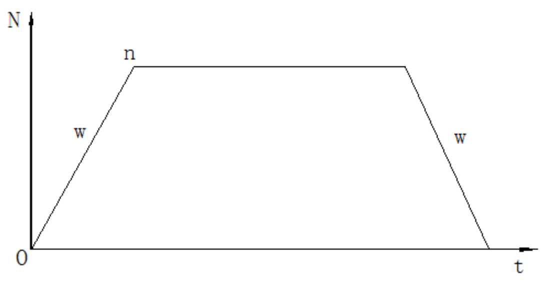


FIGURE 2 The process of motor's starting and stopping. $n$ is the rated speed of the motor, $w$ is the acceleration of the motor

The $L$ represents the distance moved by the nozzle in the direction of $X(Y)$ axis, the $M$ represents the number of rotations of the shaft driven by servo motor, the $P_h$ represents the helical pitch. Both sides of the Equation (1) are divided by the time, the relation between the velocity in axial of the nozzle and the velocity will be:

$$v = \frac{L}{t} = \frac{M}{t} P_h = n \times P_h , \tag{2}$$

and both sides of Equation (2) are differentiated, the relation is as follows:

$$a = \frac{dv}{dt} = \frac{dn}{dt} P_h = w \times P_h , \tag{3}$$

$a$ represents the axial acceleration, the $w$ represents the servo motor's acceleration.

Establish a model and analysis it for the process when the nozzle is going through a righted-angled path (Figure 3). The direction of the scanning speed is assumed to parallel the $X$ and $Y$ axes (For the convenience of analysis, the same conclusion can be got in other angles).

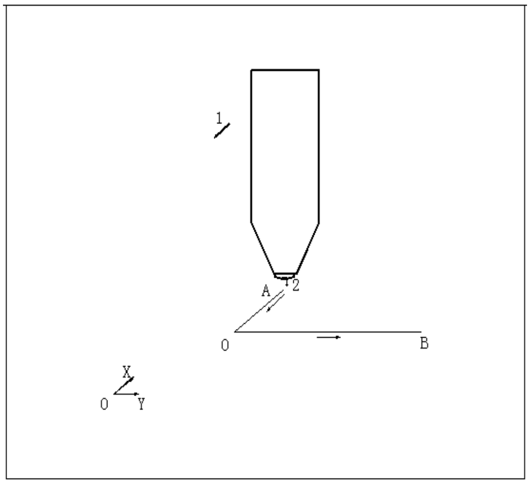


FIGURE 3 The scanning path 1. The scanning speed $v_2$. 2. The extruding speed $v_1$

As the scanning speed of the nozzle is composed of the motors' speed in the $X$ and $Y$ axes, The scanning speed in path AO means the speed of the motor in $X$ axis. The nozzle decelerates in path AO and the deceleration can be deduced by Equation (3).The scanning speed of the nozzle is $v_1$,The extruding speed is $v_2$,the distance of decelerating is $S$, the time of nozzle spending in the decelerating distance is $t_1$.

The time spent in path AO with decelerating speed:

$$t_1 = v_1 / a . \tag{4}$$

The time spent in path AO with uniform speed:

$$S = v_1 \times t_2 ,$$

$$S = v_1^2 / 2a ,$$

$$t_2 = v_1 / 2a . \tag{5}$$

The different time between them:

$$\Delta t = t_1 - t_2 = v_1 / 2a . \tag{6}$$

Analysing the process of extruding material and the condition of the material on the working platform, as shown in Figure 4.In the circumstances of uniform speed, the quantity *m* of the material comes out of the nozzle in unit time *t*:

$$m = v_2 \times t \,. \tag{7}$$

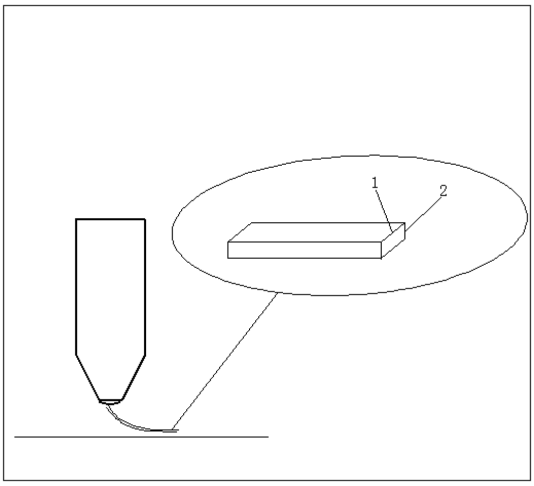


FIGURE 4 the amplification of line-width 1. Line width *d*. 2. Height of layer *h*

The quantity of the material extruded by nozzle on the working platform ($\rho$ is the density of the material) [5]:

$$m = v_1 \times d \times h \times t \times \rho \,. \tag{8}$$

The quantity of the material stays the same from the nozzle to the working platform because there is no loss, the following formula can be got combining Equations (7) and (8) [6]:

$$v_2 \times t = v_1 \times d \times h \times t \times \rho \,. \tag{9}$$

If the line width and line height are wanted to keep the same when scanning speed $v_1$ is decelerating, the $v_2$ should be decelerated along with the $v_1$, which can be known from Equation (6).

$$\Delta m = \rho \times v_2 \times \Delta t = (v_1 \times v_2 \times \rho) / 2a \,. \tag{10}$$

Therefore, there is 2 times of quantity extruded when the nozzle goes through a righted-angle path combining the path AO and path OB. Substituting Equations (2) and (3) into Equation (10), the quantity extruded more than the standard is $(\mathrm{n} \times v_2 \times \rho) / w$ .

There are two mainly filling ways in rapid prototyping technology presently which are straight filling and offsetting filling. The way of the straight filling (Figure 5a) working is moving back and forth in a straight direction and has nothing to do with the outline of the model to be done. The outline is added after each layer is done. But the offsetting filling (Figure 5b) is working in a way, which is close to the outline of each layer. The scanning path from inside to outside parallels the outline related to each layer of the model [7].

It fills perpendicularly to the working path between the two back and forth in order to keep the material continuous although the straight filling is not complex. The nozzle always meets the condition of big change in direction which causes the accumulation of the material no matter the simple straight filling or the complex offsetting filling. There are more than dozens and hundreds of layers in a model and each layer's error will be accumulated which may affect the accuracy of the model even destroy the structure.

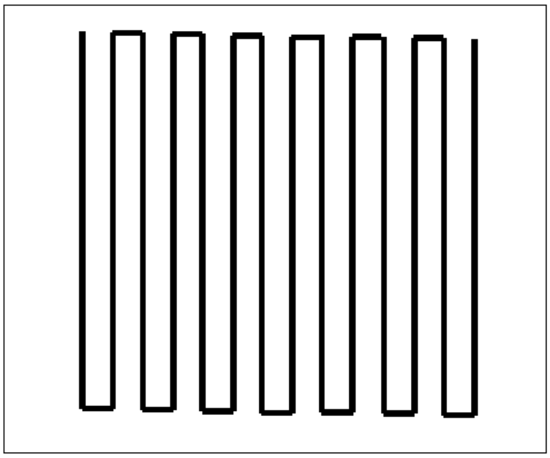

FIGURE 5a straight filling

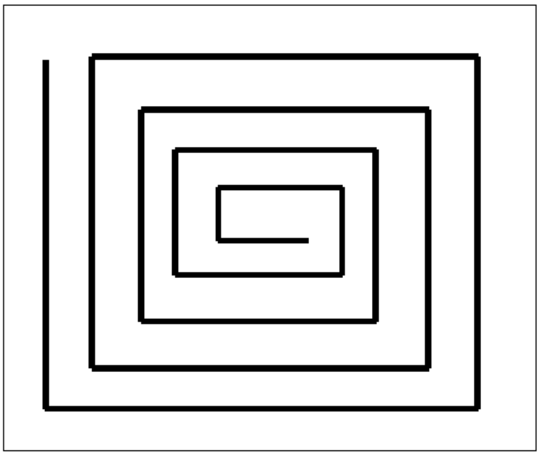

FIGURE 5b offsetting filling

## 3 The measures of improvement

The paper takes the nozzle of fused deposition molding machine the MEM-300 (Figure 6) of Tsinghua University as the experimental object and bring a method to improve the controlling. The screw extruder which simplifies the process and reduces the cost of the trial [8] is one of the main extruder in the field of FDM presently. The main factor affecting the extruding speed is the balance between the flowing resistance and driving force of the extruding motor in liquefaction pipe and nozzle where the liquid material goes through [9]. The extruding motor is the only problem to be considered to the extruding speed because the model is made by one material. The motor driver transmits the fixed frequency of pulse to the extruding motor in order to make the material out of the nozzle with an unchanged speed in the whole process once the machine starts working. According the above analysis, the reason to the error is that the extruding speed does not match the scanning speed when the nozzle is going to have a big change in direction.

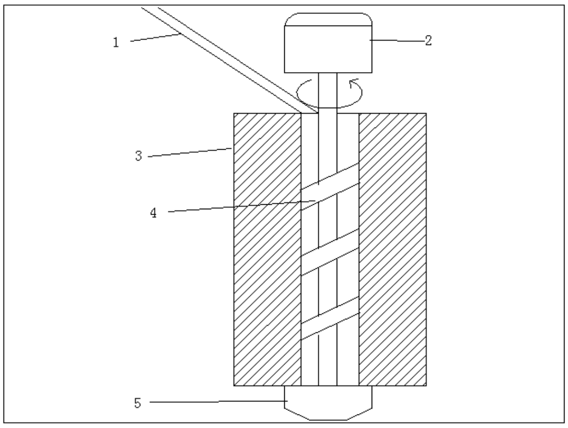


FIGURE 6 The structure of the nozzle 1. Feeding channel. 2. The extruding motor. 3. The heater. 4. Screw arbour. 5. The nozzle

If the extruding speed is reduced during the changing through controlling the extruding motor, the error will be decreased. The purpose of the study is to measure the line width in the different working frequency of the extruding motor. The reasonable speed could be chose when the nozzle is going to have a big change in direction. It may lay the foundation of the whole process's automation. The extruding motor is controlled by the PC software in normal condition and the extruding motor works with a set frequency once the software is started. The set speed is suitable which is based on a large number of experiments and the experiment is much significate based on the speed above.

After the oscilloscope detects the signal which is sent out by the PC to control the stepper motor driver, it could found the frequency of the signal is 1000Hz.

The external equipment of extruding motor is composed of step motor drive controller YJ01, stepper motor driver DM422C and the DC power to the driver.

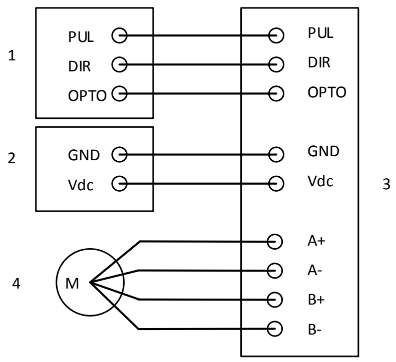


FIGURE 7 The connection of equipment 1. Stepper motor drive controller. 2. DC power. 3. Stepper motor driver. 4. Stepper motor

The Figure 7 is the connection of the equipment. The Figure 8 is the analysis of the righted-angle path. The line width D is the right line to be measured because the line width D is the critical place of the velocity's change and the maximum variation of the line width.

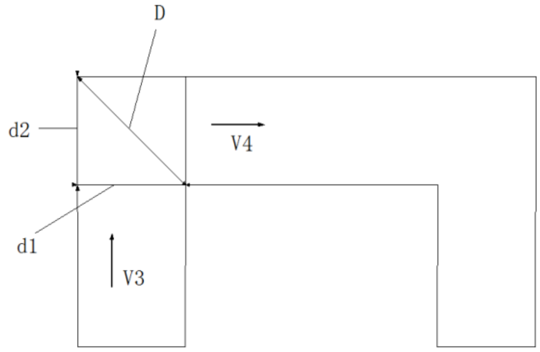


FIGURE 8 The amplification of the right-angled path

The scanning speed of the nozzle is changeless in the ideal condition, $v_3 = v_4$, according to the Equation (8):

$$v_3 \times d_1 \times h \times t \times \rho = v_4 \times d_2 \times h \times t \times \rho \,, \tag{11}$$

$$d_1 = d_2 = d \,. \tag{12}$$

So, $D = \sqrt{2}d$ .

TABLE 2 The line-width under different frequency of the motor (mm)

| Motor's frequency(Hz) | 500 | 550 | 600 | 650 | 700 |
|---|---|---|---|---|---|
| Line-width in right-angled *d* | 0.85 | 0.82 | 0.84 | 0.89 | 0.89 |
| | 0.86 | 0.81 | 0.85 | 0.83 | 0.93 |
| | 0.82 | 0.83 | 0.89 | 0.86 | 0.90 |
| | 0.81 | 0.87 | 0.86 | 0.90 | 0.95 |
| | 0.78 | 0.86 | 0.86 | 0.92 | 0.95 |
| | 0.78 | 0.88 | 0.91 | 0.91 | 0.94 |
| | 0.75 | 0.88 | 0.93 | 0.88 | 0.93 |
| | 0.87 | 0.83 | 0.84 | 0.89 | 0.91 |
| $\bar{d}$ | 0.815 | 0.8475 | 0.8725 | 0.885 | 0.925 |

Nozzle's temperature: 200°C the scanning speed: 10mm/s material: Polyurethane

According to the Table 1, the average of the straight line width d is 0.62mm and the bevel width D of righted-angle should be 0.87mm. The accuracy of the model is only controlled in the range of 0.1~0.2mm due to many factors' influence in the FDM process at present [10]. It is known from Table 1 the range of straight line width d is from 0.59mm to 0.65mm and the range of bevel width D should be from 0.83mm to 0.91mm.

TABLE 3 The percentage of the different frequency

| motor's frequency (Hz) | 500 | 550 | 600 | 650 | 700 |
|---|---|---|---|---|---|
| percentage | 37.5% | 75% | 87.5% | 87.5% | 50% |

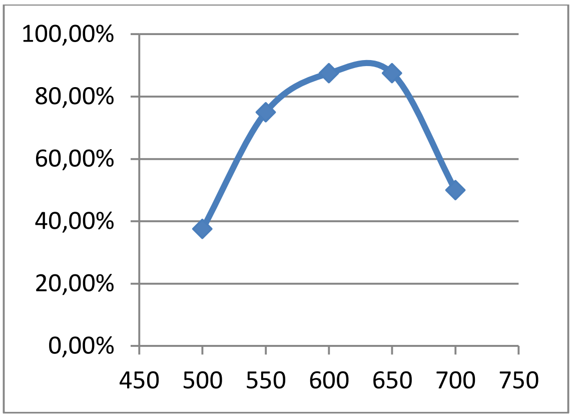


FIGURE 9 Scatter diagram of Table 2

Table 3 is percentage of Table 2 and Figure 9 is scatter diagram of Table 3.The data of line width is most in range of 0.83~0.91mm when the extruding motor's frequency is 550Hz,600Hz and 650Hz after analysing the above charts. The line width meets the requirement when the frequency of the extruding motor is between 550Hz and 650Hz during a righted-angle path according to Figure 9. In order to get rid of the limitation of the machine's structure, the frequency of the extruding motor should be changing along with the different path in the whole working process.

## 4 Conclusions

This paper has deeply analysed the accuracy of the FDM from the mechanical structure of the nozzle and brought a new method to improve the accuracy with the proof by experiment. The model's accuracy is still restricted by the structure of the working platform even the nozzle and other factors which affect the FDM's accuracy have been improved and it still may not meet the requirement. The accuracy of FDM will be much improved if the intelligent control system which makes the controlling of extruding motor automatic rapidly was taken.

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## References

[1] Tyberg J, Bøhn J H 1999 FDM systems and local adaptive slicing *Materials & Design* **20**(2-3) 77-82

[2] Huo X-Y, Tao M-Y, Ye C-S 2004 Analysis for Factors that Affect the Precision of the Shaped Pieces on Fused Deposion Modeling Process *Machinery & Electronics* (9) 77-8 *(in Chinese)*

[3] Jia Z-Y, Zou G-L, Guo D-M, Wang D-X 2002 Study on spinning line model and method for compensation in FDM *China Mechanical Engineering* **13**(23) 1997-2000

[4] Zhang Y, Zhou T-R, Xu C-H 2007 Factors and Countermeasures Influencing the Precision in FDM *Journal of Nanchang University* **29**(3) 252-5 *(in Chinese)*

[5] Wang Y-Q, Fang Y, Le G et al. 2009 Finite Element Aided Design of Nozzle Head in FDM *Aviation Precision Manufacturing Technology* **45**(3) 32-6 *(in Chinese)*

[6] Li Y-Q, Shi T-C 2010 Accuracy Control Studyof Rapid Prototyping Machine by FDM *Machine Tool & Hydraulics* **38**(23) 65-9 *(in Chinese)*

[7] Chen J 2009 Analysis of scanning ways in FDM *Huazhong University of Electronic Science and Technology Thesis (in Chinese)*

[8] Guo Y-B, Fan Z, Dong XZ 2007 Discussion of screw extruding and plasticizing fuses deposition advanced rapid molding technology *Modern Manufacturing Engineering* **12** 76-8 *(in Chinese)*

[9] Gu YH, Xiao Q 2003 Analysis on the Extrusion Rate Control of Molten Polymer in Fused Deposition Modeling *New Technology& New Process* (6) 25-6 *(in Chinese)*

[10] Xiao Q, Gu Y-H, Jiang K-Y 2004 Optimal Control of Nozzle Extrusion Parameters for Fused Deposition Modeling Processes *China Mechanical Engineering* **15**(1) 17-9 *(in Chinese)*

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