Real-time regulation of filling speed based on multiparameter synergistic coupling effect in fused deposition modeling

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Abstract. This paper aimed to perform a preliminary study on real-time regulation of filling speed by considering multiparameter synergistic coupling effect in fused deposition modeling. Bivariate experiments and sampling printing tests on designed samples, under different parameter combinations which are made up by filling speed, layer thickness, nozzle temperature and corner angle, were carried out to build and validate a real-time regulation model of filling speed by employing error analysis and multivariate nonlinear regression method. Results showed that the equivalent dimensional deviation values and area deviation values of Sample A, Sample B, Sample C by using real-time regulation algorithm of filling speed are lower than or close to the concentrated averages by using the optimal constant filling speed, with the maximum of 0.32 mm and 0.46 mm². Actual and theoretical build time of Sample D at real-time regulated filling speed are less than those at 20 mm/s (“low speed”), and close to those at 45 mm/s (“medium speed”) or 70 mm/s (“high speed”), which indicates that the method of real-time dynamic adjusting filling speed can not only improve printing accuracy, but also give a full consideration to printing efficiency at the same time.

1. Introduction

Fused deposition modeling (FDM), also known as fused layer modeling (FLM) or fused filament fabrication (FFF) [1], a kind of additive manufacture (AM) or called 3D printing technology, is now widely applied in the industrial, medical, and educational field [2-6]. However, due to the weakness of surface roughness, easy-warpage, material limitation, and staircase effect, printing accuracy and efficiency of FDM are not good at all [7-14], meanwhile it is not easy to balance accuracy and efficiency at the same time. Moreover, it is also difficult to build large-scale and complex FDM parts due to their low mechanical strength caused by interlamellar distortion [15]. The above disadvantages result in low value-added of FDM products and hinder the development and industrialization of FDM.

In terms of the above issues, many scholars focused on FDM parametric optimization research to improve manufacturing precision or mechanical properties of parts [16-26]. In our previous work, it was found that filling speed, layer thickness, nozzle temperature and filling ratio have significant influence on dimensional accuracy of FDM parts and their printing efficiency [27]. In addition, each layer’s scanning trajectory shapes of contours and alteration also play an important role in constraining FDM’s printing accuracy and build time. Hence, real-time dynamic adjusting and controlling filling speed and extrusion velocity during FDM process is very important, which can help us balance printing accuracy and efficiency simultaneously [28].

Based on HBOT motion system, Qin et al [29] proposed a real-time adaptive look-ahead speed control algorithm to enhance printing accuracy and efficiency of high-speed machining, to avoid speed
fluctuation caused by acceleration/deceleration (ACC/DEC), and to increase smoothness of feed rate in continuous corners or curves machining. Experiment and validation results showed that the proposed speed control algorithm can improve fabrication precision as well as build time of FDM. Ertay et al [30] presented a synchronous speed control scheme of tangential path velocity and material deposition rate to improve the material accumulation problem at corners and high curvature positions of FDM parts. The system optimized the feed while respecting the heater’s limit and the jerk, acceleration and velocity limits of the machine tool’s drives along printing path with curvatures. Through using this scheme to control the nozzle’s movement, dimensional accuracy of FDM parts were also improved effectively. Geng et al [31] studied the effect of filling velocity and extrusion velocity on the microstructure and dimensional accuracy of polyetheretherketone (PEEK) filament and found that: it is very important to coordinate and synchronize filling velocity and extrusion velocity since it determines the size of the extruded filament and directly affects manufacturing precision. Their experiment results also showed that the proposed optimal control algorithm between extrusion velocity and diameter of extruded filament can improved printing stability of FDM and dimensional accuracy of parts. Nevertheless, synergistic coupling effect of parameters occurred in FDM process [32-34], which may affect the real-time dynamic adjustment and control of filling speed, is needed to be considered.

In this research, a preliminary study on real-time regulation of filling speed by considering multiparameter synergistic coupling effect in FDM was performed. Equivalent dimensional deviation, area deviation at corner contours, and build time were selected as FDM evaluation indexes. Four sample types were designed for experiments under different parameter combinations which are made up by filling speed, layer thickness, nozzle temperature and corner angle. The optimal values of filling speed which can realize the lowest values of equivalent dimensional deviation or area deviation under different combinations of layer thickness, nozzle temperature, and corner angle, were recorded for the following modeling. Multivariate nonlinear regression operation was run to build a real-time regulation model of filling speed based on multi-parameter synergistic coupling effect. Error analysis and sampling printing tests were also carried out to validate the performance of real-time regulation of filling speed.

2. Methodology

2.1. Material and equipment
Polyactic acid (PLA) filaments were chosen to build all experimental samples, with diameter of φ1.75 ± 0.02 mm and density of 1.25 ± 0.05 g /cm³. Material’s melting temperature ranges from 190 °C to 220 °C.

A desktop FDM printer (Type A001, made in China) with φ0.4 mm nozzle diameter was employed. A zinc alloy electronic digital caliper (Model LF170) with 0.01 mm resolution, and a professional grade all-metal digital microscope (BRESSER MDA2000, made in Germany) with highest 200,000 pixels resolution and maximum 200x magnification were used for dimensions and area measurements.

2.2 Sample design
Four types of samples with a different cross-section were designed, as shown in figure 1. Their thickness is the same of 6mm. Figure 1a is a kind of cuboid named Sample A, with 60 mm length and 15 mm width. Figure 2b is a cube named Sample B, with 30 mm length of side. Figure 1c is a right-angled trapezoid named Sample C, with 60 mm length and 15 mm width, as well as a variable angle $\alpha$ ($0^\circ < \alpha < 90^\circ$). Figure 1d is an irregular solid included six cantilevers, named Sample D, with 70 mm total length and 110 mm total width. Each cantilever of Sample D has a corner contour end with a constant corner angle value of $15^\circ/30^\circ/45^\circ/60^\circ/75^\circ$.

2.3 Experimental design matrix
Filling speed $v$, layer thickness $t$, nozzle temperature $T$, and corner angle $\alpha$ were selected as main parameter variables, as shown in table 1. Other process parameters were treated as quantitative values, as shown in table 2. Bivariate experiments between filling speed $v$ and the other three parameters of $t$,
$T$, $\alpha$ were carried out, respectively.

![Diagram](image)

Figure 1. Sample design of experiments. (a) Sample A, (b) Sample B, (c) Sample C, (d) Sample D.

Table 1. Four main parameter variables and their values.

| Variable                  | Value                      |
|---------------------------|----------------------------|
| Filling speed $v$ (mm/s)  | 20, 30, 40, 50, 60, 70     |
| Layer thickness $t$ (mm)  | 0.1, 0.15, 0.2, 0.25, 0.3  |
| Nozzle temperature $T$ (°C) | 184, 192, 200, 208, 216    |
| Corner angle $\alpha$     | 15°, 30°, 45°, 60°, 75°, 90°|

Table 2. Value setting of other process parameters.

| Parameter                  | Value         | Parameter                  | Value         |
|----------------------------|---------------|----------------------------|---------------|
| Shell thickness (mm)       | 0.4           | Retraction speed (mm/s)    | 40            |
| Retraction distance (mm)   | 4.5           | Travel speed (mm/s)        | 90            |
| Hot bed temperature (°C)   | 65            | Fill density               | 15%           |

The absolute value of equivalent dimensional deviation $e$ was selected as one of printing accuracy evaluation indexes, which can be calculated by equation (1) and equation (2). When $e$ increases, printing accuracy decreases.

\[
\begin{align*}
X_e &= \bar{X}_i - X \\
Y_e &= \bar{Y}_i - Y \\
Z_e &= \bar{Z}_i - Z \\
\end{align*}
\]

\[
e = |X_e| + |Y_e| + |Z_e|
\]

(1)

Where $X_e$, $Y_e$, $Z_e$ are the dimensional deviation values of three coordinate directions; $\bar{X}_i$, $\bar{Y}_i$, $\bar{Z}_i$ are the corresponding averages calculated by measured data; $X$, $Y$, $Z$ are the corresponding theoretical values.

The value of area deviation $s$ at the corner contour was selected as another one of printing accuracy evaluation indexes, which can be calculated by equation (3). When $s$ increases, printing accuracy decreases.

\[
s = |X_s| + |Y_s| + |Z_s|
\]
\[ s = S_1 + S_2 \]  

Where \( S_1 \) is the area deviation around the corner due to material repeated deposition; \( S_2 \) is the missed deposition area. As shown in figure 2, \( S_1 \) and \( S_2 \) were obtained by the following method: (1) First, cross-sectional projections of actual corner zones were shot by the digital microscope, referenced by a scale line overhead. (2) Second, images of projections were imported in a computer. Edges of actual corner profiles were calibrated through CAD software. (3) Finally, \( S_1 \) and \( S_2 \) were calculated by running the area calculation module of CAD software.

![Figure 2. Measurement example of \( S_1 \) and \( S_2 \) at a convex corner with \( \alpha = 15^\circ \).](image)

Build time was selected as printing efficiency evaluation index, including actual build time and theoretical build time. Actual build time is recorded manually through a timer. Theoretical build time is automatically calculated by slicing software. Theoretical build time is not completely equal to actual build time due to hardware restriction on acceleration and deceleration function of the printer.

According to Sample A and Sample B, 60 groups’ printing tests of \( v - t \) (\( T = 200^\circ C, \alpha = 90^\circ \)) and 60 groups’ printing tests of \( v - T \) (\( t = 0.20 \text{ mm}, \alpha = 90^\circ \)) were carried out, and the corresponding optimal values of filling speed \( v_{opt} \) which can realize the lowest value of \( e \) under different \( v - t \) or \( v - T \) combination were recorded. As to Sample C, 30 groups’ printing tests of \( v - \alpha \) (\( T = 200^\circ C, t = 0.20 \text{ mm} \)) were carried out, and the corresponding optimal values of filling speed \( v_{opt} \) which can obtain the lowest value of \( s \) under different \( v - \alpha \) combination were also recorded. In addition, 16 \( v_{opt} \) values according to Sample A and Sample B under extra \( t, T \) combinations defined by parameter uniform distribution rules were also added by the same experimental procedure, as to increase the multivariate nonlinear regression sample size.

Each group of above experiments were repeated for three times to achieve averages of \( e \) or \( s \).

3. Results and discussion

3.1 \( v_{opt} \) of Sample A, B, C
All optimal values of filling speed \( v_{opt} \) of Sample A, B, C under different parameter combinations were filled in table 3 to table 6.

3.2 Modeling of real-time regulation of filling speed
According to the above results, two analytical fitting models of \( V_A, V_B \) for Sample A(C), Sample B to real-time dynamic adjusting filling speed, were deduced by employing the multivariate nonlinear regression method, as shown in equation (4) and equation (5). Layer thickness, nozzle temperature, and corner angle in the functions are regarded as impact factors. Roughly, by given 0.5 weight for each equation, a generalized analytical fitting model \( V \) of real-time regulation of filling speed can be combined as equation (6) illustrates.

\[ V_A = 2225 + 405t - 23.13T + 1.821\alpha - 1072t^2 + 0.059T^2 - 0.0152\alpha^2 \]  

\[ V_B = \text{equation for Sample B} \]  

\[ V = \text{combined equation for real-time regulation} \]
\[ V_B = -1859 + 293t + 18.40T + 1.41\alpha - 591t^2 - 0.046T^2 - 0.0101\alpha^2 \] (5)

\[ V = 183 + 349t - 2.37T + 1.616\alpha - 831t^2 + 0.0066T^2 - 0.0127\alpha^2 \] (6)

\[ 0^\circ < \alpha \leq 90^\circ \]

Table 3. \( v_{opt} \) of Sample A and Sample B @ \( T = 200 \, ^\circ C, \alpha = 90^\circ \).

| Parameter | Value |
|-----------|-------|
| \( t \) (mm) | 0.10 0.15 0.20 0.25 0.30 |
| \( v_{opt} \) (mm/s) | Sample A | 20 20 70 70 20 |
| | Sample B | 20 70 70 70 70 |

Table 4. \( v_{opt} \) of Sample A and Sample B @ \( t = 0.20 \, mm, \alpha = 90^\circ \).

| Parameter | Value |
|-----------|-------|
| \( T \) (\(^\circ C\)) | 184 192 200 208 216 |
| \( v_{opt} \) (mm/s) | Sample A | 40 20 60 50 60 |
| | Sample B | 30 30 50 60 60 |

Table 5. \( v_{opt} \) of Sample C @ \( T = 200 \, ^\circ C, t = 0.20 \, mm \).

| Parameter | Value |
|-----------|-------|
| \( \alpha \) | 15° 30° 45° 60° 75° |
| \( v_{opt} \) (mm/s) | 30 50 60 50 70 |

Table 6. Extra \( v_{opt} \) values of Sample A and Sample B @ \( \alpha = 90^\circ \).

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{\( v_{opt} \) of Sample A/B (mm/s)} & \text{\( t \) (mm)} & \text{0.10} & \text{0.15} & \text{0.25} & \text{0.30} \\
\hline
\text{184} & 60/30 & - & - & 30/70 \\
\text{192} & - & 70/55 & 70/70 & - \\
\text{208} & - & 65/70 & 40/20 & - \\
\text{216} & 70/50 & - & - & 70/20 \\
\hline
\end{array}
\]

3.3 Error analysis

Distribution frequency of the lowest values of \( e \) and \( s \) corresponding to different parameter combinations of Table 3 to Table 6 were counted, as shown in figure 3. The lowest values of \( e \) statistical calculated from Sample A are mainly concentrated in the range of \([0.26 \sim 0.35]\) mm, with an average of 0.30 mm and an amount of 47 groups. As for Sample B, the corresponding results are \([0.11 \sim 0.30]\) mm, 0.22 mm and 53 groups. The lowest values of \( s \) statistical calculated from Sample C are mainly concentrated in the range of \([0.26 \sim 0.50]\) mm², with an average of 0.44 mm² and an amount of 19 groups. The above concentration ranges and averages of \( e \) and \( s \) indicate that dimensional accuracy or surface roughness of FDM parts can be improved to some extent by using optimal parameter combinations.
3.4 Validation

15 groups of parameter combinations of layer thickness, nozzle temperature, corner angle, and corresponding real-time regulated filling speed, were chosen for sampling printing tests, as shown in table 7. Group 1-5 were applied on Sample A. Group 6-10 were applied on Sample C. Values of real-time regulated filling speed for sampling printing tests on Sample A and Sample B were calculated by equation (4). Group 11-15 were applied on Sample B, and their values of real-time regulation of filling speed were calculated by equation (5). All groups’ e and s were also filled in table 7.

By comparing the results of table 7 and figure 3, we found that each group’s e and s are lower than or close to the lowest averages. The maximum value of e is 0.32 mm at “t = 0.15 mm, T = 184 °C, V_A = 51 mm/s” when printing Sample A, which is mainly caused by lower melting temperature and larger aspect ratio of cuboid samples [27]. The maximum value of s is 0.46 mm² at “t = 0.15 mm, T = 200 °C, V_A = 28 mm/s, α = 15°” when printing Sample C, which is mainly caused by lower corner angle with larger area of repeated and missed deposition zones. All in all, printing results indicate that the proposed algorithm of real-time regulation of filling speed based on parameter synergistic coupling effect can effectively improve printing accuracy of FDM.

Figure 3. Distribution frequency histogram of the lowest values of e or s. (a) Sample A, (b) Sample B, (c) Sample C.
12 groups of parameter combinations were designed for Sample D and their printing tests were carried out to further validate the performance of the real-time regulation algorithm of filling speed. Three constant filling speed of 20 mm/s (“low speed”), 45 mm/s (“medium speed”), 70 mm/s (“high speed”), and corresponding real-time regulated filling speed $V_{cal}$ calculated by equation (6) were selected to build Sample D at “$t = 0.20\text{mm}, T = 200\text{ ℃} / t = 0.15\text{mm}, T = 184\text{ ℃} / t = 0.25\text{mm}, T = 216\text{ ℃}”.

Calculated values of real-time regulation of filling speed under different parameter combinations were listed in Table 8. Since it was difficult to build each cantilever of Sample D at its correspondent $V$ in the same process due to device’s control system and hardware limitation, average build time of those printing tests by employing real-time regulation of filling speed were adopted to evaluate printing efficiency.

| No. | $t$ (mm) | $T$ (℃) | $\alpha$ | $V_{cal}$/(mm/s) | $e$ (mm) | $s$ (mm²) |
|-----|--------|--------|--------|-----------------|-------|-----------|
| 1   | 0.1    | 208    | 90°    | 46              | 0.31  | -         |
| 2   | 0.15   | 184    | 90°    | 51              | 0.32  | -         |
| 3   | 0.2    | 200    | 90°    | 46              | 0.23  | -         |
| 4   | 0.25   | 216    | 90°    | 66              | 0.26  | -         |
| 5   | 0.3    | 192    | 90°    | 33              | 0.17  | -         |
| 6   | 0.15   | 200    | 15°    | 28              | -     | 0.46      |
| 7   | 0.3    | 200    | 30°    | 33              | -     | 0.45      |
| 8   | 0.2    | 200    | 45°    | 57              | -     | 0.30      |
| 9   | 0.1    | 200    | 60°    | 52              | -     | 0.18      |
| 10  | 0.25   | 200    | 75°    | 53              | -     | 0.21      |
| 11  | 0.1    | 208    | 90°    | 46              | 0.19  | -         |
| 12  | 0.15   | 184    | 90°    | 44              | 0.20  | -         |
| 13  | 0.2    | 200    | 90°    | 60              | 0.09  | -         |
| 14  | 0.25   | 216    | 90°    | 50              | 0.17  | -         |
| 15  | 0.3    | 192    | 90°    | 57              | 0.12  | -         |

Values of area deviation and build time under different parameter combinations were plotted in figure 4 and figure 5 for comparison. Figure 4 shows that the area deviation of employing real-time regulated filling speed is less than that of 45 mm/s (“medium speed”), 70 mm/s (“high speed”) and close to that of 20 mm/s (“low speed”) at the same $\alpha$ in general, which again proves that the method of real-time regulation of filling speed can improve printing accuracy of FDM and can achieve the “low speed” printing effect. Figure 5 shows the comparison of printing efficiency between real-time regulated and
Figure 4. Printing accuracy comparison between real-time regulated filling speed and constant filling speed. (a) @ \( t = 0.20 \) mm, \( T = 200^\circ \text{C} \), (b) @ \( t = 0.15 \) mm, \( T = 184^\circ \text{C} \), (c) @ \( t = 0.25 \) mm, \( T = 216^\circ \text{C} \).
constant filling speed through actual and theoretical build time. Results shows that the theoretical and actual build time by using real-time regulated filling speed are less than those of 20 mm/s (“low speed”), and close to those of 45 mm/s (“medium speed”) or 70 mm/s (“high speed”). All the above results indicate that the method of real-time regulation of filling speed can give a full consideration to printing accuracy and efficiency of FDM at the same time.

4. Conclusion
(1) Interactive coupling between filling speed and other parameters can influence on printing accuracy and efficiency of FDM. Results of bivariate experiments between filling speed and layer thickness/nozzle temperature/corner angle show that optimal filling speed of different parameter combinations can be realized and employed to improve dimensional precision and surface quality to some extent. As an example, the concentrated averages of equivalent dimensional deviation of Sample A and Sample B respectively are 0.30 mm and 0.22 mm, and the concentrated average of area deviation of Sample C is 0.44 mm².

(2) The proposed real-time regulation algorithm of filling speed based on parameter synergistic coupling effect can effectively improve printing accuracy and efficiency of FDM. Results of sampling printing tests for Sample A, Sample B, and Sample C show that values of equivalent dimensional deviation and area deviation are lower than or close to the concentrated averages, with the maximum of 0.32 mm and 0.46 mm². Area deviation comparison and build time comparison of sampling printing tests for Sample D at real-time regulated filling speed and three constant filling velocity (“low speed”, “medium speed”, “high speed”) also prove that the method of real-time dynamic adjusting filling speed can not only improve fabrication accuracy of FDM, but also give a full consideration to printing efficiency at the same time.

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