Study on Size Error Compensation of Connecting Bracket Based on Fused Deposition Modeling

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Abstract: In the integrated additive manufacturing of electronic products, the connecting bracket is a typical fixed structure for embedding electronic components such as PCBs, sensors, batteries, etc. The dimensional accuracy of column spacing affects the stability of embedded components directly. In this paper, aiming at the printing error of connecting bracket column spacing during the Fused Deposition Modeling (FDM), the printing error compensation is studied via the single factor experiments. The impact of design size on printing error is analyzed, and the printing error compensation model is established. Based on the FDM printing process of the connecting bracket, the main influencing factors of the printing error are analyzed. The results show that the column spacing printing error is the result of the combination of the dimension error of column printing, the dimension error of base printing and the motion error of the machine. Finally, based on the error compensation model, the compensated connection bracket is printed and the PCBs embedding verification is performed. The PCB can be embedded steadily, which indicates that the established model has higher precision.

1. Introduction

With the development of 3D printing, the additive manufacturing of structure parts have gradually evolved into integrated additive manufacturing of electronic products. During the printing, the structures are manufactured by FDM, the Printed Circuit Boards (PCBs), sensors, and other electronic components are embedded in the connecting brackets fabricated by FDM. The connection electric circuits are printed subsequently, which ultimately facilitates the integrated manufacturing of “structure-circuit-electronic component” for electronic products [1]. The process is shown in figure 1. This technology subverts the traditional manufacturing method of electronic products, and it also provides more space for designing and manufacturing, as well as simplifying the manufacturing process. It is expected to provide a brand new idea and solution for the development of innovative products, and to become one of the research hotspots in 3D printing [2-4].
The effective and stable embedding of PCBs, sensors and other electronic components is the key to realize the integrated additive manufacturing of electronic products. Currently, the electronic components are embedded into the reserved cavities of FDM printing connecting brackets by setting the pause program [5-7]. However, in the embedding process, due to the printing error of the dimension between two columns of the connecting brackets, it is easy to cause the unstable embedding of components and other problems. Therefore, it is necessary to carry out an error compensation study on the size of FDM printed connecting brackets.

Numerous studies have been conducted to solve the size error compensation for FDM parts. Tong et al put forward an error compensation method for slicing software, which can reduce the average volume error of printed parts by about 30% [8]. Yaman et al proposed a method of the internal structure of parts, which can control the shrinkage of circular and square holes and make error compensation for the size of characteristic holes [9]. Zou et al set up a compensation model of ideal contour line from the FDM's microscopic size, and verified that this method could compensate the outer contour size of the model correctly [10]. Dong et al analyzed the printing error caused by heating and contract on cooling of materials with the example of 3D printed threaded connector, and proposed that the printing error can be reduced by reducing the material shrinkage rate and establishing a compensation model [11]. However, the existing studies are mostly based on the analysis of size error caused by a single factor. On the one hand, the comprehensive influence of multiple factors such as model size interaction and nozzle movement form are not taken into account, and the dimensional accuracy after compensation still needs to be improved. On the other hand, there is still less research on the printing error compensation of the connecting brackets for components embedding. Therefore, for the FDM printing of connecting brackets, it is still necessary to study dimensional error compensation in-depth, and to reveal the law that how multiple factors affect the dimensional accuracy, which will provide technical support for the effective and stable embedding of electronic components.

In this paper, the single-factor experimental design is utilized to carry out the FDM printing connecting brackets experiment. The correlation between the design size and the printing size error are analyzed and to build an error compensation model. Then, the causes of size error are deeply studied to reveal the influence mechanism of multiple factors on size error. Finally, a verification experiment is carried out to verify the validity of the error compensation model.

2. Experimental design
The FDM printer used in this experiment is Mass Portal Pharaoh ED 20, as shown in figure 2. The forming space size of device is $\Phi$ 200mm×200mm (bottom diameter ×height). This printer using Delta architecture technology, can achieve fast printing with less vibration and noise. The printing material is PolyPlus PLA supplied by Polymaker. In order to ensure the consistency of different experimental process, printing parameters are set to machine default parameters. The parameters as follows: Nozzle diameter is 0.4 mm, Contour width is 0.4 mm, Scanning times is 1, Layer thickness is 0.2 mm, Printing speed is 2400 mm/min, Filling rate is 5%, Nozzle temperature is 210℃.
According to the basic structure of the connecting brackets in figure 1, the experimental parts are designed, shown as figure 3. The height of the base $h$ is 2mm, and the spacing of the columns in Y direction $m$ is 5mm. The dimension $L$ is the column spacing, which is the measured size of this experiment. $L_2$ is the base length, $L_1$ is the column length, and the column design size is $5\text{mm} \times 5\text{mm} \times 10\text{mm}$ (length $\times$ width $\times$ height). The spacing size $L$ of the experimental variables is shown in table 1, a total of 26 levels are set. Each group printed four samples, that is, print size data of 8 column spacing are obtained for each groups.

![Figure 3. 3D model of the experiment piece.](image)

### 3. The experimental results

The FDM printed connecting brackets experiment is carried out. By using the vernier caliper with a precision of 0.02 mm to measure the column spacing dimension $L$, and to record the data and calculate the average print size. The printing average size subtracted from the column spacing design size is the printing size error $\Delta$. The specific data is shown in table 1.

| Design size (mm) | Printing size (mm) | Printing average size (mm) | Printing size error (mm) |
|------------------|--------------------|---------------------------|-------------------------|
| 3                | 2.80 2.80 2.86 2.86 2.78 2.78 2.84 2.84 | 2.82 | 0.18 |
| 5                | 4.84 4.90 4.84 4.68 4.88 4.80 4.80 4.86 | 4.83 | 0.18 |
| 9                | 8.80 8.80 8.82 8.86 8.78 8.82 8.86 8.84 | 8.82 | 0.18 |
| 14               | 13.84 13.80 13.82 13.86 13.84 13.80 13.82 13.82 | 13.82 | 0.18 |
| 18               | 17.78 17.82 17.80 17.80 17.82 17.84 17.84 17.80 | 17.82 | 0.18 |
| 22               | 21.86 21.82 21.94 21.80 21.82 21.82 21.86 21.82 | 21.84 | 0.16 |
| 24               | 23.92 23.86 23.86 23.94 23.86 23.88 23.88 23.88 | 23.88 | 0.12 |
| 28               | 27.88 27.88 27.86 27.86 27.92 27.84 27.86 27.88 | 27.87 | 0.13 |
In this section, the size error of the column itself, the size error of the base and other factors could be studied. The printing size error of the column spacing will be clarified.

It can be found that the spacing \( L \) of the column is actually indirectly formed by printing the base \( L_2 \) and two columns \( L_1 \), and its measured size \( L = L_2 - 2L_1 \). It can be seen that the printing size error of column spacing \( L \) is affected by the printing size error of base size \( L_2 \) and column itself \( L_1 \). In this section, the size error of the column itself, the size error of the base and other causes of the error will be studied further, and the comprehensive influence of each factor in the final printing size error of the column spacing will be clarified.

The scatter diagram of printing size error for column spacing size as shown in figure 4, where the abscissa is the design size of column spacing, and the ordinate is the printing size error. Linear regression analysis was carried out on the printing size error data, which get design error compensation model of printing size error \( \Delta \) and size \( L \):

\[
\Delta = -0.0016L + 0.1867, \quad R^2 = 0.894
\]  \hspace{1cm} (1)

Where, \( R^2 \) is the coefficient of determination, which is used to measure the goodness of fit of the regression equation. The closer the value is to 1, the higher the degree of interpretation of the dependent variable by the independent variable in the regression equation, and here is the degree of fitness is good.

**Figure 4.** The relation between printing size error and design size.

### 4. Error analysis

As can be seen from figure 4, when the design size is within 100mm, the printing average size of the column spacing formed by FDM is all smaller than the design size, and the printing size error gradually decreases with the increase of the design size. According to the structure of the experimental parts as shown in figure 2, it can be found that the spacing \( L \) of the column is actually indirectly formed by printing the base \( L_2 \) and two columns \( L_1 \), and its measured size \( L = L_2 - 2L_1 \). It can be seen that the printing size error of column spacing \( L \) is affected by the printing size error of base size \( L_2 \) and column itself \( L_1 \). In this section, the size error of the column itself, the size error of the base and other causes of the error will be studied further, and the comprehensive influence of each factor in the final printing size error of the column spacing will be clarified.
4.1 Error analysis of column size $L_1$

Select one of the experimental parts of each size, and measure the printing size of the four columns by the vernier caliper. The average value was calculated. The specific data is shown in table 2.

Table 2. Parts design size, column printing size and printing size error.

| Design size (mm) | Printing size (mm) | Printing average size (mm) | Printing size error (mm) |
|------------------|--------------------|----------------------------|-------------------------|
| 3                | 5.10 5.08 5.14 5.10 | 5.10                       | -0.10                   |
| 5                | 5.06 5.12 5.12 5.06 | 5.09                       | -0.09                   |
| 9                | 5.10 5.12 5.10 5.14 | 5.12                       | -0.12                   |
| 14               | 5.16 5.14 5.12 5.2  | 5.15                       | -0.15                   |
| 18               | 5.16 5.12 5.12 5.14 | 5.13                       | -0.13                   |
| 22               | 5.18 5.14 5.12 5.16 | 5.15                       | -0.15                   |
| 24               | 5.08 5.14 5.14 5.18 | 5.14                       | -0.14                   |
| 28               | 5.22 5.18 5.16 5.16 | 5.18                       | -0.18                   |
| 32               | 5.16 5.20 5.14 5.22 | 5.18                       | -0.18                   |
| 36               | 5.08 5.16 5.18 5.12 | 5.14                       | -0.14                   |
| 40               | 5.12 5.16 5.20 5.20 | 5.17                       | -0.17                   |
| 44               | 5.16 5.22 5.16 5.20 | 5.18                       | -0.18                   |
| 48               | 5.16 5.16 5.12 5.18 | 5.15                       | -0.15                   |
| 52               | 5.16 5.22 5.20 5.26 | 5.21                       | -0.21                   |
| 56               | 5.16 5.18 5.16 5.20 | 5.17                       | -0.17                   |
| 60               | 5.16 5.20 5.18 5.16 | 5.17                       | -0.17                   |
| 65               | 5.24 5.22 5.20 5.18 | 5.21                       | -0.21                   |
| 69               | 5.22 5.20 5.20 5.26 | 5.22                       | -0.22                   |
| 73               | 5.20 5.18 5.22 5.2  | 5.20                       | -0.20                   |
| 77               | 5.18 5.24 5.22 5.14 | 5.20                       | -0.20                   |
| 81               | 5.26 5.18 5.24 5.20 | 5.22                       | -0.22                   |
| 85               | 5.16 5.16 5.18 5.14 | 5.16                       | -0.16                   |
| 89               | 5.16 5.18 5.22 5.14 | 5.18                       | -0.18                   |
| 93               | 5.20 5.18 5.28 5.24 | 5.22                       | -0.22                   |
| 97               | 5.20 5.22 5.24 5.18 | 5.21                       | -0.21                   |
| 100              | 5.18 5.20 5.20 5.24 | 5.21                       | -0.21                   |

The column design size minus the printing average size gets the printing error $\Delta L_1$, the column size print error scatter diagram as shown in figure 5, where the abscissa is design dimension of the parts spacing, and the ordinate is the printing error of $L_1$.

![Figure 5. Printing size error of 5mm × 5mm (length × width) column.](image-url)
The data is fitted to the printing error data to obtain an error compensation model of the printing error $\Delta L_1$ and the design size $L$:

$$
\Delta L_1 = -9e^{-10}L^4 + 3e^{-7}L^3 + 5e^{-5}L^2 - 0.0036L - 0.0089, \quad R^2 = 0.733
$$  \tag{2}

As shown in figure 5, the print size of the column is larger than the design size, and the deviation is between $+0.09$mm$\sim+0.23$mm. As the column spacing increasing, the printing error of $L_1$ increases gradually. The mean error is 0.17mm. This data shows that the printing size error of column size $L_1$ will lead to an average decrease of 0.17mm in the column spacing size $L$ of the experimental parts compared with the designed size. Comparing the error compensation model shown in (1), when $L=0$, $\Delta=0.1867$, which is the print size error when the column spacing $L$ is designed to be 0. It can be seen that when $L=0$, the error of the column size $L_1$ accounts for 91.05% of the error of the column spacing dimension $L$, which is the main reason that the design spacing of the column is larger than the printing size. But at the same time, it can be seen that due to the size of the column tends to be gentle as the column spacing increases, and the trend of printing error do not match the linear decrease of the design size. Therefore, the base size $L_2$ needs to be analyzed.

### 4.2 Error analysis of base size $L_2$

According to the formula $L=L_2-2L_1$, the size of the base $L_2$ is another factor affecting the dimensional accuracy of column spacing. It can be seen from figure 3 that theoretical base size $L_2=L+2L_1$. According to the analysis in section 4.1, there is a printing error in column size $L_1$. In order to avoid the influence of $L_1$ when measuring the base size $L_2$, according to the structure of the base, the design of the printing test part is shown in figure 6. The size of experimental parts in the Y and Z directions are fixed, which are 5 mm and 10 mm respectively. The dimensions in X direction are set to 5 groups of different levels, which are 5mm, 20mm, 40mm, 60mm and 80mm. After printing, the vernier caliper was used to measure the printing size of the experimental parts in the X direction, and the results are shown in table 3.

![Figure 6. Printing test part of base size.](image)

| Design size (mm) | Printing size (mm) | Printing average size (mm) | Printing size error (mm) |
|------------------|--------------------|----------------------------|-------------------------|
| 5.00             | 5.00               | 5.02                       | 0.02                    |
| 20.00            | 20.16              | 20.12                      | -0.12                   |
| 40.00            | 40.18              | 40.12                      | -0.18                   |
| 60.00            | 60.20              | 60.22                      | -0.22                   |
| 80.00            | 80.32              | 80.36                      | -0.32                   |

Plot the scatter diagram of printing average error changing with design size $L_2$, as shown in figure 7.

Table 3. Printing size, printing average size and printing size error of the test parts.
Figure 7. Relationship between printing size error and design size.

Linear regression analysis is performed on the printing size error $Δ_2$ to obtain the relationship between the design size $L_2$ and the printing size error $Δ_2$:

$$Δ_2 = -0.0037L_1 + 0.02, R^2=0.95(3)$$

As shown in figure 7, with the increasing of base design size $L_2$, the print size error $Δ_2$ increases gradually. According to formula $L = L_2 - 2L_1$, base printing size error will cause the column spacing print size error to decrease with the design size increases, which is an important reason for the variation trend of the printing size error of the column spacing as shown in figure 4. But at the same time, it can be seen that the reduction degree of printing error in figure 4 and figure 7 is not completely consistent, indicating that there are other influencing factors.

4.3 Analysis of other error factors

The structure of FDM printer used in the experiment is Delta parallel mechanism. Some studies have pointed out that the operating accuracy of parallel mechanism is not evenly distributed in its workspace. The farther the position points are from the central axis, the larger the motion error will be [12]. Comparing the printing size which design size is 5mm in table 2 and table 3. In table 2, it can be find that the distance between center position of the columns and the center of the printing platform is $(L + L_i)/2$, the actual print size is 0.09 mm larger on average. Differently, the experimental parts size which in table 3 are placed at the center of the printing platform, and the actual print size is 0.02 mm larger on average. Therefore, it is necessary to consider the impact of the machine’s motion error on the printing size of the connection brackets.

There are five experimental parts are designed, the size of parts are $5\text{mm} \times 5\text{mm} \times 5\text{mm}$ (length $\times$ width $\times$ height), as shown in figure 8. The experimental parts No. 3 is placed in the center of the printing platform, and other experimental parts are placed symmetrically along the Y direction of the platform. After printing is completed, the printing size in the X direction is shown in table 4.

Table 4. Experimental part size at different positions.

| Part numbers | Printing size (mm) | Printing average size (mm) |
|--------------|-------------------|--------------------------|
| 1            | 10.10 10.12 10.10 | 10.12                    |
| 2            | 10.18 10.20 10.18 | 10.20                    |
| 3            | 10.04 10.04 10.06 | 10.08                    |
| 4            | 10.22 10.24 10.20 | 10.24                    |
| 5            | 10.22 10.24 10.22 | 10.22                    |

Figure 8. Part printing experiments at different positions.
As can be seen from table 4, the printing error of column size at the center of the printing platform is the smallest, and the size error of both sides is larger. This result also further explained the experimental results in Section 3.1, and why the printing size of the column increases with column spacing increasing. It is verified that the motion accuracy of the Delta mechanism is not evenly distributed in its workspace, and the closer the position point is to the central point, the higher the motion accuracy is, that indicating the printing size error is related to the printing position. This factor combined with the size error of the base causes the size error of the column spacing to decrease as the design size increasing.

5. Experimental verification
In this paper, the size error compensation model of desktop FDM printer is obtained through experimental research, as shown in formula (1). In order to verify the validity of the model, 5 PCBs of different sizes were selected for verification experiments. Firstly, the design size was compensated according to the compensation model, the original PCBs size were brought into the formula (1) to obtain the compensation value, and plus the original size value as the final design dimension of the column spacing. The original size of PCBs and the size after compensation are shown in table 5.

| Number | 1 | 2 | 3 | 4 | 5 |
|--------|---|---|---|---|---|
| O size (mm) | C size (mm) | O size (mm) | C size (mm) | O size (mm) | C size (mm) |
| Length | 28.08 | 28.22 | 90.24 | 90.27 | 45.14 | 45.25 | 40.14 | 40.26 | 20.12 | 20.27 |
| Height | 33.12 | 33.25 | 95.36 | 95.38 | 30.06 | 30.19 | 40.20 | 40.32 | 24.16 | 24.30 |
| Width | 1.64 | 1.82 | 1.64 | 1.82 | 1.64 | 1.82 | 1.64 | 1.82 |

The design validation model is shown in figure 9. After the printing is completed, embedding PCBs into the connection brackets to test the embedding situation, the result as shown in figure 10.

| Figure 9. Varification model. |
| Figure 10. PCBs embedding verification. |

Experimental verification shows that based on the error compensation model, designing of dimensional error compensation for connection brackets can ensure PCBs embedded smoothly, and there is no shaking phenomenon after embedded or unable embedding phenomenon.

6. Conclusion
In this paper, aiming at the problem of unstable component embedding due to the printing error of the FDM printed connecting brackets, based on the FDM research on error compensation of column spacing is carried out, and the error compensation model of the column spacing size was established. After in-depth analysis of the cause of the error, the main conclusions are summarized as follows:

1) The average print size of the column spacing of the FDM forming connection brackets are smaller than the design size, and the print size error decreases linearly with the increase of the design size.

2) Column spacing size error is the result of the combination of column size error, base size error and machine motion error. Among them, the column size error is the main reason that why the column
Spacing design size is larger than the print size. The combination of the base size error and the machine motion error causes the column spacing size printing error to decrease with the increasing of the design size.

In the following work, the error compensation model of FDM printing column spacing size will be further studied. It is expected to establish a theoretical error compensation model which consider the forming direction, layer thickness and other process parameters, and provide theoretical guidance for the integrated additive manufacturing of electronic products.

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