Research on curved surface 3D printing system based on rotary cylinder

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Abstract

FDM technology faces pain points such as poor forming surface quality, dependence on support structures, low consumable utilization, and low printing efficiency. Although robotic arm-based 3D printing technology can solve some of the pain points, there is currently no mature solution to comprehensively solve these problems. Considering the FDM printing characteristics of the spiral structure, a curved surface 3D printing system based on rotary cylinder was proposed. Rotary cylinder structure is used as the surface printing abasement, a plane-based curved path planning method is proposed for generating the plane-based curved paths. The classical plane-based path planning theory is applied in the proposed curved path planning method by means of a mapping process from the cylindrical 3D curved path to the cylindrical 2D. The test experiments verify the feasibility of this scheme and its progressiveness. Compared to the path planning methods of ModelLight and Cura software in the plane 3D printing technology, the proposed rotating 3D printing system significantly improves printing efficiency and saves hundreds of times the memory occupied by generated printing files, and provides better surface quality and higher material utilization. This work lays the foundation for the subsequent research on high-speed 3D printing systems.

Keywords: Rotary cylinder, Path planning, Rotating 3D printing, FDM

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1 INTRODUCTION

3D printing technology, also known as additive manufacturing technology, is an emerging manufacturing technology that uses digital models as the basis to stack materials layer by layer to create a solid. It covers digital manufacturing fields such as computer-aided design (CAD), computer-aided manufacturing (CAM), and computerized numerical control (CNC). Among the current mainstream 3D printing processes, FDM (Fused Deposition Modeling) technology is the most widely used 3D printing technology, which achieves the processing and manufacturing of 3D models by heating and melting filamentous materials and selectively stacking the melted materials layer by layer through an extrusion head.

The main pain points faced by FDM technology are as follows: (1) poor surface quality. This is an inherent flaw of conventional FDM printing technology. In the planar FDM printing, the 3D model needs to be sliced. Due to the presence of layer thickness, the 3D solid surface exhibits a step effect during the forming process, which affects the surface smoothness of the printed model. Although this problem can be alleviated by the adaptive and partitioned slicing method, the step effect cannot be eliminated. (2) dependence on support structures. In the planar FDM printing, it is necessary to add support structures to successfully print 3D models with overhang features. However, the added support structures often require additional printing time and material consumption, and make it relatively difficult to remove and clean the support structures in post-processing, The smoothness of printed model in contact with the support structures will also decrease. (3) low consumable utilization and low printing efficiency. when printing spiral structure models, the printing paths are often composed of a large number of short straight paths and vacant paths. The former to some extent limits the speed of the nozzle during printing, while the latter wastes a lot of time on the nozzle's non printing movement.

In order to address the aforementioned pain points faced by FDM technology, the robotic arm-based FDM printing technology is proposed. Owing to the more DOFs for printing, the arm-based FDM breaks through constraints of the planar FDM printing, and can solve the pain points such as step effect fundamentally. Dai et al. proposed a novel support-free FDM printing method based on robotic arm structure, the support-free FDM printing is achieved through a volume-to-surface slicing and a surface-to-curves path planning. Although this arm-based FDM solves the problems of adding support structures and high consumables usage, the surface quality of printed models still needs further improvement, as shown in Figure 1(a). Ezair et al.proposed a spatial curved path planning method based on volume coverage. Due to the use of spatial curves as the printing path, the spring model with spiral structure can be manufactured more conformal, and provides higher mechanical performance. However, this method still requires the addition of support structures to support the overhang areas, and the surface smoothness of the spring model in contact with the support structure still needs to be improved, as shown in Figure 1(b).

(a) the robotic arm-based FDM (b) the curved path-based FDM

Figure 1. FDM printing experimental cases.

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In addition, the printed models fabricated by arm-based FDM have low accuracy, this is mainly due to the poor repeated positioning accuracy of multi-DOF robotic arms, which is related to factors such as machining errors, assembly errors, and component damage. The arm-based FDM also suffers from low printing efficiency, and it is mainly caused by the continuous changes in the forming direction during the printing process, which leads to continuous adjustments in the acceleration and deceleration planning of various joints in the multi axis system. Especially for the relatively complex speed planning problem of multi axis FDM in odd and unusual regions, which makes it impossible to run at the highest printing speed.

Considering the FDM printing characteristics of the spiral structure, a new rotating 3D printing system is proposed to comprehensively solve the above problems. The remainder of this paper is organized as follows. After reviewing related works in Section 1, the principles of rotating 3D printing system is introduced in Section 2. Afterwards, a plane-based curved path planning method is proposed in Section 3. Results and discussions are illustrated in Section 4, which is followed by conclusions in Section 5.

2 PRINCIPLE OF ROTATING 3D PRINTING SYSTEM

Compared to the Cartesian structure, The most significant feature is that the rotating cylinder structure is used as a printing base, which is called the rotary cylinder structure, and the FDM principle is shown in Figure 2(a). Similar to the Cartesian structure, the proposed Rotary cylinder structure also has three degrees of freedom, the difference is that one DOF is used to control the rotation of the cylinder base. The FDM system is shown in Figure 2(b). The FDM system is composed of a motion module, a print head module, a control board and a rotating base. the motion module has three groups of stepper motors, Two groups of motors are used to control the Z axis and the X axis, and the other group is used as the Y axis to control the rotation of the rotating base. The printhead module is mounted on the X axis and moves horizontally along the axis line of the rotating cylinder. The rotating base is composed of a simple cylindrical pipe, which is fixed on the Y-axis motor by a caliper structure. The GCode file is used as the print file, and needs to be loaded into the control board. The Marlin firmware library built into the control board is responsible for parsing and processing the print file, thus achieving the printing control of the rotary FDM.

(a) the system principle (b) the physical system

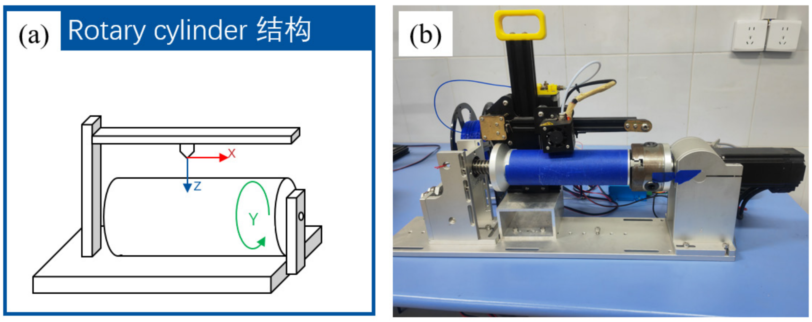

Figure 2. The principle of the rotating 3D Printing system.

In general, the Marlin firmware library can be used to control cartesian structured FDM printing, and can be set up by a configuration file. However, the Marlin library does not support the rotary cylinder structure. Compared with the Cartesian structure, the main difference in the kinematic characteristics of Rotary cylinder structure lies in the motion control mode of the rotary axis. By solving the kinematic difference, the Marlin firmware library can be further used in the rotary 3D printing system.

Considering that during the printing process, the radius of the printed model corresponding to the rotation axis will become larger and larger, thereby affecting the linear velocity of the rotating cylindrical surface. There are two main effects. On the one hand, under the same rotation angle of the rotation axis, the arc length of the motion at different printing radius is different. When the rotation axis rotates at the same angle α,

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the length of is less than , since the radius is less than . On the other hand, under the same angular velocity of the rotating axis, the printing surface with different radius has different linear velocities, as is shown in Figure 3. the linear velocity of the printing surface with the radius is smaller than the radius . In order to ensure the same amount of material extrusion in the same print length at different radius heights, the influence of the rotation radius at different printing heights and the rotation speed of the rotation axis should be taken into account.

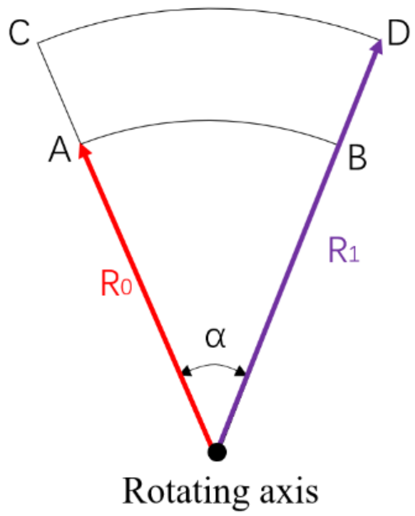

Figure 3. Schematic diagram of relationship between printing radius, rotation angle, and printing arc length

3 PLANAR BASED CURVED PATH PLANNING METHOD

Aiming at the path planning problem of cylindrical surface, Guo et al. proposed a cylindrical surface slicing algorithm to get the slicing results. Boolean operation is utilized in their approach to calculate the intersection line between cylindrical surface and the 3D model, and the curved slicing result can be obtained in their approach. Take the spring model with spiral structure as an example, as is shown in Figure 4(a). The slicing results generated by Guo's method can be seen in Figure 4(b). Then the curved line filling algorithm should be carried out in 3D space, which is a complicated and time-consuming process.

(a) Spring model and specification parameters(b) Curve path planning result.

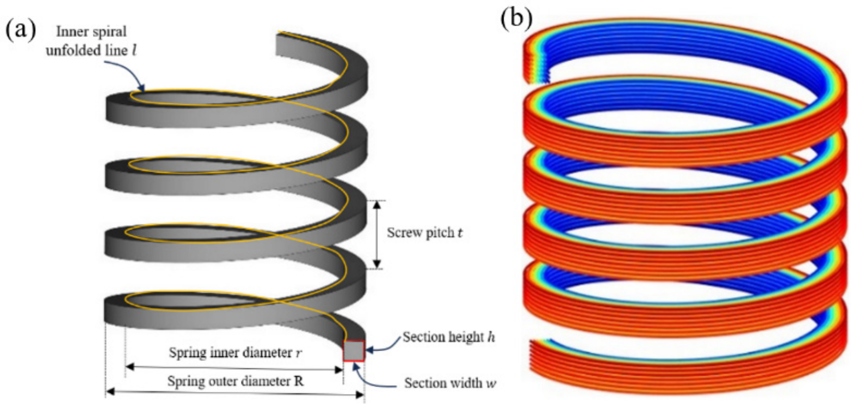

Figure 4. Spring Model and Conventional Cylindrical Path Planning Process.

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However, the cylindrical surface slicing algorithm based on mesh model Boolean operation is relatively complex and has low efficiency of intersection Boolean operation. Moreover, the obtained curved slicing layers needs to be generated curved paths in 3D, which have to be approximated by a large number of small straight lines. However, the above data processing scheme is not optimal. On the one hand, the generated print file will inevitably contain a large number of GCode instructions, which will not only increase the memory occupation of the print file, but also aggravate the burden of print instruction parsing and processing on the underlying processing chip. On the other hand, a large number of small linear paths are not conducive to the optimization of the printing speed of the underlying motion control system, thus reducing the printing efficiency of FDM.

By observing the printing characteristics of the rotating 3D printing system, a plane-based surface path planning method was proposed. The main idea of the proposed plane-based curved path planning method is to expand the surface of the cylindrical abutments into a plane, which is called 2D plane space of the cylindrical abutments. The 2D plane space thus can be utilized to carry out the curved path planning. Therefore, it is necessary to further solve the problem of material extrusion compensation in the mapping process of cylindrical surfaces with different printing heights.

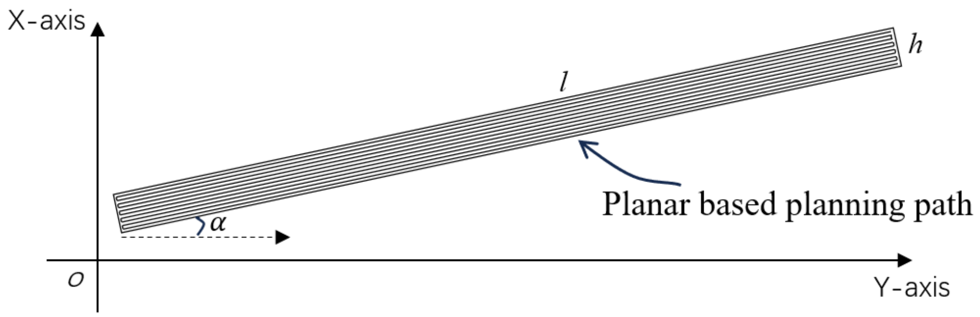

Figure 5. 2D plane space of cylindrical base

Taking the spring structure as an example, the spiral structure model is first expanded along its inner wall helix, and then the expanded inner wall outline can be placed in the 2D plane space of the cylindrical abutment, as shown in Figure 4. The length of the unfolded rectangle is the length of the unfolded line along the inner wall of the spring structure, the width is the height of the spring section, and the inclination angle is calculated in virtue of the formula (1):

$$\alpha = \arctan\left(\frac{t}{2\pi r}\right) \tag{1}$$

where is the pitch length of the spring structure and is the radius length of the inner wall of the spring structure. It should be noted that although the printing radius increases with the increase of the printing height, the inclination angle of the expanded plane contour is not affected, because all paths of the non-first layer of the printing surface are mapped to the surface of the cylindrical abutment, so the radius here is a constant value, and the value of the inclination angle is unchanged.Finally, the classical Zigzag path filling algorithm in the plane-based 3D printing system can be applied directly to generate curved paths in the 2D plane space of the cylindrical abutments, as shown in Figure 4.

Another problem is the compensation of extruded material in non-first layer printing. In the data processing of Marlin library based on Cartesian kinematics model, the extrusion amount of material is proportional to the linear distance of the plane print path. It is assumed that the coefficient value is , and the value can be calculated according to the printing process parameters configured in the Marlin library. Therefore, during the print movement in the non-first layer, it is assumed that the radius value of the first printing is , the current non-first printing layer is , the length of the planned linear print path is , which has and in the x com-

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ponent and y component, respectively. The material extrusion amount according to the current straight path L can be calculated in virtue of formula (2), and no compensation is required for the printing in the first layer.

$$M = K \cdot \sqrt{(\frac{R_i}{R_0} \cdot L_y)^2 + {L_x}^2} \tag{2}$$

4 EXPERIMENT AND DISCUSSION

In the construction of the proposed rotating 3D printing system, MKS Robin 3D development board was used as the motion control board, the open source Marlin firmware library that configured as Cartesian kinematics mode was used as the chip embedded programs, and the supervise soft was developed by C++ to implement the proposed plane based curved path planning method and generated the print file for printing the sprint structure. The printing process parameters used in the printing experiment for the spiral structure model are summarized in Table 1. In the comparative experiment, HORI model Z500 commercial FDM equipment was selected. The slicing software used for HORI equipment was ModelLight, and the open-source mainstream slicing software Cura was selected for comparative analysis.

Table 1. FDM Printing Process Parameters

Process parameters	unit	parametervalue
Print speed	mm/min	2000
Travel speed	mm/min	2400
Print temperature	℃	200
Nozzle diameter	mm	0.4

Firstly, ModelLight software, Cura software and the planar-based curve path planning method were respectively used for fabricating the spring model, and the generated print files were rendered respectively, as shown in Figure 5. It can be seen that ModelLight and Cura generated automatically the support structures for supporting the overhangs of the sprint model for success fabrication. In addition, the surface of the printed models fabricated by ModelLight and Cura suffer the problem of step effect, which can be obviously noticed. After comparative analysis, it can be found that the print file generated by our approach does not suffer from step effect, and no additional support structure needs to be added during the fabrication procedure.

(a) ModelLight *(b) Cura* *(c) the proposed method*

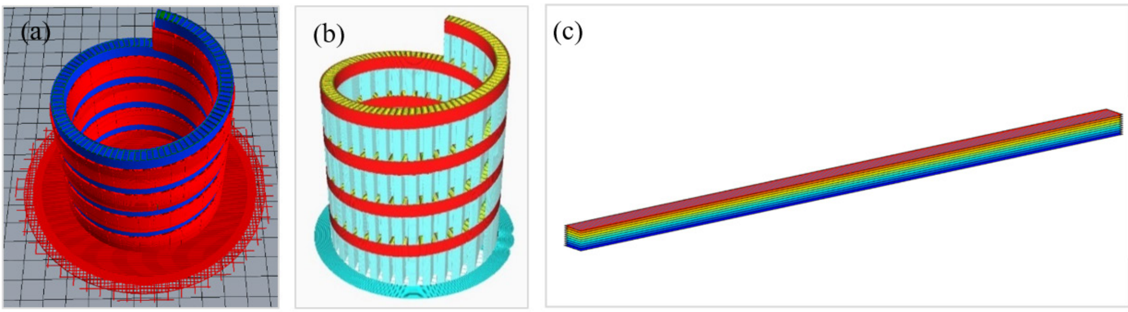

Figure 6. Rendering Results of Different Path Planning methods for Spring Model.

With regard to the memory usage, it is found that the print file generated by ModelLight was 29565KB, the print file generated by ModelLight was Cura was 29565KB, and the print file generated by our approach was 36KB. It can be obviously seen that the proposed method in this work has the smallest memory consumption, which is 0.1% of the former and 0.3% of the latter. On the one hand, the supported structures were avoided in the proposed method, which reduces the GCode orders that needs to be added in the print

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file. On the other hand, the proposed method adopts the plane-based curve paths instead of the curve paths approximated by straight lines, which also needs to be stored in print files, thus further reducing the memory consumption of print files.

Secondly, The print files generated by ModelLight and Cura were used to fabricate the spring models via Horizon 500 device, the printed results without removing support structures are shown in Figure 6(a) and (b). It can be seen that the support structures added by ModelLight and Cura methods can effectively support the overhangs of the spring model, but these printed support structures need to be manually stripped during post-processing, which increases the difficulties and time cost of post-processing. Moreover, removing these support structures will also cause secondary damage to the surface of the printed model, thus further reducing the print quality, as shown in Figure 7. By comparing the printing quality of the spring model fabricated by three methods, it is obvious that the proposed method does not need to add support structure and provides the best print quality.

(a) ModelLight (b) Cura (c) the proposed method

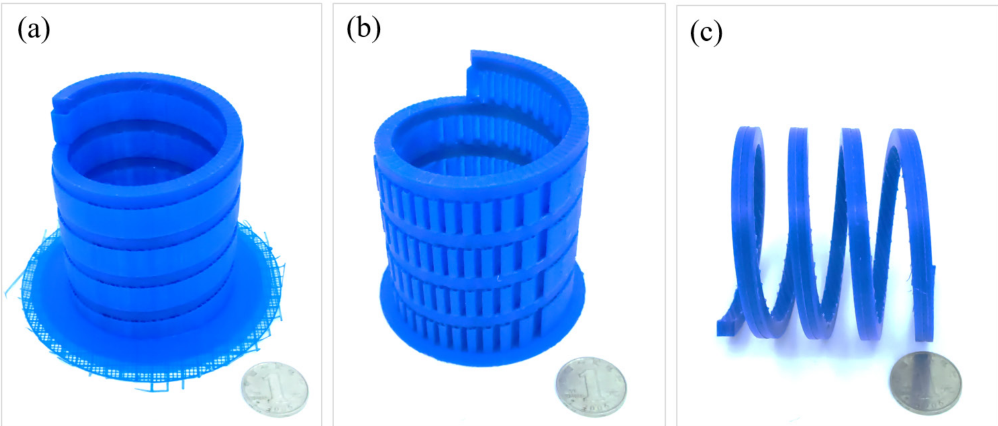

Figure 7. Printing results via different methos for sprint models.

(a) ModelLight (b) Cura (c) the proposed method

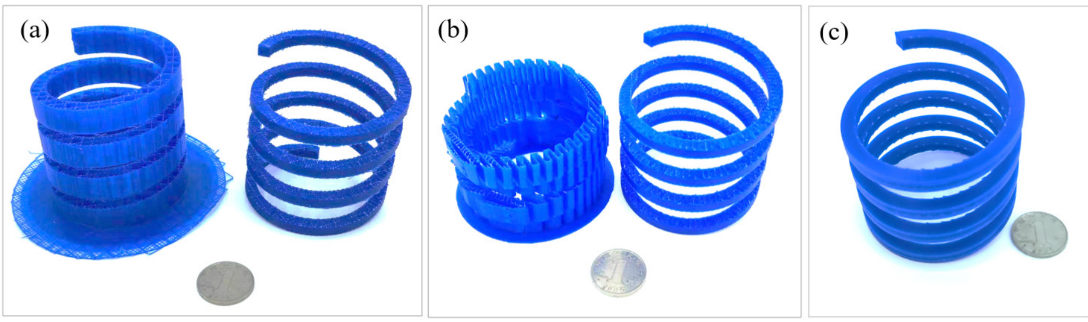

Figure 8. The printed sprint models and the removed supports.

In order to further compare and analyze the use of printing materials and printing efficiency, the experimental data of three methods on printing sprint models were carried out, and statistics are shown in Table 2 and Table 3. The printed sprint models and the removed supports are shown in Figs. In terms of the utilization rate of printed materials, ModelLight and Cura methods both need to print support structures, which leads to the utilization rate of printed materials only 41.18% and 59.32% respectively. However, the proposed method in this paper does not need to print support structures, so the utilization rate of printed materials can be 100%. Three printing experiments were conducted under the same conditions using the process parameters in Table 1. With regard to the Printing Efficiency, the proposed method has the shortest printing time, and compared with ModelLight and Cura methods, the proposed method can increase significantly the

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printing efficiency by 71.18% and 50.69% respectively. This is due to the fact that the print path generated by ModelLight and Cura methods contains a part of the support structure, which leads to a longer printing time. In addition, the printing path of the spring model generated by these methods contains a large number of short lines and vacant lines, which decrease the printing efficiency. Therefore, from the perspective of printing efficiency, the proposed method is the highest, and the efficiency improvement advantage is obvious.

Table 2. Statistics on Printing Materials of Different Printing Methods.

Printing method	Weight of supports (g)	Weight of models (g)	Utilization rate
ModelLight	30	35	41.18%
Cura	24	35	59.32%
The proposed method	0	35	100%

Table 3. Statistics on Printing Efficiency of Different Printing Methods.

Printing method	Printing time (min)	Efficiency advantage
ModelLight	753	71.18%
Cura	327	50.69%
The proposed method	217	-

5 CONCLUSIONS

In this paper, according to the characteristics of FDM printing of spiral structure, a new design and control method of rotary 3D printing system is proposed to comprehensively solve the pain points of poor forming surface quality, dependent support structure, low utilization rate of material and low printing efficiency faced by FDM. In the proposed rotary 3D printing system, a cylinder structure is used as the rotary printing base, and a plane-based curved path planning method is proposed in the data processing. In virtue of a mapping process from the cylindrical 3D curved path to the cylindrical 2D plane, the path planning problem of 3D cylindrical surface can be solved directly by applying the classical plane-based path planning theory. The experimental results show that by using plane-based curve path instead of curved path based on straight line fitting, FDM printing efficiency is significantly improved and the memory occupied space of FDM print files is saved. Moreover, support structure is not required in the printing process of the proposed system and there is no step effect in the planning path. The printing quality of the spring model and the utilization rate of printing material are improved. Further research can be conducted on the ultra fast FDM printing technology based on the proposed rotating FDM system. This work serves as the foundation for subsequent research work.

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