The Implementation of Agile SFFS using 5DOF Robot

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Abstract: Several Solid Freeform Fabrication Systems(SFFS) are commercialized in a few companies for rapid prototyping. However, they have many technical problems including the limitation of applicable materials. A new method of speedy prototyping is required for the recent manufacturing environments of multi-item and small quantity production. The objectives of this paper include the development of a novel method of SFFS, the CAFL^{VM} (Computer Aided Fabrication of Lamination for Various Material), and the manufacture of the various material samples for the certification of the proposed system and the creation of new application areas. For these objectives, the technologies for a highly accurate robot path control, the optimization of support structure, CAD modeling, adaptive slicing was implemented. In this paper, we design an algorithm that the cutting path of a laser beam which is controlled with constant speed. The laser beam is tangentially controlled in order to solve the inaccuracy of a 3D model surface. The designed algorithm for constant-speed path control and tangent-cutting control is implemented and experimented in the CAFL^{VM} system.

Keywords: Solid Freeform Fabrication Systems(SFFS), Computer Aided Fabrication of Lamination for Various Material(CAFL^{VM}),Constant-speed path control, tangent-cutting control

1. INTRODUCTION

Solid Freeform Manufacturing is a method using a CAD description and various materials to fabricate complex 3D object. This emerging field began with rapid-prototyping machines that fabricated 3-D objects from modeling materials. A desirable extension is the ability to manufacture functional components directly from an electronic description, making possible rapid turnaround of the design-and-test cycle, achieving batch-size-of-one manufacturing, and offering a totally new manufacturing technique capable of constructing complex external and internal geometric features. The idea of rapid production conjures up questions an issues such as “how would designs change if one could manufactures parts without the constraints imposed tooling?” Using this approach, one could design and manufacture parts without regard to draft, die lock conditions, or even assembly.[1][2][3]

Historically, these problems have created a need to reduce the complexity of part geometry and have stifled the imagination and creativity of designers. This, in turn, has made it difficult to manufacture dome products that may have broad market appeal. In the future, companies will pay a premium for the flexibility of machines that can produce quantities of production parts quickly and economically, without the need for tooling. Its analogy is with an up-and-coming area of manufacturing under development for several years at the Massachusetts Institute of Technology, Carnegie Mellon University, and The University of Texas at Austin, among other places. Researchers here in Austin, have been working on technologies termed solid freeform fabrication or, as reported in the popular press, desktop manufacturing, rapid prototyping, and layered manufacturing.[1]

Thanks to the rapid modeling techniques available today for solid freeform fabrication, modifications to these designs can be made quickly and assessed in the most effective manner. The models are often created overnight. Design Edge uses prototype services, which can quickly provide models from its 3-D computer files of component parts. These prototyping services supply physical prototypes made with selective laser sintering or stereolithography apparatus. The cost of this method varieties with the quality of finish desired and with turnaround times. Although it may seem expensive to the uninitiated, the numerous iterations of physical models cost far less than go the mistakes, missed opportunities, and under-optimized designs that can be avoided by physical model reviews.

The CAFL^{VM}(Computer Aided Fabrication of Lamination for Various Material) system makes 3D solid models of various material using a 2D cutting method of a laser beam STL(STereoLithography) 2D data, derived from CAD 3D image, by sequentially laminating the part cross-sections. The constant-speed control and path control is started with the STL data. [3][13].

After STL file is modified in data format to be available for control, the fabrication of the 2D part is with constant speed, conducted from the 2D position data by laser beam.

However, there is a notable problem with the conventional 2D lamination method.[9][10]. Inaccuracy of the 3D model surface, which is caused by the stair-type surface generated under the influence of vertical 2D cutting. Tangential cutting by a laser system should be developed to overcome the inaccuracy. For the mechanical system of tangential cutting, 5DOF SFFS is at least required.

Therefore, this paper develops the 5DOF SFFS controller to solve tangential cutting. We propose design and manufacturing of a 5DOF controller, path controller, and support mechanism for curved shape - development of optimized laser path and laser focusing compensation - development of path control S/W using intelligent control in this paper.

2. 5DOF CAFL^{VM} SYSTEM

2.1 CAFL^{VM} SYSTEM

The CAFL^{VM} system makes 3D solid models out of various materials by a laser cutting method. It is a new machine for rapid prototyping, tooling and manufacturing. It's process is an automated fabrication method in which a 3D object is constructed from STL(STereoLithography) 2D data of CAD system, derived from a CAD 3D image, by sequentially laminating the part cross-sections.

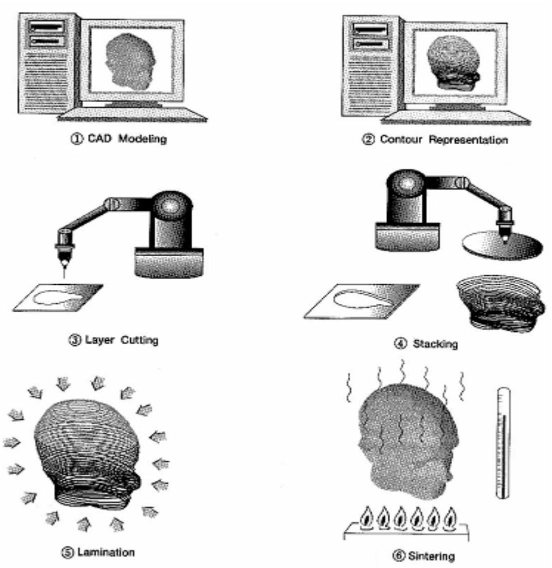

Figure 1. Systematic Flow of CAFL^{VM} system

WindowsNT and TMS32C44 DSP is used as the process for high accuracy of the control experiment environment. The IP(Industry pack) carrier board has four slots that uses a DSP-Link3 connection for communication with the host process. Servo-driving system consists of independent five servo drive units for driving 5DOF manipulation robot.

5DOF CAFL^{VM} system is composed of five AC Servo motors and three prismatic and two rotation joints. The control environment diagram of CAFL^{VM} system is shown in figure 2.

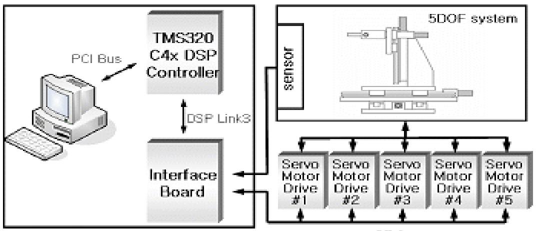

Figure 2.Configuration of CAFL^{VM} System

2.2 Mathematical Analysis of 5DOF CAFL^{VM}

The skeleton structure of our 5DOF CAFL^{VM} is schematically illustrated in Figure 3.

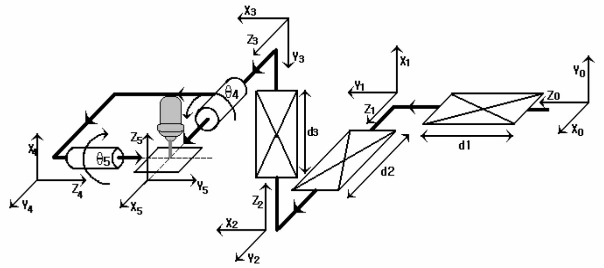

Figure 3.The skeleton structure of 5DOF CAFL^{VM}

The 5DOF system consists of three translational axes (X,Y,Z) and two rotational axes(Roll, Pitch). Denavit-Hartenberg parameters for 5DOF CAFL^{VM} are given in Table I.

TABLE **I.** Link parameters of the 5DOF system

LINK.	α	A	d	θ
1(X)	90°	0	d_1	90°
2(Y)	90°	0	d_2	90°
3(Z)	90°	0	d_3	0
4(Roll)	90°	0	0	θ_4
5(Pitch)	90°	0	0	θ_5

α : A rotation about the z-axis.
d : The distance on the z-axis.
a : The length of each common normal (Joint offset).
θ : The angle between two successive z-axis (Joint twist).

$$A_1^0 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & \mathrm{d}_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2^1 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & \mathrm{d}_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3^2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & \mathrm{d}_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2\text{-}1)$$

$$A_4^3 = \begin{bmatrix} c_4 & 0 & s_4 & 0 \\ s_4 & 0 & -c_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_5^4 = \begin{bmatrix} c_5 & 0 & s_5 & 0 \\ s_5 & 0 & -c_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The 4×4 homogeneous transformation matrices for each of the five joints of position and orientation are explained in Equation (2-1). We simplify s_i =sin(θ $_i$), c_i =cos(θ $_i$). From these matrices, the position and orientation of the 5th axis can be calculated in terms of the joint variables in Equations (2-2)

$$A_5^0 = A_1^0 A_2^1 A_3^2 A_4^3 A_5^4 = \begin{bmatrix} c_4c_5 & s_4 & c_4s_5 & d_1 \\ s_5 & 0 & -c_5 & d_2 \\ -s_4c_5 & c_4 & -s_4s_5 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2\text{-}2)$$

3. CONTROL ALGORITHM OF CAFL^{VM} SYSTEM

3.1 Constant-Speed Algorithm of CAFL^{VM}

The CAFL^{VM} system makes 3D solid model of various material using 2D cutting method of laser beam. We can see in the figure 4 that 2D cutting points are got by the intersection of a facet and a slicing plane.

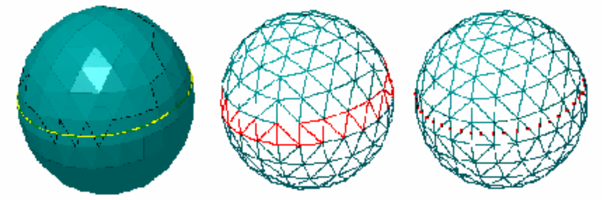

figure 4. Cross Facet and intersection

The precise 2D cut can be guaranteed only by constant-speed path control. To track the desired position with constant speed, STL 2D data are converted to 2D position data for control, by solving the crossing points of facet's subset and slicing plane.

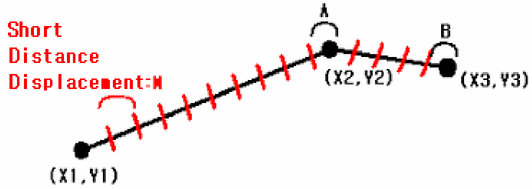

figure 5. Control Method for constant-speed

A distance is decided by a time and a speed. So we firstly decide a speed and a time interval for a reference segment. Thereafter, every speed value in all the distance is changed in the constant speed. finally, The number of segment **M** and segment time interval **T** is derived. The detail algorithm is shown as figure 6. **X, Y** are 2D position data, **P** is the number of segments, and **Xmov**, **Ymov** are moving distance of X and Y.

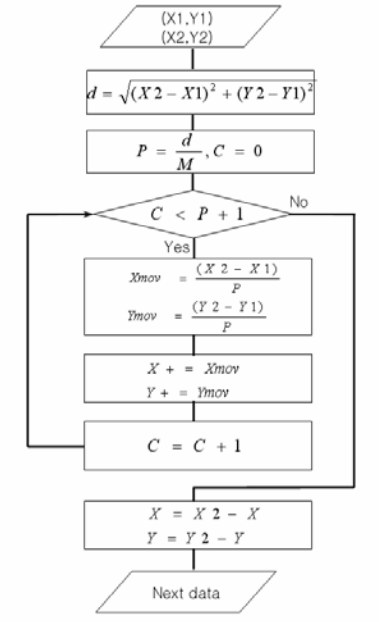

figure 6. Flow of Constant Speed control

The composition of X and Y coordinates is a vector, because the driving distance is vector. So, the total distance P is divided a moving distance into m segments. Then, we can get the m segments which consist of the time T of the reference speed calculated by a reference distance.

3.2 Tangent-Cutting Control CAFL^{VM} System

Tangential cutting by a laser system should be developed to overcome the inaccuracy. A minimum DOF of SFFS is required for the tangent-cutting control. This paper develops the 5DOF SFFS controller to condone the tangential cutting. The architecture of the tangent-cutting controller (TCC) system is shown in figure 7.

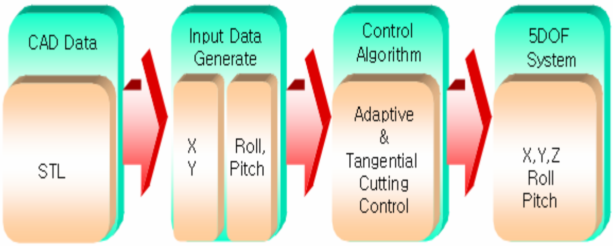

figure 7. The Architecture of TCC

The inverse kinematics for the tangent-cutting is straightforward. For simplicity, we place the origin of 0th frame at the laser focal point and align the z_0 axis with the laser beam. The last frame, frame-5, can be selected with considerable freedom. We choose to place the origin of the 5th frame at the intersection point of the two rotational axes, and we choose the z_5 axis to be perpendicular to the table surface.[9] Cutting trajectories, specified in terms of (**T**(translation), **O**(orientation)), are defined with respect to this 5th frame.

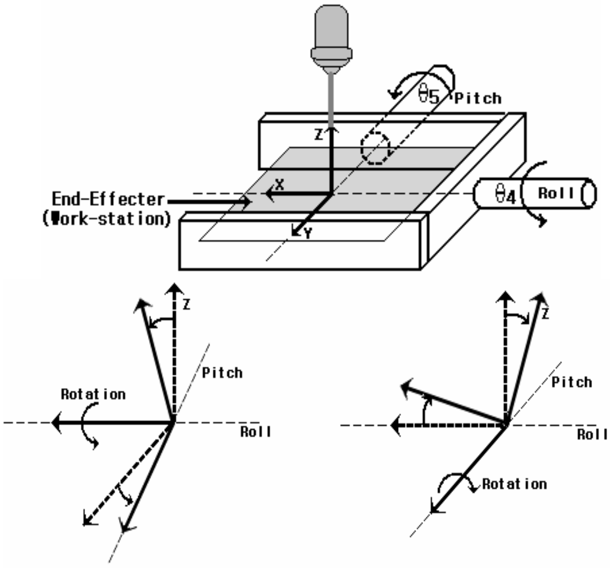

figure 8. Tangential Movement of 5DOF SFFS

It only remains to derive the inverse kinematics, relating the mechanism coordinates (dx, dy, dz, θ_4, θ_5) to the cutt

-ing specifications (**T**, **O**). Define a cutting frame, which we will refer to as the WS-frame The vector pair (**T**, **O**). This frame has its origin at **T** and its z axis parallel to **O**. The directions of the x and y axes of the WS-frame will be irrelevant. The WS-frame expressed with respect to the 5-th frame is then given by:

$$A^5_{WS} = \begin{bmatrix} n_x & t_x & b_x & p_x \\ n_y & t_y & b_y & p_y \\ n_z & t_z & b_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3-1}$$

The components px, py, pz, bx, by, and bz are the components of **T** and **O**.

We can then calculate the position and orientation of the WS- frame relative to the base frame of the 5-axis system by:

$$A^0_{ws} = A^0_5 \; A^0_{ws} \tag{3-2}$$

$$= \begin{array}{cccc} & & ① & ② \\ \nabla & \nabla & b_x c_4 c_5 + b_y s_4 + b_z c_4 s_5 & p_x c_4 c_5 + p_y s_4 + p_z c_4 s_5 + d_1 \\ \nabla & \nabla & b_x s_5 - b_z c_5 & b_x s_5 - p_z c_5 + d_2 \\ \nabla & \nabla & -b_x s_4 c_5 + b_y c_4 + b_z s_4 s_5 & -p_x s_4 c_5 + p_y c_4 + p_z s_4 s_5 + d_3 \\ 0 & 0 & 0 & 1 \end{array}$$

The five joints must be controlled so that the cutting vector, **T**, is placed at the focal point of the laser and the orientation vector, **O**, is aligned with the direction of the laser beam. Such requirement can be expressed by the relation of:

$$A^0_{WS}\begin{bmatrix}0\\0\\1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\1\\0\end{bmatrix}, \quad A^0_{ws}\begin{bmatrix}0\\0\\0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\end{bmatrix} \tag{3-3}$$

We can drive Equation (3-4) from Equation (3-3) by using the forward kinematics

$$p_x = -\frac{d_2}{s_5},$$

$$p_y = -\frac{d_2 c_4 c_5 - d_1 s_5}{s_4 s_5}$$

$$b_x = -\frac{s_4 c_5}{s_4 s_5 + c^2{}_5},$$

$$b_y = c_4,$$

$$b_z = -\frac{s^2{}_4}{s_4 s_5 + c^2{}_5} \tag{3-4}$$

(s_i =sin(θ i), c_i =cos(θ i))

Finally, We can slove the inverse knematics by(3-4)

$$d_1 = -p_x c_4 c_5 - p_y s_4,$$

$$d_2 = -p_x s_5 \;,$$

$$d_3 = p_x s_4 c_5 - p_y c_4$$

$$\theta_4 = \tan^{-1}\left(\frac{b_x c_5 + b_z s_5}{-b_y}\right),$$

$$\theta_5 = \tan^{-1}\left(\frac{b_z}{b_x}\right) \tag{3-5}$$

(s_i =sin(θ i), c_i =cos(θ i))

We can get all parameters for the tangent-cutting from Eq.(3-4),(3-5). The parameters are assigned into each joint. The detail algorithm of tangent-cutting, using them, is shown as figure 9. **X, Y** are 2D position data, **R**, Pt are Roll and Pitch segment, P is the number of segments, and **Rmov, Ptmov** are moving angle of **R** and **Pt**.

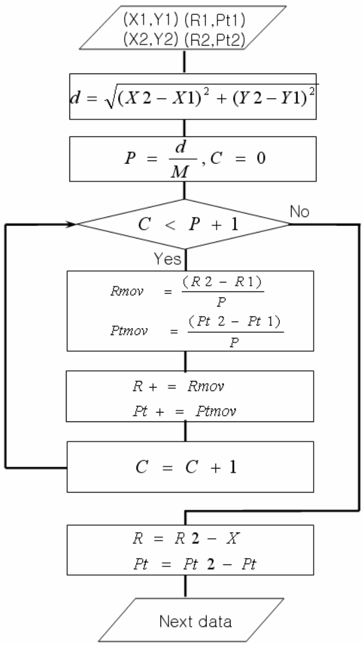

figure 9 .Flow of tangential-cut control

4. Experiment of CAFL^{VM} system

4.1 Experimental Result of Constant-speed Control

The experiment, that a 3D object is constructed from a solid CAD representation by sequentially laminating the part cross-sections on the CAFL^{VM} System. The 2D slice which is going to be cut by the control algorithm is shown in figure 10.

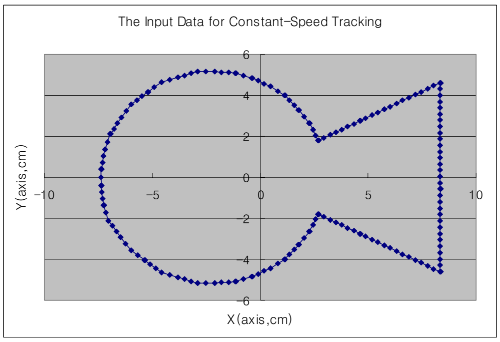

figure 10. The Input Data for Constant-Speed Tracking

The figure 11 shows real-process of fabrication using constant-speed tracking and a fabricated sample with accuracy. Because the constant-speed control is perfect in this experiment, a good 2D solid model and a 3D object is made without any changeable stay-time in a point laminating the part cross-sections. The simulated input data for constant speed is shown in the figure 10. Also, the experimental result is shown in the figure 11. The figure 10 shows a good tracking data from the 2D position data. The figure 11 shows the higher performance, without any position error.

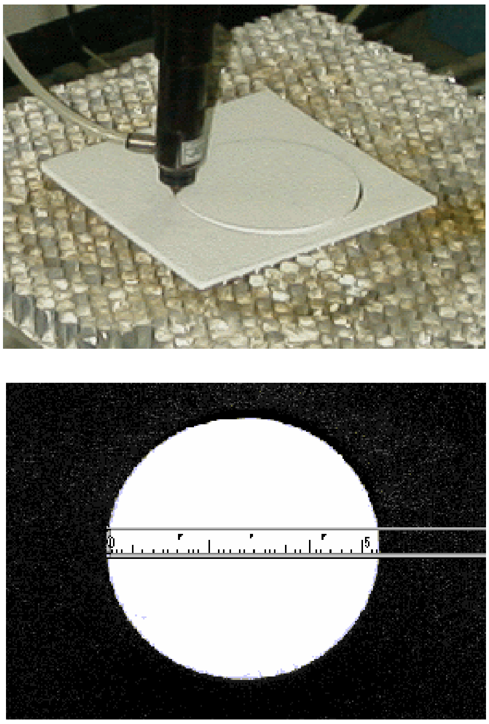

figure 11. The Result of Constant-Speed Contorl

4.2 Experimental Result of Tangential Cutting

The 5DOF system consists of a laser system, limit sensor, home sensor and pneumatic system for the clearness of cutting face. The digital controller can automatically drive all the devices

5DOF CAFL system used in the experiment is shown in figure 12. There is a Z-sxis(the 3th joint) for the control of the focus distance of material and laser. (X, Y) axis covers planar movement. 4th and 5th joints are rotated for the tangential cutting by (Roll, Pitch) data.

figure 12. 5DOF CAFL^{VM} System

The control H/W unit of the 5DOF system is five servo drivers in which speed and position control can be switched. We designed a special circuit for the rejection of power and radiation noise.

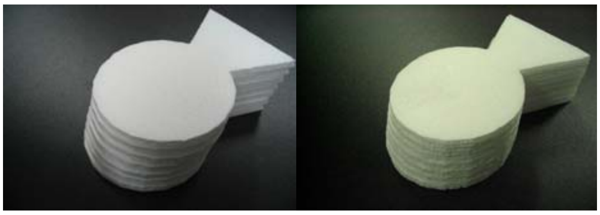

figure 13. 2DOF Cutting Sample(Left)
5DOF Tangential-Cutting Sample(Right)

Finally, 2DOF cutting sample and 5DOF Tangent-cutting sample are compared in figure 13. We can know that 3D Model surface of the 5DOF Tangent-cutting sample is more precise than 2DOF

5. CONCLUSIONS

We developed a position-tracking algorithm to be controlled with constant speed and a tangent-cutting controller to solve inaccuracy of the 3D model surface. We successfully implemented these into the 5DOF CAFL^{VM} system developed in this paper.

The fabrication of the 2D part was, with constant speed, conducted from the 2D position data by laser beam. If the constant-speed control were not perfect, a good 2D solid model could not be made because of changeable stay-time in a point laminating the part cross-sections. In the shorter stay-time, the 2D part could not be cut. In the longer stay-time, the material of the part cross-sections could be burned. Therefore, we developed the constant-speed path control algorithm to stably solve the problem, and confirmed its high-performance through the experimental results from the application into CAFL^{VM} system.

The tangent-cutting processing method is necessary to overcome the inaccuracy of the 3D model surface, which is caused by the stair-type surface generated in virtue of vertical 2D cutting. We designed the tangent-cutting control algorithm to stably solve the problems, and confirmed its high-performance through the experimental results from the application into the 5DOF CAFL^{VM} system.

6. UNITS AND SYMBOLS

5.1 Units

cm(m/100) , s(sec), m,

5.2 Symbols

[1] SFFS: Several Solid Freeform Fabrication Systems
[2] CAFL^{VM}: Computer Aided Fabrication of Lamination for Various Material
[3] STL: STereoLithography
[4] TCC: tangent-cutting controller

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