# Advanced 3D Path Planning for Robotic Calligraphy Based on LLM-Driven Text Prompts

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***Abstract*—Chinese calligraphy is a complicated art form that requires precise control of movement and brush dynamics, making it a challenging task for robotic systems. This paper presents a novel approach to enabling robotic manipulators to perform Chinese calligraphy using 3D path planning algorithms and a large language model (LLM) as input generators. The proposed framework integrates an LLM to generate textual content prompts, which are then transformed into detailed 3D Bézier curve trajectories which represent the strokes of Chinese characters. These trajectories are optimized to ensure smooth and accurate motion of the robotic manipulator, taking into account the brush's pressure, orientation, and speed to emulate traditional calligraphy techniques. Experimental results demonstrate the effectiveness of the approach in producing visually authentic Chinese calligraphy with high precision and artistic quality. This work highlights the potential of combining LLM with advanced robotic path planning to bridge the gap between traditional art and robot world.**

***Index Terms*—Robotic Calligraphy, LLM, Bézier Curve, Trajectory Generation, Path Planning**

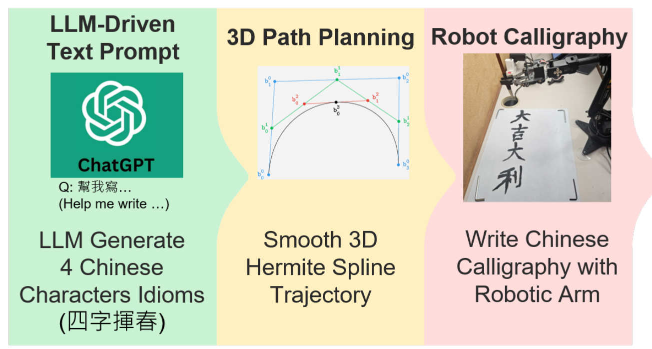


**Fig. 1:** System overview of robotic calligraphy.

## I. Introduction

Chinese calligraphy is a revered art form that has been practiced for thousands of years, symbolizing the rich cultural heritage of East Asia. The act of writing calligraphy involves not only the correct depiction of strokes but also the careful manipulation of brush dynamics, such as pressure, angle, and speed, to convey artistic intent. This complexity has inspired the development of robotic systems capable of replicating calligraphic writing. However, achieving human-like precision and artistic quality in robotic calligraphy remains a significant technical challenge [1] [2] [3] [4].

Traditional robotic calligraphy [5] [6] [7] systems primarily rely on static 2D path planning techniques to generate the trajectories required for writing strokes. While these systems can reproduce the basic shapes of Chinese characters, they often fail to emulate the nuanced variations in brush pressure, orientation, and stroke speed that define the expressive nature of traditional calligraphy. The challenge lies in controlling line thickness variations, which traditional calligraphers achieve through subtle brush pressure adjustments. Furthermore, some works rely on predefined character libraries or manual trajectory design [8] [9], which limits the flexibility and scalability of robotic calligraphy systems, making it difficult to generalize their application to a wide range of characters.

To address these challenges, we propose a novel framework that integrates a large language model (LLM) with advanced 3D path planning algorithms to enable robotic manipulators to perform Chinese calligraphy with high precision and artistic quality. LLM is used as a content generator, transforming textual prompts into detailed character representations. These representations are then converted into 3D trajectories, capturing strokes' spatial and temporal dynamics. By optimizing these trajectories for brush pressure, orientation, and speed, our system mimics the intricate motions of a human calligrapher. Our approach enhances the expressive quality of robotic output and provides a scalable solution for generating a wide variety

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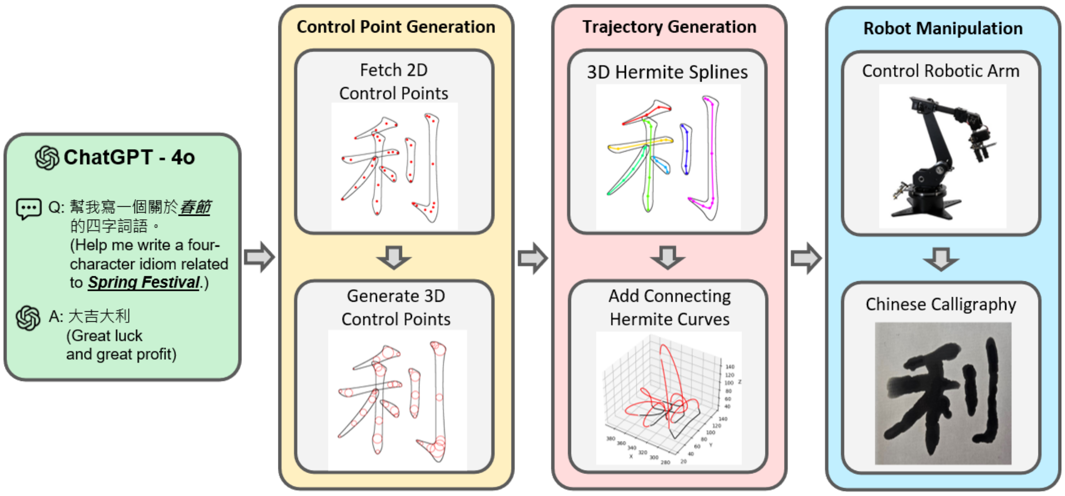


**Fig. 2:** Workflow of the robotic calligraphy system.

of characters and styles.

Our contribution offers several key advantages are listed as follows.

1) We used LLM to generate diverse and contextually relevant prompts, enabling the creation of custom phrases without relying on predefined characters.
2) We developed a Bézier curve trajectory generation algorithm for 3D path planning, ensuring smooth, precise, and realistic stroke dynamics that closely mimic traditional calligraphy techniques.
3) We conducted experiments of our robotic calligraphy system. The results demonstrated the system's ability to produce visually authentic Chinese calligraphy.

## II. Methodology

This section describes the methodology used in our framework to enable robotic systems to perform Chinese calligraphy. Our approach integrates a large language model (LLM) for content generation, control point generation from stroke data, trajectory planning, and robotic arm manipulation to achieve precise and authentic calligraphy.

### A. Text Prompt Generation Using LLM

To generate textual content for calligraphy, we used the Hong Kong University of Science and Technology (HKUST) GenAI Platform API[1] to produce input prompts. The LLM is tasked with generating diverse and contextually relevant Chinese text based on user-specified themes or phrases. This flexibility allows the robotic system to create calligraphy for a wide variety of characters and styles without relying on predefined templates or datasets. The generated textual content serves as the basis for constructing the corresponding 3D paths of the strokes. The integration of the HKUST GenAI Platform's API into the robotic calligraphy system enables seamless text prompt processing for generating Chinese characters.

[1]HKUST GenAI Platform https://itso.hkust.edu.hk/services/general-it-services/generative-ai-tools

### B. Control Points Generation

After determining the input Chinese characters, we used the Make Me a Hanzi dataset[2], which contains over 9,000 of the most common simplified and traditional Chinese characters. This dataset provides two essential components: dictionary data, which includes character definitions and stroke sequences, and stroke-order vector graphics, which provide detailed vectorized representations of each stroke, including median points and boundaries. The red median points within the vector graphics were used as spline control points for trajectory generation as in Fig.3.

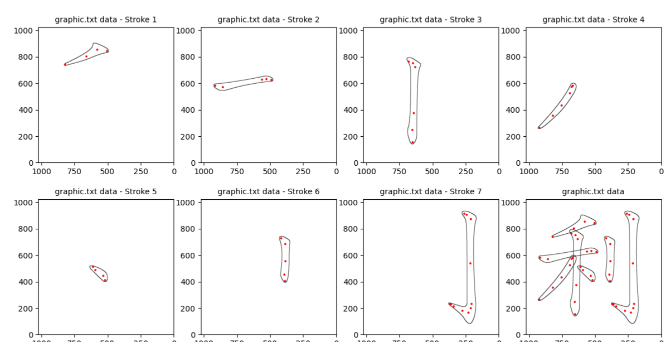


**Fig. 3:** Median points and boundaries with stroke order of character "利".

While the writing surface is inherently two-dimensional, the unique properties of Chinese calligraphy brushes allow for a sense of three-dimensionality. In our framework, the XYZ coordinate system is defined with the +X axis extending horizontally to the right, the +Y axis extending horizontally forward, and the +Z axis pointing vertically upwards, out of the writing surface. When the brush is pressed down, the stroke becomes thicker, while lifting the brush produces thinner strokes. By adjusting the Z-coordinate, based on the pressure

[2]Make Me a Hanzi dataset https://github.com/skishore/makemeahanzi

inferred from the control points, the algorithm can construct 3D trajectories that capture the interplay between stroke thickness and motion, emulating the nuanced dynamics of traditional calligraphy.

To calculate the Z-coordinate for each control point and emulate the brush dynamics, we implemented a process based on fitting circles. Specifically, for each control point, we calculated the largest fitting circle that did not intersect the black stroke boundaries. The generated results are shown in Fig. 4.

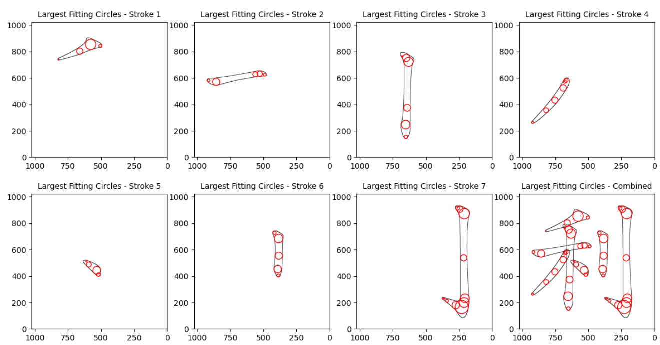


**Fig. 4:** Largest fitting circles of control points and boundaries with stroke order of character ”利”.

The radius of the fitting circle at each point was used to infer the stroke thickness. A larger radius indicated a thicker stroke, requiring the robotic arm to press the brush closer to the paper by lowering the Z-coordinate. Conversely, a smaller radius indicated a thinner stroke, necessitating the brush to be lifted away from the paper by increasing the Z-coordinate. The Z-coordinates are calculated using Eq.(1). This method ensures that the thickness variations in the strokes accurately mimic the traditional brush dynamics of Chinese calligraphy, where pressure influences the appearance of the strokes.

$$Z_{\mathrm{h}} = Z_0 + \frac{r_{avg} - r_c}{s} \tag{1}$$

$Z_h$ is the height of the brush, $Z_0$ is the calibrated initial height of the brush, $r_{avg}$ is the rough estimate of the average radius value of the control points fitting circles of all characters in the dataset and we set $r_{avg} = 20$, $r_c$ is the radius of the largest fitting circle, $s$ is the scaling factor and we set $s = 4$.

### *C. Trajectory Generation*

To produce smooth and fluid trajectories for each stroke based on the stroke-order vector, we used 3D Hermite curves, as shown in Eq.(2) to connect the control points [10]. Hermite curves leverage the start and end positions, along with their corresponding velocities as control points, allowing precise control over the shape and smoothness of curves, making them ideal for modeling the complex and flowing strokes of Chinese characters.

$$H(t) = \begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix} \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} P_{0x} & P_{0y} & P_{0z} \\ P_{1x} & P_{1y} & P_{1z} \\ V_{0x} & V_{0y} & V_{0z} \\ V_{1x} & V_{1y} & V_{1z} \end{bmatrix} \tag{2}$$

Time $t$ ranges from 0 to 1, $P_0$, $P_1$ are the 3D Position Vectors of the start and end positions, and $V_0$, $V_1$ are their corresponding 3D Velocity Vectors.

Originally, we used Catmull-Rom splines, a type of Bézier spline, to connect the Hermite curves or the control points. Catmull-Rom splines connect multiple Hermite curves using control velocities in Eq.(3). This maintains $C^1$ continuity between multiple Hermite curves, creating a smooth trajectory along multiple control points.

$$V_i = k(P_{i+1} - P_{i-1}) \tag{3}$$

However, there are some strange twists and backward movements in the middle of the spline, as in Fig. 5, because it overshoots when the control points are not uniformly spaced. Even if a smaller tension parameter $k$ is used, the backward movements still exist in a lot of Chinese characters, making the trajectory non-smooth and resulting in sudden stops in the middle.

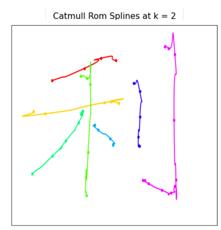


**Fig. 5:** Catmull-Rom splines applied on the character ”利”.

Therefore, we modified the magnitude of the control velocities $V_i$ to the minimum between the two magnitudes: the magnitude between the current point and the next control point $|P_{i+1} - P_i|$, and the magnitude between the current point and the previous control point $|P_i - P_{i-1}|$. This limits the control velocity to prevent it from becoming unreasonably large and overshooting.

$$V_i = k \cdot \min\left(|P_{i+1} - P_i|, |P_i - P_{i-1}|\right) \frac{P_{i+1} - P_{i-1}}{|P_{i+1} - P_{i-1}|} \tag{4}$$

We used the modified Catmull-Rom spline with control velocities $V_i$ in Eq.(4) to connect the $n$ control points in a stroke. Next, we connect different strokes together using a Hermite curve in Eq.(2). The starting point control velocity $V_0$ is set to $\frac{V_{n-1}}{|V_{n-1}|} \times v_{lift}$ and the ending point control velocity $V_1$ is a 3D vector that points directly downward in the -Z direction.

The $V_0$ in the connecting Hermite curve has the same direction as the $V_{n-1}$ in the spline. Therefore, it has $G^1$ continuity and the robotic arm would lift the brush up smoothly after writing a stroke as in Fig. 6. The $V_1$ in the connecting Hermite curve ensures that the brush lifts up and leaves the paper when the robotic arm moves to the next stroke.

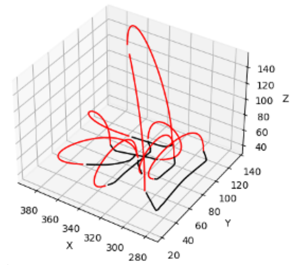


**Fig. 6:** Generated trajectory of character ”利”.

### D. Robot Manipulation

The robotic arm in this framework featured five degrees of freedom, providing sufficient flexibility to replicate the intricate motions required for calligraphy. The arm was modeled using the Denavit-Hartenberg (DH) method [11], which provides a systematic framework for describing the linkages and joints of robotic manipulators. The kinematic model of the arm was implemented to facilitate trajectory planning and control.

## III. Experiments, Results, and Analysis

This section describes the experimental setup, the implementation of two experiments to evaluate the framework, and an analysis of the results. The experiments demonstrate the effectiveness of the system in generating and performing robotic calligraphy for various input prompts.

### A. System Experiment Setup

The experimental setup consisted of a Chinese calligraphy kit, a robotic arm, and a laptop, which is shown in Fig. 7. The RoArm-M1 robotic arm, a five Degree-of-Freedom (5-DoF) manipulator, was used for precise motion control. The robotic arm was connected to the laptop via a USB serial cable, enabling movement commands. The calligraphy kit included a traditional ink brush, a water-writing cloth for practicing Chinese calligraphy, and an ink plate.

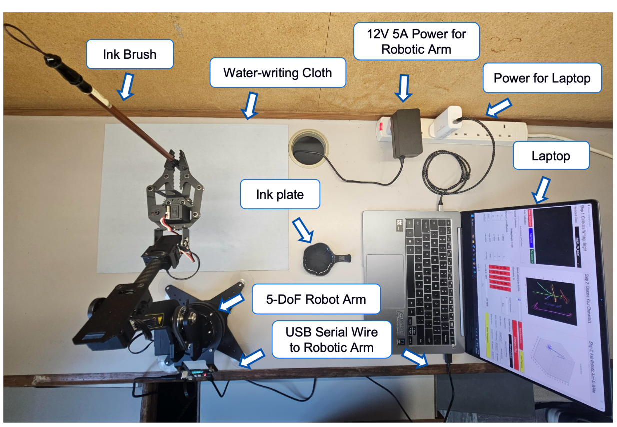


**Fig. 7:** Experiment setup of robotic calligraphy system.

The system was powered by a 12V 5A power supply for the robotic arm and a separate power adapter for the laptop. The laptop ran with a custom-designed user interface (UI) as shown in Fig. 8, displayed the generated 3D path planning trajectories and allowed the user to input commands. This setup integrated all components necessary for performing robotic Chinese calligraphy experiments in a controlled environment.

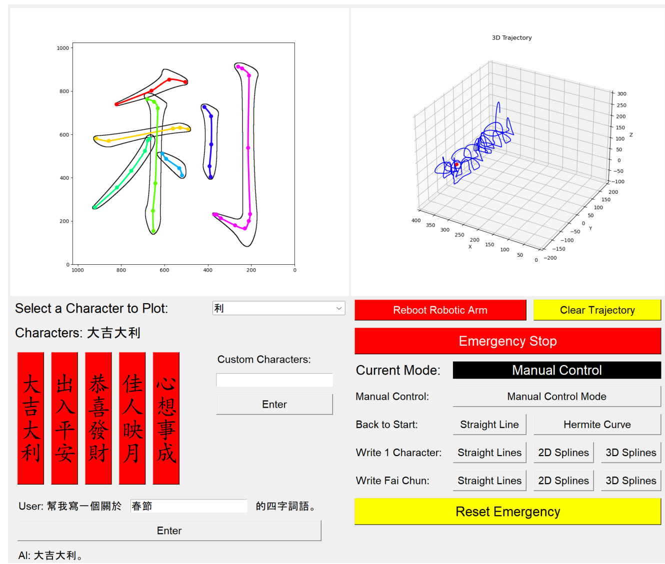


**Fig. 8:** User Interface (UI) of the robotic calligraphy system.

### B. Prompts Input and Generation

This experiment aimed to take an LLM-generated textual input, process the corresponding Chinese characters, and generate accurate control points for stroke trajectories. The example input prompt provided to the LLM and the generated output answers were listed in Table I.

**TABLE I:** Examples of input prompts to LLM and the generated output.

| | |
|---|---|
| Input: | 幫我寫一個關於春節的四字詞語。 |
| | (Write a four-character idiom related to Spring Festival.) |
| Output: | 大吉大利 |
| | (Great luck and great profit.) |
| Input: | 幫我寫一個關於清明節的四字詞語。 |
| | (Write a four-character idiom related to Qingming Festival.) |
| Output: | 春回大地 |
| | (Spring returns to the earth.) |
| Input: | 幫我寫一個關於七夕的四字詞語。 |
| | (Write a four-character idiom related to Qixi Festival.) |
| Output: | 心心相印 |
| | (Hearts resonate with each other.) |
| Input: | 幫我寫一個關於中秋節的四字詞語。 |
| | (Write a four-character idiom related to Mid-Autumn Festival.) |
| Output: | 佳人映月 |
| | (Beautiful person reflected in the moon.) |

The generated Chinese characters were then processed to create spline control points. The characters were drawn on a 1024 × 1024 canvas, which served as a virtual representation of the writing surface. Using the Make Me a Hanzi dataset, the stroke-order vector graphics of the characters were extracted, and the control points were calculated based on the method described in Section II-B. The Z-coordinates of the control points were determined by the fitting circle we generated. The generated control points were then used to construct the 3D Bézier trajectories for the robotic arm.

In this experiment, the system successfully interpreted the input prompt and generated accurate trajectories for the output Chinese phrases which are shown in Fig. 9.

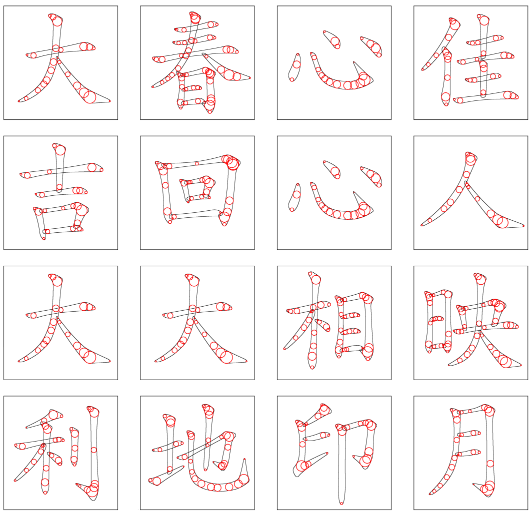


**Fig. 9:** Largest fitting circles of control points for the example output.

### C. Robotic Calligraphy

This experiment evaluated the system's ability to generate and execute calligraphy strokes based on the output phrases. The robotic arm follows 3D trajectories derived from our path planning algorithm, then converted into precise movement paths for the robotic manipulator.

The calligraphy process began with the robotic arm dipping the ink brush into the ink plate to ensure adequate ink coverage. Following this, the arm executed the planned trajectories on the water-writing cloth, replicating the strokes of the generated Chinese character. The 5-DoF robotic arm precisely controlled the brush's orientation, pressure, and speed to mimic the subtle variations of a human calligrapher's strokes.

The results shown in Fig.10 demonstrated the system's capability to produce consistent and expressive strokes, with smooth transitions between different components of the character. Each stroke exhibited balanced proportions and accurate alignment, reflecting the effectiveness of the path planning algorithm and the manipulator's dexterity. This experiment highlights the potential of robotic systems to replicate intricate artistic techniques, such as Chinese calligraphy, using advanced motion control and trajectory optimization.

## IV. CONCLUSION

This paper presented a robotic calligraphy system, combining 3D path planning algorithms with LLM to generate

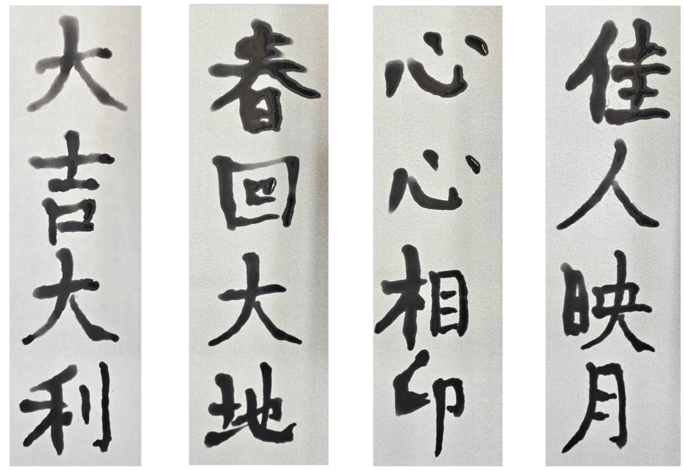


**Fig. 10:** Results of robotic calligraphy.

expressive and precise characters. The system successfully enabled a robotic manipulator to emulate the intricate strokes of Chinese calligraphy. The framework's ability to process multiple prompts and adapt to diverse characters underscores its potential for practical applications. Moreover, the results demonstrated the importance of incorporating brush dynamics, including pressure, orientation, and speed, into the trajectory planning process to replicate the artistic nuances of human calligraphy. This research demonstrates the potential of content generation with advanced robotic path planning to bridge the gap between traditional artistic practices and modern automation technologies.

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