THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY | DEPARTMENT OF ELECTRONIC & COMPUTER ENGINEERING

Computer Vision-based Path Planning for Robot Manipulator Using Bézier Curves (WKT06)

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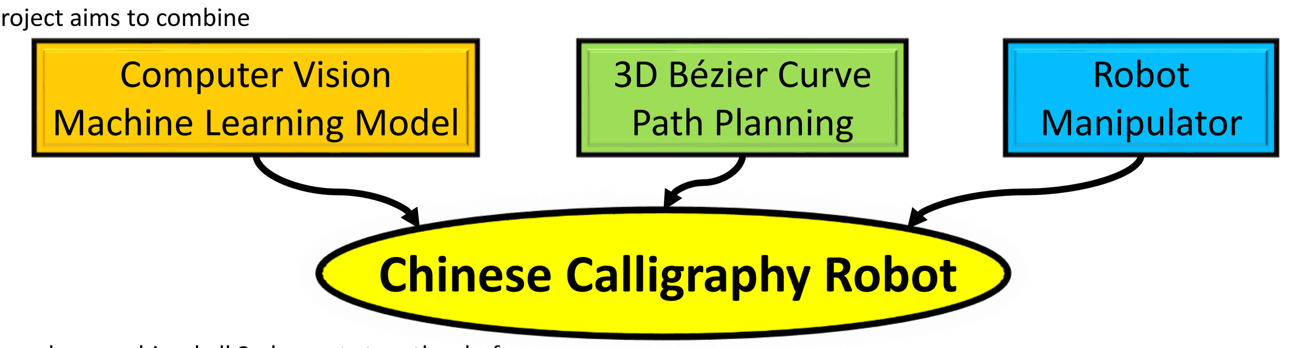
Introduction

Overview

This project aims to combine



as no one has combined all 3 elements together before.

Objectives

1. To develop and simulate a 3D Bézier curves path planning algorithm that generates smooth trajectories for the robot manipulator system.
2. To implement the Bézier curves path planning algorithm within the robot manipulator system for writing Chinese calligraphy, demonstrating the algorithm's precise and fluid movements.
3. To utilize machine learning model on computer vision system to identify whether the Chinese writing brush (毛筆) touches the paper with an accuracy of 90% or above.
4. To demonstrate the advantages of using Bézier curves in robotic path planning compared to traditional methods, focusing on improvements in smoothness, speed, and accuracy.

Why Chinese Calligraphy?

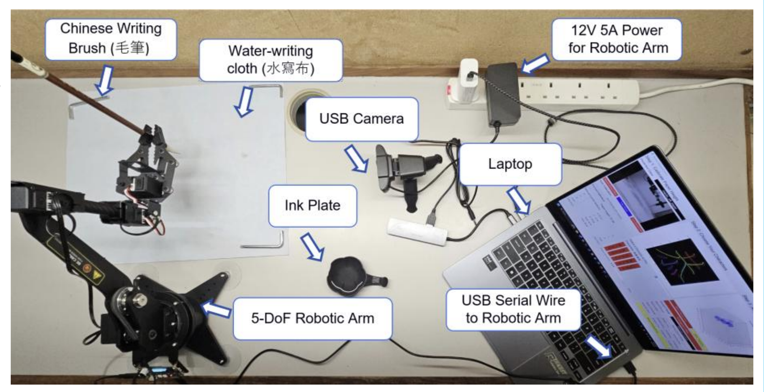
Chinese calligraphy is an ideal application for showcasing the 3D Bézier-curved-based path planning algorithm through clear trajectory visualization. The **characters represent a 2D plane**, while the **thickness of the brush strokes emphasizes the third dimension**. As the brush moves lower, the strokes become thicker, and vice versa, visualizing all three dimensions. This aspect allows for a detailed evaluation of the system's smoothness and accuracy in a higher dimension, setting it apart from other applications.

Experiment Setup

The robot manipulator system comprises several key components: a Waveshare RoArm-M1 5 DoF robotic arm, a Windows laptop, a 480p USB camera, a Chinese writing brush (毛筆) of 0.9cm diameter, a reusable water-writing cloth, and an ink plate.

The robotic arm is connected to the laptop via a USB serial wire to send JSON control commands.

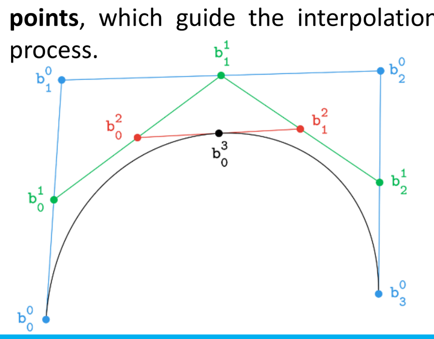
The water-writing cloth turns black when wet and white when dry, simplifying the testing process as it only requires water.



Background Knowledge

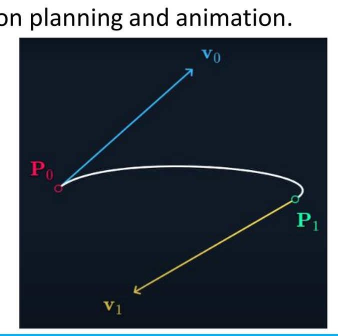
What is Bézier Curve?

A Bézier curve is a mathematical tool used in computer graphics and motion planning to create smooth, non-circular curves defined by control points. The shape of the **Bézier curve is determined by these blue control points**, which guide the interpolation process.



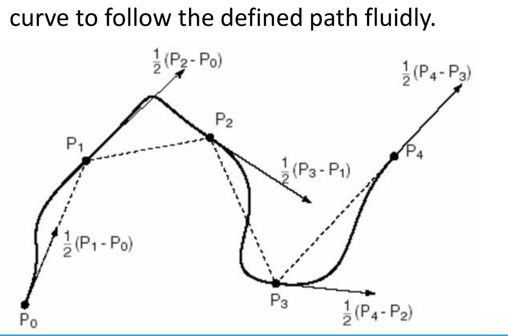
What is Hermite Curve?

A Hermite curve is a special type of Bézier curve that **defines the velocity** at the start and end points **rather than** just the control **points** along the curve. This approach allows for better control of the path's velocity, making it particularly useful for motion planning and animation.



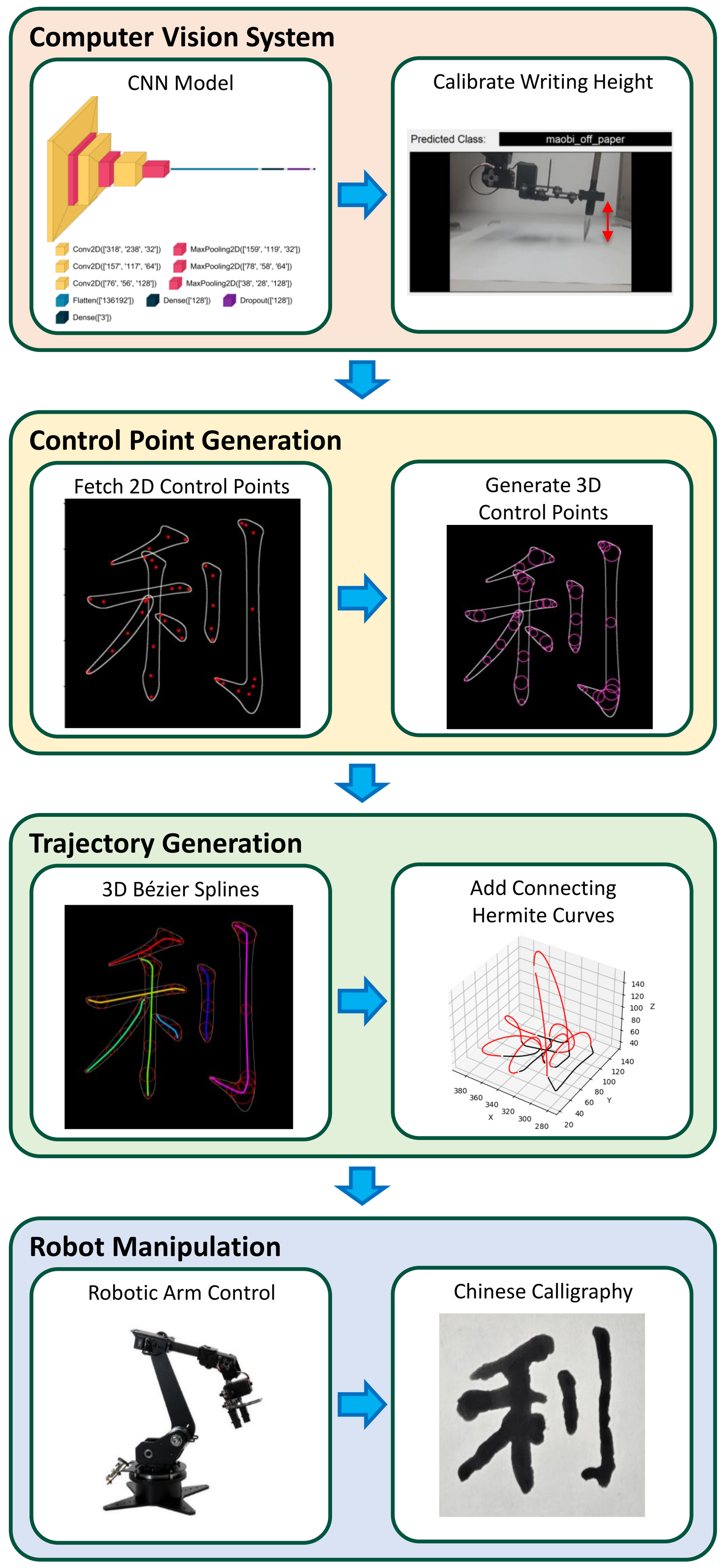
What is Catmull-Rom Spline?

A Catmull-Rom spline **connects multiple** segments of Bézier or **Hermite curves**, ensuring smooth transitions and maintaining C¹ and C² continuity. **Control velocities** for the tangents are **calculated using the positions of adjacent control points**, allowing the curve to follow the defined path fluidly.



Methodology

Workflow



CNN Object Classification Model

A Convolutional Neural Network (CNN) is used to classify images from the USB camera into 3 different categories: "maobi_on_paper", "maobi_off_paper", and "no_maobi". **The model detects** whether the Chinese writing brush (毛筆) is in contact with the paper by identifying the **bending of the brush when it touches the surface**. This capability enables the program **to calibrate the optimal height** of the gripper between "maobi_on_paper" and "maobi_off_paper", ensuring that the brush barely makes contact with the paper. This writing height avoids overly thick, blurry brush strokes when writing.

Largest Fitting Circles for 3D Coordinates

The red 2D **control points** and the white outer frame of the Chinese character are **taken from** an open-source dataset called **Make Me a Hanzi**. For each control point, we determine the largest circle that can fit within the outer frame of the brush stroke. The **radius of this circle corresponds to the thickness** of that segment of the stroke. As the writing brush moves lower, the thickness of the brush stroke increases. Therefore, we can easily generate the Z coordinates of the control points using the following formula to convert them into 3D:

$$Z_{\text{coord}} = \text{calibrated\_writing\_height} + \frac{\text{average\_radius} - \text{largest\_fitting\_circle\_radius}}{\text{scaling\_factor}}$$

Modified Catmull-Rom Spline Trajectory

The **3D control points** of the Chinese character are **connected using Hermite curves** as shown in the formula below:

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

However, Hermite curves requires control velocities V_0 and V_1. So, V_0 and V_1 are generated with the formula below that is **inspired by Catmull-Rom Spline** to ensure C¹ continuity:

$$V_i = \begin{cases} k(P_1 - P_0) & \text{if } i = 0 \\ k \cdot \min\left(|P_{i+1} - P_i|, |P_i - P_{i-1}|\right) \dfrac{P_{i+1} - P_{i-1}}{|P_{i+1} - P_{i-1}|} & \text{if } 1 \le i \le n-2 \\ k(P_{n-1} - P_{n-2}) & \text{if } i = n-1 \end{cases}$$

A **connecting Hermite curve** is added in the end of each brush stroke to **ensure smooth lifting of the brush** after writing and smooth movement towards the next stroke.

Robot Calligraphy Control

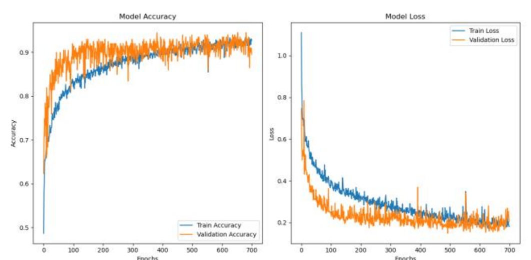
The target 3D coordinates are sent to the robotic arm in JSON format via a USB serial port to controls its movement. The robotic arm will then write with the Chinese writing brush (毛筆) on its gripper.

Results

Computer Vision System

CNN Object Classification Model Training

A total of 794 images were collected using a USB camera, supplemented by 200 random online images, resulting in a dataset of 994 images. After annotation, preprocessing, and augmentation, the dataset was expanded to **2,386 images**. The CNN model was trained on this dataset for **700 epochs**, achieving **a peak validation accuracy of 94.47%**, which exceeds the objective of 90% accuracy.



Gripper Writing Height Calibration

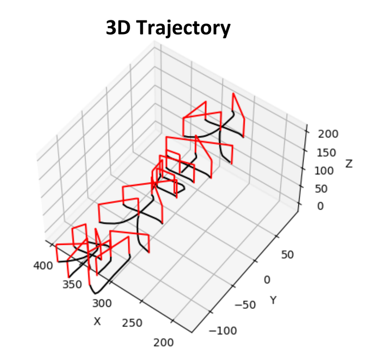
As the Chinese writing brush (毛筆) is not fixed onto the robotic arm, we need to calibrate the writing height between the gripper and the paper. It can calibrate successfully in a controlled environment but might prone to errors when there are shadows or background changes.

3D Bézier Curve Path Planning

Three different algorithms were developed to compare their performance against each other.

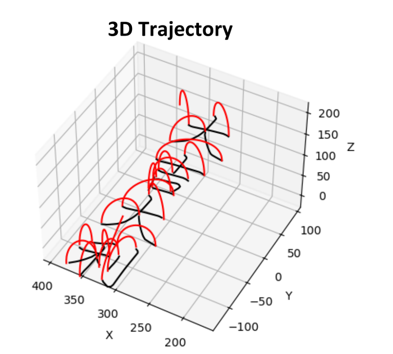
Straight-Line Algorithm

The 2D Control Points are fetched. All control points are extended to 3D with a fixed Z coordinate. All control points are **connected with straight lines**. This acts as a **benchmark algorithm** for comparison.



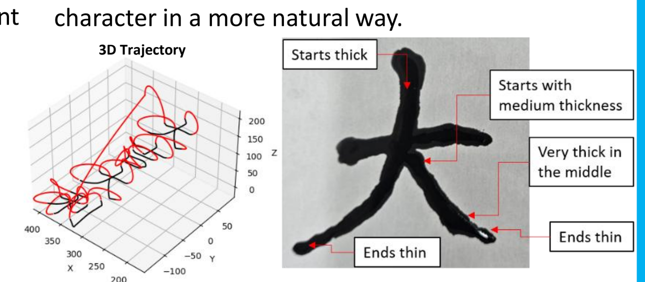
2D Spline Algorithm

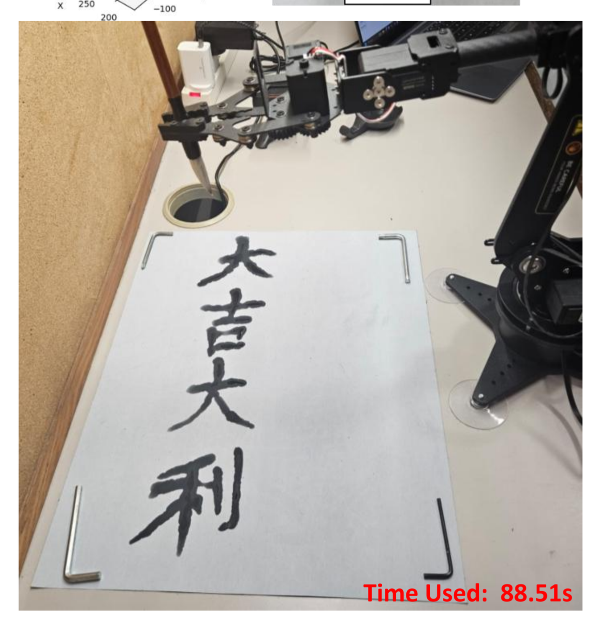
The 2D Control Points are fetched. All control points are extended to 3D with a **fixed Z coordinate**. The control points are connected into a 2D Spline. Some **simple connecting Hermite curves** are added to connect different strokes.



3D Spline Algorithm

All procedures in the workflow are implemented. As you can see from the results below, the **thickness** of a character has **changed within a brush stroke**. This shows that the robotic arm is moving in a 3D trajectory and tries to write the character in a more natural way.





Conclusion

To summarize, this project aims to combine computer vision, Bézier curve path planning, and robot manipulation into a Chinese calligraphy robot that writes Fai Chun (揮春) in Cantonese and chunlian (春聯) in Mandarin. By utilizing **Hermite curves and Catmull-Rom Splines for path planning**, the algorithm enables the robotic arm to create smooth, 3D curved paths, enhancing the quality of the strokes. The written characters illustrate the 2D trajectory, while the thickness of the brush strokes represents the third dimension of the path. The calibration of the distance between the Chinese writing brush (毛筆) and the paper, managed by a **CNN model**, **ensures** optimal stroke thickness and **consistent contact with the paper**, demonstrating the effective integration of these technologies for artistic expression.