Painting Brush Control Techniques in Chinese Painting Robot

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***Abstract* - This paper describes a Chinese painting robot (CP robot) that can be categorized as an art robot. The whole system consists of a robot arm, robot hand, Chinese brush, and system controller. In Chinese painting, the following four objects: bamboos, plum blossoms, chrysanthemums, and orchids are often used to practice painting techniques. This paper focuses on how to draw bamboos by a CP robot. When a bamboo drawing is presented, the CP robot decomposes the drawing into stems, joints, branches, and leaves. According to the drawing order information, the system controller creates the trajectory of the Chinese brush. The trajectory of the Chinese brush is considered as B-spline curves determined by the points included in the drawing order information. The trajectory and the pressure control information are sent to the CP robot to imitate painter's behavior. The experiment results show that the proposed techniques are efficient for the CP robot to perform the fundamental drawing in Chinese painting.**

Index Terms – Chinese painting robot, B-spline, painting brush trajectory control, painting brush pressure control

I. INTRODUCTION

In recent years, besides industrial robots, a variety of robots such as humanoid robots, pet robots, rehabilitation robots, human care robots, and so on [1], have been developed. From now on, the researches in robotics field will become further more vigorous and more diverse. In the very near future, robots will fill the every corner of our human community. And in every aspect of our daily life, robots will coexist and co-operate with people, behaving as intelligent and friendly partners. This paper describes a Chinese painting robot (CP robot) that can be categorized as an art robot. The Chinese painting has more than four thousand years history in which Chinese brushes, Chinese ink, a stone slab, and Chinese paper are used. The Chinese brush is similar to the brush used for watercolour painting in the West, but it has a finer tip suitable for dealing with a wide range of subjects and for producing the variations in line required by different styles. Fig.1 (a) shows three different Chinese brushes, and (d) shows the pose of holding the brush. The Chinese ink has been used in Chinese character calligraphy and Chinese painting for over two thousand years. When the ink cake is ground on the painter's stone slab with fresh water, ink of various consistencies can be prepared depending on the amount of water used. Thick ink is very deep and glossy when applied to paper or silk. Thin ink appears lively and translucent. As a result, in Chinese painting (ink-and-wash paintings) it is possible to use ink alone to create a rhythmic balance between brightness and darkness, and density and lightness, and to create an impression of the subject's texture, weight and colouring. Fig. 1(b) shows a Chinese ink cake, (c) a stone slab, and (e) grinding ink on the stone slab. Chinese painting may be done either on Chinese paper or silk. Different paper produce different results; some are rough and absorb

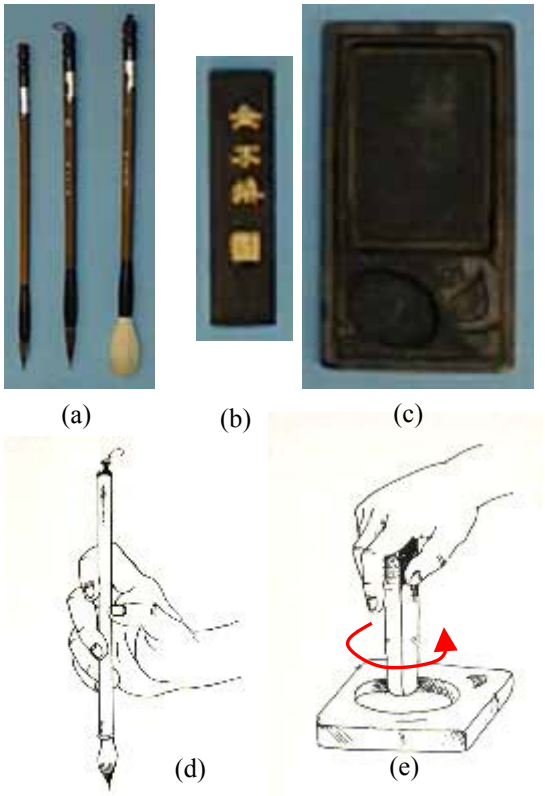

Fig. 1 (a) Painting brushes, (b) Chinese ink, (c) stone slab, (d) pose to hold the Chinese brush, and (e) grinding ink on the painter's stone slab.

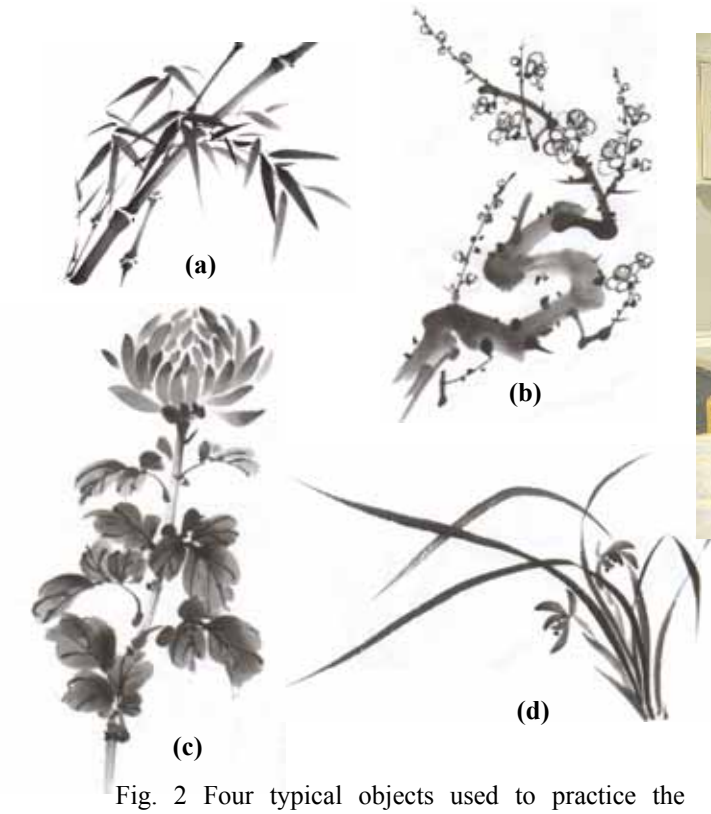

Fig. 2 Four typical objects used to practice the fundamental drawing skills in Chinese painting: (a) bamboo, (b) plum blossom, (c) chrysanthemum, and (d) orchid.

ink quickly like a sponge, others have a smooth surface which resists ink. Chinese paper is usually known as rice paper in English.

The bamboo, plum blossom, chrysanthemum, and orchid are four typical objects used to practice the fundamental drawing in Chinese painting. Fig.2 shows four drawing of these four objects, (a) bamboo, (b) plum blossom, (c) chrysanthemum, and (d) orchid. This paper focuses on how to draw bamboos by a CP robot. In the following the Chinese brush is simply called *painting brush*, and Chinese ink called *ink*, Chinese paper called *paper,* if no confusion or not for emphasis.

II. Modeling Chinese Painting As A Problem In Robot System

The Chinese painting is very difficult and complicated. It contains both physical factors and emotional factors. The physical factors are latent in the shape of the objects or the shape of the elements of the objects. The emotional factors change upon the emotion of the painter, and there are a lot of variations. Here we limit to discuss the realization of the physical factors in general case, *i.e.*, the painter is with calm emotion. The physical factors are as follows: the start and the end of every drawing, the route through which the painting brush will pass, the changes of the width and so on. However, the basic operation is to control the painting brush move on the paper and control the pressure to the

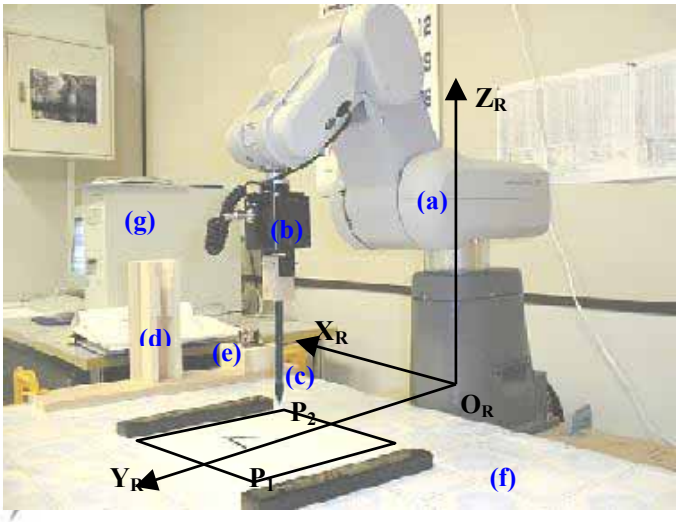

Fig 3. Prototype of CP robot.

painting brush. This can be robotized as the problem to generate the 3D trajectory of the painting brush in the robot coordinate system Σ_R. Let $P(x, y, z)$ express a point on the 3D trajectory of the painting brush. The change of z-coordinate means the change of the *pressure to the painting brush*, and x- and y-coordinates form a *2D trajectory of the painting brush in XY-plane*. If this plane is set on the painting table as shown in Fig.3, the robot hand holding a painting brush will draw the target object on the paper that is placed on the painting table, when it is controlled to move along the 2D trajectory in xy-plane. Fig.3 shows the prototype of CP robot system, which consists of (a) robot arm, (b) robot hand, (c) painting brush, (d) painting brush holder, (e) Chinese ink holder, (f) painting table, and (g) system controller. As shown in Fig. 3, Σ_R is a right-hand Cartesian coordinate system. The area for CP robot drawing is lied on XY-plane in Σ_R, and is determined by $P_1(x_R, y_R, 0)$ and $P_2(x_R+T_R, y_R-T_R, 0)$, where T_R is size of the writing area. The centre of the writing area is given by $(x_R+T_R/2, y_R-T_R/2, 0)$. The robot arm has 5 DOF (degrees of freedom). The rotation range for the 1st joint (waist) is 300°, 2nd joint (shoulder) 130°, 3rd joint (elbow) 120°, and pitch and roll of 4th joint (wrist) are ±110° and ±180°, respectively. The lengths for the offset, upper arm, and forearm are 120 mm, 250 mm, and 200 mm, separately. The force of the arm is 2kg, including the hand weight. The hand has "open" and "close" operations. The robot arm controller receives the command from the system controller. The position resolution of the hand is ±0.1 mm. The maximal velocity of the hand tip is 1500 mm/S.

In the following, we firstly briefly relate the fundamental knowledge for Chinese painting, and then describe the 2D trajectory control of the painting brush in xy-plane, and the pressure control of the painting brush along the 2D trajectory.

III. TRAJECTORY CONTROL AND PRESSURE CONTROL OF PAINTING BRUSH

A. Fundamental Knowledge in Chinese Painting

The Chinese painting contains three primitive operations as described below [5]. The first primitive operation in Chinese painting is to prepare three kinds of ink with different ink density, and then put each type of ink in different plates. These three kinds of ink are thick ink, middle-thick ink, and light ink. Besides the ink, it is also necessary to prepare fresh water, towels, and trial plate for test drawing.

Next primitive operation is to adjust the ink absorbed by the painting brush head. It contains the following steps. (i) Wash the painting brush with water, wipe the water in the painting brush head lightly, (ii) take the light ink with the head of the painting brush and adjust its amount in edge of the plate, (iii) use one third of the painting brush head to take middle-thick ink and adjust its amount on the edge of the plate, (iv) use the tip of the painting brush head to take the thick ink, (v) test the thickness of the ink on a trial plate.

The third primitive operation is the movement control of the painting brush. It contains the control of the painting brush pose, the pressure to the painting brush head, and the trajectory of the painting brush. Fig.4 (a) shows the vertical painting brush (VPB) technique, in which the painting brush is perpendicular to the paper, and the tip of the painting brush head passes the centre of the drawing. It is also called hidden tip (of the painting brush head) technique. (b) shows a drawing generated by pressing the painting brush lightly and moving to right quickly with VPB technique, and (c) shows the same drawing generated with the same technique but pressing the painting brush strongly. Fig. 4 (d) displays the slant painting brush (SPB) technique, in which the painting brush inclines and the tip of painting brush head is exposed on one side of the drawing. (e) is a drawing painted by pressing the painting brush lightly and moving to right quickly with SPB technique, and (f) is the same drawing created with the same technique but pressing the painting brush strongly. For the drawing in (b) and (c), the pressure to the painting brush head is controlled from 0 at the start point, to the strongest at the point around one fourth to one third of the entire drawing, and then is reduced to 0 gradually, in accompanying with the movement of the painting brush toward the end of the drawing. However for the drawings in (e) and (f), the pressure to the painting brush is controlled at the same level from the start to the end of the drawing. This creates different drawings.

A large amount of work in Chinese painting is to repeat the second and third primitive operations related above. But it integrates many factors such as ink thickness, ink distribution adjustment, trajectory control, pressure control, painting brush head pose control, and so on. The painter changes the combination of these factors from time to time. It needs several to tens of years for a painter to master all of these skills to reach at high level. The following mainly relates how to control robot to draw bamboo painting.

B. Robotizing of Bamboo Painting Problem

Fig.5 shows a bamboo painting. The basic drawing elements in the bamboo painting are (1) stems, (2) joints, (3) branches, and (4) leaves. The painters determine their shapes according to the reference bamboo target. They may also draw these elements according to their imagination or their drawing experience. For the robot drawing, the shapes of the elements are generated from the control points. At present, the control points are given manually on the reference picture. But they can be detected from the reference image automatically with image processing techniques.

The stem, S, can be represented by two elements, S_1 and S_2. S_1 is the stem that lies between two joints completely, and can be expressed with four control points, P_{s1}, P_{s2}, P_{s3}, and P_{s4}, S_2 is the stem that does not lie between two joints completely, and can be expressed with three control points, P_{s1}, P_{s2}, and P_{s3}, as shown in Fig. 5. Because stems are usually straight and thick, they can be drawn straight. For S_1, the pressure to the painting brush head does not change, but for S_2, the pressure is gradually reduced to 0.

The branch, B, can be represented by two elements, B_1 and B_2. B_1 is the branch that lies between two joints completely, and can be expressed with six control points, P_{b1}, …, P_{b6}, as shown in Fig. 5, B_2 represents the top-most part of the branch, and can be expressed with five control points, P_{b1}, …, P_{b5} (it can be considered that P_{b6} overlaps with P_{b56}). Because branches are usually thin and weak, it is necessary to draw them as curves.

The joint can be drawn with the same technique as branch, but it is aligned in the direction perpendicular to the stem or branch.

The leaf, L, can be represented with four control points, P_{L1}, …, P_{L4}, as shown in Fig. 5. To draw bamboo leaves beautifully, the trajectory of the painting brush head needs to be a smooth curve, and the pressure to the painting brush also needs to be a smooth curve. The following sections will discuss how to draw stems, braches, joints, and leaves. Each of them contains two factors, the pressure control and trajectory control of the painting brush.

C. Painting Brush Pressure Control

The control of the pressure to the painting brush is, in fact, to control the thickness of the drawing. This is realized by controlling *z*-coordinates of the painting

brush. After taking the ink, the painting brush is moved to its default position $P_d(x_d, y_d, z_d)$, where x_d and y_d represent the center of the drawing area.

At the default position, the distance from the tip of the painting brush head to the paper is z_d, as shown in Fig.6 (a). The z-coordinate of the painting brush is controlled in the range of z_d - d_{min} to z_d - d_{max}, where d_{min} is the distance that the painting brush is moved downward along -Z axis so that the tip of the painting brush head just touches the paper, as shown in Fig.6 (b), and d_{max} is the length of the painting brush head. Let d denote the distance that the writing brush is moved downward from its default position along -Z axis, which is called width of the stroke, and $d_{min} \le d \le d_{max}$.

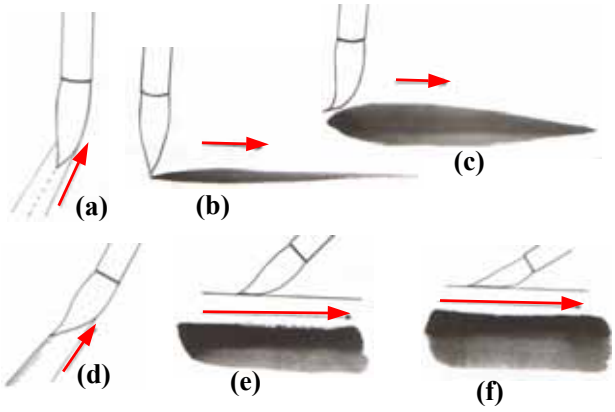

Fig. 4 Movement control of the painting brush. (a) Vertical painting brush (VPB) technique, (b) and (c) drawings by using VPB technique, (d) slant painting brush (SPB) technique, (e) and (f) drawings by using SPB technique.

Further, let us introduce $d_x = d/F_x$, and $d_y = d/F_y$ (F_x and F_y are constant ratios to d), which are used to control the painting of the start and end of the element. When the painting brush is moved from (x_d-2d_x, y_d+d_y, z_d-d_{min}) to (x_d+2d_x, y_d-d_y, z_d-1.1d), the tip of the writing brush is in the shape as shown in Fig.6 (c). Then it is moved to (x_d, y_d, z_d-d), and then it is controlled to draw the element. This operation is necessary for drawing the start of the stem as that in human calligrapher. The thickness of the drawing is controlled according to

$$z_k = z_d - (d - k\eta \frac{d - d_{\min}}{M}) \quad (1)$$

where z_k is the z-coordinate of the points on the trajectory (k = 0, 1, …, M-1), and η controls the degree of the inclination of the drawing, *i.e.*, controls the speed that the drawing gets thin or thick when the painting brush is moved across the trajectory of the current drawing.

D. Painting Brush Trajectory Control

The B-spline fitting is employed to generate the trajectory of the branch, joint, and leaf. The following, firstly, introduce B-spline fitting in general, and then explain how to uses B-spline fitting techniques for drawing branches, joints, and leaves.

For the control points P'_j (j = 1, …, 4), B-spline curve determined by these control points is calculated [2] [4]. This B-spline is considered as the 2D trajectory of the writing brush. In detail, B-spline curve is obtained according to

$$x_{i,m}(t) = \sum_{j=0}^{m} x'_i B_{i+j,m+1}(t), \quad (2.a)$$

$$y_{i,m}(t) = \sum_{j=0}^{m} y'_i B_{i+j,m+1}(t) \quad (2.b)$$

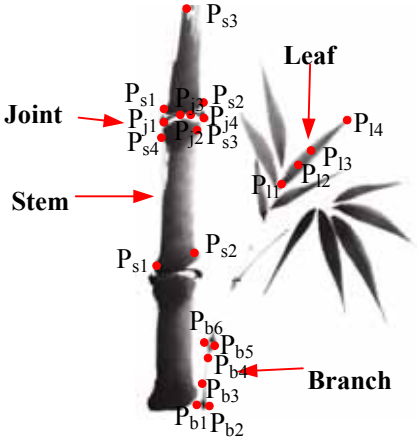

Fig. 5 Components of Bamboo painting.

and

$$B_{i,k}(t) = \frac{t - q_i}{q_{i+k-1}} B_{i,K-1}(t) + \frac{q_{i+k} - t}{q_{i+k} - q_{i-1}} B_{i+1,K-1}(t) \quad (3.a)$$

$$B_{i,1}(t) = \begin{cases} 1 & (q_i \le t < q_{i+1}) \\ 0 & (t < q_i,\ t \ge q_{i+1}) \end{cases} \quad (3.b)$$

and

$$q_0 = q_1 = \ldots = q_{m+1} = 0,$$

$$q_N = q_{N+1} = \ldots = q_{N-1+m+1} = 0, \quad (4)$$

$$q_{i+m+1} = i + m/2 \quad (i=0,1, \ldots, N\text{-}m\text{-}1) \quad (5)$$

where x'_i and y'_i are coordinates of the control points, $x_{i,m}(t)$ and $y_{i,m}(t)$ are coordinates of the points on B-spline curve, m is the degree of B-spline, and N is the number of the control points, *i.e.*, knots for B-spline. Note that the number of the points on B-spline curve is $M = N \times K + 1$, where K is the number of division between two control points. Hereafter, the point on B-spline curve (node points) is denoted by Q_j (j = 0, …, M-1).

E. Drawing Stems in Bamboo Painting Problem

The following are the details to draw S_1 and S_2.

(1) S_1 Drawing

(i) Pressure: η in Eq. (1) is set to 0.

(ii) Writing the start of S_1

Trajectory: $\Phi_1(x_1\text{-}2d_x,\ y_1\text{+}d_y,\ z_d\text{-}d_{min}) \rightarrow \Phi_2(x_1\text{+}2d_x,\ y_1\text{-}d_y,\ z_d\text{-}1.1d) \rightarrow P_{s1}(x_1, y_1, z_d\text{-}d)$.

Note that Φ_1 and Φ_2 are the auxiliary control points created from the control point P_{s1}, x_1 and y_1 are coordinates of P_{s1}, and the change of z-coordinate is to make the tip of the painting brush incline to draw with SPB technique.

(iii) Movement of the painting brush

Trajectory: $P_{1s} \rightarrow P_{2s} \rightarrow P_{3s}$

Note that P_{1s}, P_{2s}, and P_{3s} are the control points, and the width is $z_d\text{-}d$.

(iv) Writing the end of S_1

Trajectory: $\Phi_3(x_{s4}\text{-}2d_x,\ y_{s4}\text{+}d_y,\ z_d\text{-}d_{min}) \rightarrow \Phi_4(x_1\text{+}2d_x,\ y_1\text{-}d_y,\ z_d\text{-}1.1d) \rightarrow P_{s4}(x_4, y_4, z_d\text{-}d) \rightarrow P_{s3}(x_3, y_3, z_d\text{-}d)$.

Note that Φ_3 and Φ_4 are the auxiliary control points created from the control point P_{s4}, x_4 and y_4 are coordinates of P_{s4}.

(2) S_1 Drawing

(i) Pressure is controlled according to Eq. (1).

(ii) Writing the start of S_2 is the same as that in S_1 drawing.

(iii) Movement of the painting brush is the same as that in S_1 drawing.

(iv) Writing the end of S_2

Trajectory: $P_{s3}(x_3, y_3, z_d\text{-}d) \rightarrow B_5(x_5, y_5, z_d\text{-}d_{min})$.

F. Drawing Branches in Bamboo Painting Problem

The following shows the details of B_1 and B_2 drawing.

(1) B_1 Drawing

(i) Pressure is controlled according to Eq. (1).

(ii) Painting the start of B_1 is the same as that in S_1 drawing.

(iii) Movement of the painting brush:

Trajectory: $P_{b1}(x_1, y_1, z_d\text{-}d) \rightarrow Q_1 \rightarrow \ldots Q_{M\text{-}1}$

Note that $Q_1 \ldots Q_{M\text{-}1}$ are points on B-spline curve.

(iv) Painting the end of B_2

Trajectory: $\Phi_1(x_6\text{-}2d_x,\ y_6\text{+}d_y,\ z_d\text{-}d_{min}) \rightarrow \Phi_2(x_6\text{+}2d_x,\ y_6\text{-}d_y,\ z_d\text{-}1.1d) \rightarrow P_{b6}(x_6, y_6, z_d\text{-}d) \rightarrow P_{b5}(x_5, y_5, z_d\text{-}d)$.

Note that Φ_1 and Φ_2 are the auxiliary control points created from the control point P_{b6}, x_6 and y_6 are coordinates of P_{b6}.

(2) B_2 Drawing

(i) Pressure is controlled according to Eq. (1).

(ii) Painting the start of B_1 is the same as that in S_1 drawing.

(iii) Movement of the painting brush:

Trajectory: $P_{b1}(x_1, y_1, z_d\text{-}d) \rightarrow Q_1 \rightarrow \ldots Q_{M\text{-}1}$

(iv) Painting the end of B_2

Trajectory: $P_{b5}(x_5, y_5, z_d\text{-}d) \rightarrow P_{b5}(x_5, y_5, z_d\text{-}d_{min})$.

G. Drawing Joints in Bamboo Painting Problem

The joints can be drawn with the same techniques as used in drawing branches.

H. Drawing Leaves in Bamboo Painting Problem

Drawing leaf is the most difficult work. It is the most often used technique in bamboo painting. To draw a leaf as beautiful as the one shown in Fig. 7 (b), both the trajectory control and pressure control of the painting brush must be as smoothly as possible. Fig. 7 (a) shows the pressure changes along the trajectory of the painting brush. At point A, the tip of the painting brush head just touches the paper. At B, the painting brush is pressed strongly to the drawing direction. At C, the pressure is reduced gradually. And at D, the tip of the painting brush head becomes to leave the paper.

Drawing leaf needs two smooth curves. The first one is the trajectory of the painting brush which is a B-spline determined by the control points, as shown in Eqs. (2) to (5). Four points, Q_0, Q_K, Q_T, and $Q_{M\text{-}1}$ from this trajectory, are used as the control points to create B-spline to control the pressure of the painting brush. Q_0 and $Q_{M\text{-}1}$ are the start and end point of the trajectory of the painting brush, respectively. Q_K is the first point

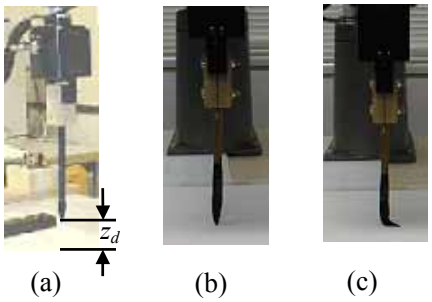

Fig 6. (a) Default position of the painting brush; (b) The position that the painting brush just touches the paper; (c) The shape of the tip of the painting brush at width d.

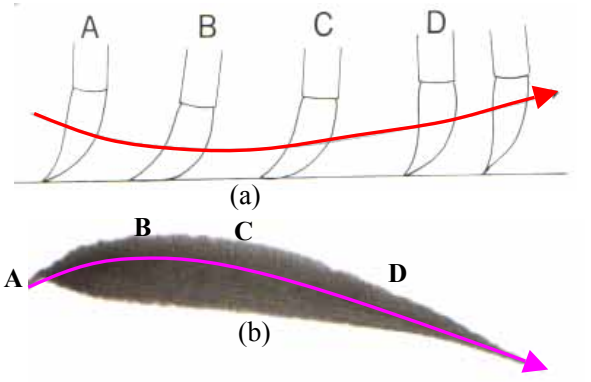

Fig 7. (a) Painting brush pressure control for drawing a leaf, (b) trajectory control for drawing a leaf.

which satisfy

$$\left\|Q_0 - Q_K\right\| \geq \left\|Q_0 - Q_{M-1}\right\| / 4 \quad (6)$$

when searching the trajectory of the painting brush from Q_0 to Q_{M-1}. And Q_T is the first point which satisfy

$$\left\|Q_0 - Q_T\right\| \geq \left\|Q_0 - Q_{M-1}\right\| / 3 \quad (7)$$

when searching the trajectory of the painting brush from Q_0 to Q_{M-1}. The z-coordinate at Q_0, Q_K, Q_T, and Q_{M-1} is z_d-d_{min}, z_d-d_{max}, z_d-d_{max}, and z_d-d_{min}, respectively. It is worth to note that y- and z-coordinates at Q_0, Q_K, Q_T, and Q_{M-1} are used to generate the pressure of the painting brush along the trajectory of the painting brush, according to Eqs. (2) to (5).

The CP robot combines above techniques and draws the bamboo as a human painter does. Next section shows the experiment results.

IV. Experiment Results

The whole system is implemented on Windows platform, and the programming language is C++. The size of the painting area T_R is set at 200 mm. The velocity of the robot hand is set at 144 mm/S. The number of division, K, between two control points is set at 3. The values of d_{min} and d_{max} are dependent on the length of the painting brush head. For the present writing brush in use, they are 8 mm and 17 mm respectively. The width of the stroke, d, is set at 10 mm. Note that d is the displacement of the robot hand along –Z axis from its default position. The ratios to the width of the stroke, *i.e.*, F_x and F_y, are set at 5. The value of the degree of inclination, η, is 1.0. Two bamboo paintings drawn by the CP robot are shown in Fig.8. (a) and (c) are input images, (b) and (d) are robot drawing of image (a) and (b), respectively.

IV. Conclusions and Future Works

This paper described the painting brush control techniques in Chinese painting. Generally, painting is a very difficult and complicated task that contains both emotional factors of the painter and physical factors of the target objects. This work tries to robotize the painting problem based on the physical factors. It focuses on the bamboo drawing. The bamboo is one of four typical objects used for practicing the fundamental drawing skills in Chinese painting. The bamboo painting contains four basic drawing elements, stems, joints, branches, and leaves. B-spline is used to generate the trajectories of the branches, joints, and leaves. It is also used to control the pressure to the painting brush head. The experiments results show that the painting problem can be robotized and the CP robot can draw better than beginners. At present, the position of stems, joints, branches, and leaves in the input images, and the positions of their control points are given manually. They can be detected automatically

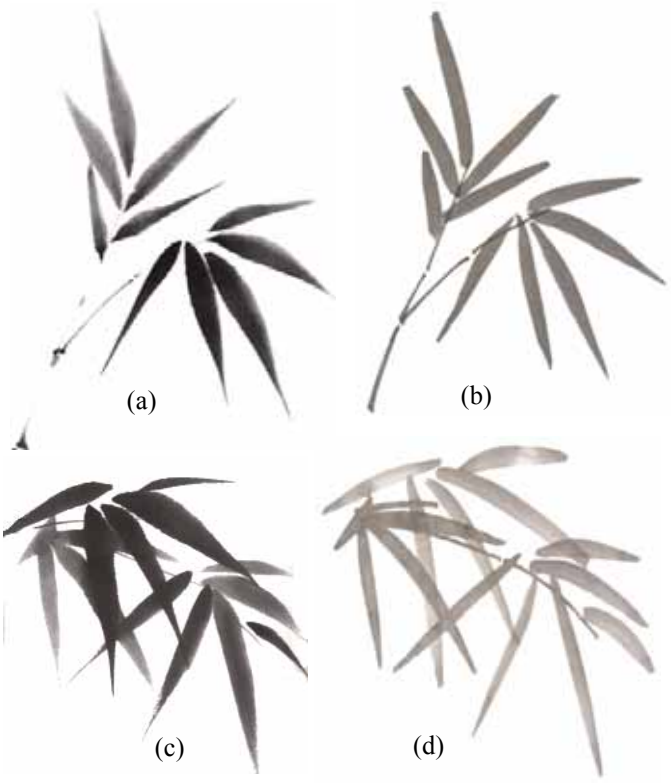

Fig 8. (a) and (c) Input images, (b) and (d) robot drawing of image (a) and (b), respectively.

from the input image by using the predetermined models of these elements. In human painting, the pressure to the writing brush and the speed of it changes from time to time according to the visual feedback. And the human artist contains many emotional factors in his/her drawing. Implementation of emotional factors and investigation of the temporal effects of the speed of the robot movement are our future works. It is also necessary to robotize the plum blossom painting problem, chrysanthemum painting problem, and orchid painting problem. These are all left to do in the future.

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