A Force-Controlled Portrait Drawing Robot

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***Abstract*— There has been a lot of research in recreational uses of robots. A robot drawing the portrait of a human face is one such famous task. This makes the robot behavior more human-like and entertaining. There have been several demonstrations of portrait drawing robots in past few years. But the existing techniques can draw only on pre-calibrated and flat surfaces. This paper demonstrates a robot equipped with force sensing capability that can draw portraits on a non-calibrated, arbitrarily shaped surface. The robot is able to draw on a non-calibrated surface by orienting its drawing pen normal to the drawing surface, the pen's-orientation being computed from the forces being sensed. In this way, the robot is also able to draw portraits on arbitrarily shaped surfaces without knowing the surface geometry. This avoids the need for calibration of robot with respect to the drawing surface. A number of portraits were drawn successfully on a flat surface without calibration. Also a map outline was drawn on a spherical globe to demonstrate the ability of robot to draw on an arbitrarily shaped surface.**

Keywords*— Edge Detection, Indirect Hybrid Position/Force Control, Force-Controlled Contour Tracing

I. INTRODUCTION

There has been extensive research to make robots behave in human-like fashion. One such task is to get a human portrait drawn by a robot. This makes robots more interactive with humans and serves recreational purpose too. References [1], [2], [3] and [4] demonstrate nice examples of a portrait drawing robot. But all current portrait drawing systems can draw only over a flat pre-calibrated surface. The portrait drawing by a robot involves two major phases. The first phase captures an image of a human face and performs image processing to obtain important features to be drawn. The features to be drawn are transferred to a robotic arm in terms of 3D coordinates which are drawn or traced by the robot on the drawing surface in the second phase. The features' coordinates are obtained in the image or camera plane. If the drawing surface is a flat two-dimensional plane, it is required to calibrate that surface with respect to the camera plane and the robot's coordinate system so that the features' coordinates can be drawn over that surface. All current portrait-drawing robots require this pre-calibration step before the robot can start drawing. If the drawing board or surface is moved or disturbed, again a fresh calibration is required. Moreover, the drawing cannot be done over arbitrarily shaped surfaces or the surfaces whose calibration is difficult to be performed. Thus available techniques can work only for flat pre-calibrated surfaces. To address this problem, the robot can be equipped with force sensing capability. References [5] and [6] deploy force sensing for robotic drawing, but only for maintaining a proper contact of drawing pen with a flat pre-calibrated drawing surface. If the full potential of force sensing is exploited, which is done in this paper, the need for calibration is avoided as well as the robot can draw over arbitrarily shaped surfaces. Section II of the paper describes the experimental setup used. Section III explains the first phase i.e. the image processing part used for portrait drawing. Section IV explains the force-controlled robot motion that enables drawing over a non-calibrated arbitrarily shaped surface. The paper is finally concluded in Section V.

II. EXPERIMENTAL SETUP

To capture the image of a human face, WolfVision Eye-12 camera with 1280 x 960 resolution was used. KUKA KR 6 ARC robot was used to draw the portraits. The robot was equipped with an ATI 6-axis Force/Torque sensor, at its wrist, required for force–controlled drawing. Proper illumination conditions must be present to attain a good quality picture and a uniform background was preferred behind the person, whose portrait needs to be drawn, so that the significant features of face can be unambiguously extracted. The complete setup is shown in Fig. 2.1.

III. IMAGE PROCESSING

This phase involves processing of the captured image so that important features of face can be extracted and finally delivered to the robot for getting drawn on a surface. First, some pre-processing of the image is required. The processed image is used for edge detection. The edges in an image will give best features to be drawn as a portrait. Finally some

Figure 2.1: Force-Controlled Robotic Drawing Setup

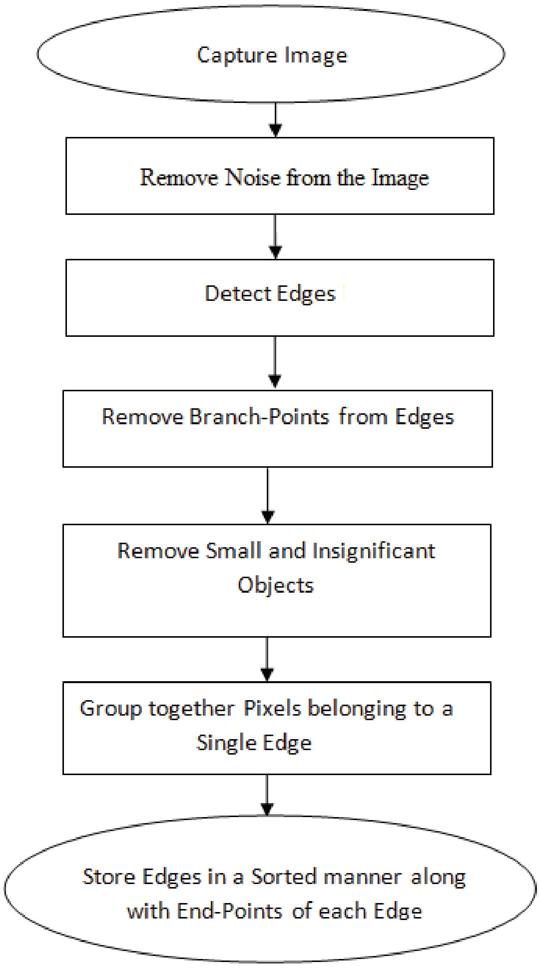

Figure 3.1: Flowchart for Image Processing part

post-processing is required before the features are sent to the robot for drawing. All these steps are explained in the following subsections and are shown in Fig. 3.1.

A. Pre-Processing

The image captured by Wolf Vision EYE-12 camera is an RGB colour image. The image is then converted into gray scale image which is a prerequisite for edge detection. Then the image is sent for noise removal using Gaussian 5x5 filter as shown in (1).

$$B = \frac{1}{159}\begin{bmatrix} 2 & 4 & 5 & 4 & 2 \\ 4 & 9 & 12 & 9 & 4 \\ 5 & 12 & 15 & 12 & 5 \\ 4 & 9 & 12 & 9 & 4 \\ 2 & 4 & 5 & 4 & 2 \end{bmatrix} * A \qquad (1)$$

Where, B is the filtered image and A is the image input.

After filtering, the image is sent for edge detection as explained in next subsection.

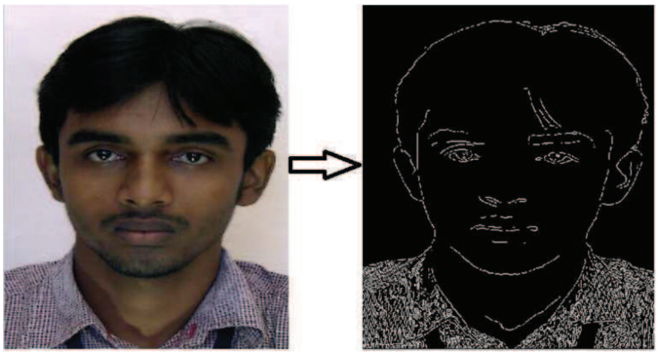

Figure 3.2: Output of Canny's Edge Detector

B. Edge Detection

Whenever we draw a portrait of a human face, we try to find out the important edges or features that need to be drawn. The edge detection is a famous image processing technique and there are several edge detection algorithms available. We tried with various algorithms and found that Canny edge detection algorithm [7] was best suited for our task. The Canny edge detector finds out real and localized edges without being affected by noise. The output of edge detection step over an image is shown in Fig. 3.2.

C. Post-Processing

After the important features of an image are detected in terms of edges, some processing needs to be performed before these edges can be transferred to the robot for drawing. This post-processing is explained in the following subsections.

- Branch Removal: There should be no branches in an edge so that the robot can draw that edge in a single go from one end of the edge to the other. For this, the branch-points were first detected. The pixel at such a point was then removed i.e. it was made 0 from 1 so that the branches were simply separated from each other as shown in Fig. 3.3.
- Removal of Small Objects: The edges which had too small number of pixels or the area covered was very small, were removed from the final output so that the noisy and unnecessary features are not drawn.

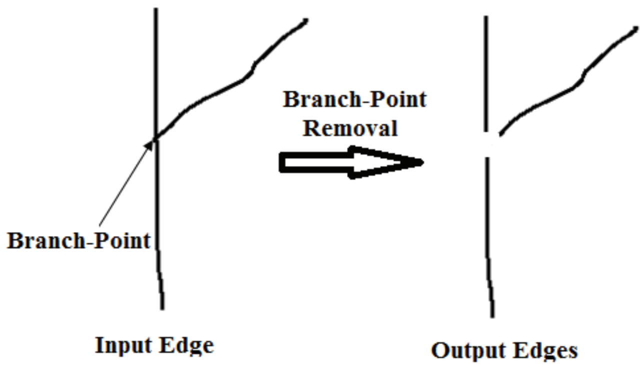

Figure 3.3: Removal of Branch-Points

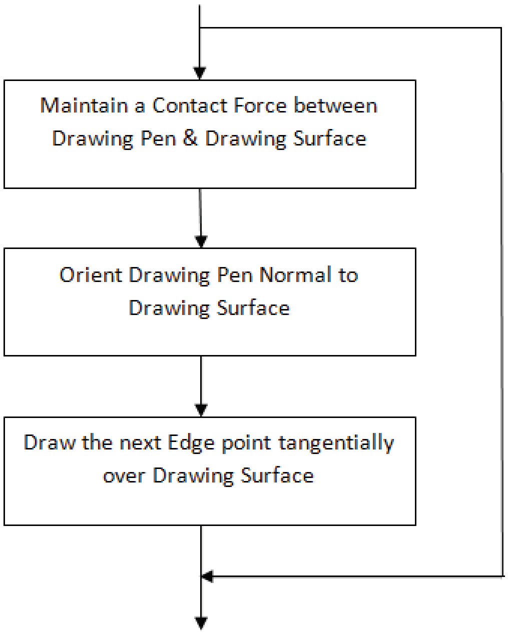

Figure 4.1:Flowchart for Force-Controlled Drawing

- Differentiation of Edges: The edges extracted by Canny's algorithm are in the form of binary pixels. What we have is a binary image in which all the pixels are set to 1 where an edge exists and the remaining are set to 0. From this image, pixels belonging to a single edge need to be grouped together so that we have a collection of edges rather than a collection of pixels. For this purpose we used 8 connectivity of the pixels and 8 connected neighbours were grouped together into a single edge. After this step, we have a set of edges that need to be drawn by the robot.
- End-Point detection: The end points of each of the edges were detected so that robot can draw that edge from start point to end point. Circular or cyclic edges in an image have no end points. For such edges, we arbitrarily removed one pixel to break the cycle, and then detected end-points of the broken cycle.
- Storage of Edges: The edges obtained were finally stored in a sorted manner from the longest edge to the shortest one so that the robot draws the most important features first moving towards the smaller ones.

IV. Force-Controlled Robot Motion

After the image processing phase is over, the stored edges are transferred to the robot so that it can draw them over a surface. We first used a flat whiteboard for portrait drawing. The edges are stored in terms of two-dimensional coordinates in the image-plane. The robot which is holding a whiteboard marker pen in its gripper needs to trace these coordinates on the whiteboard so as to draw an edge. To map these image coordinates onto the whiteboard plane, the position and orientation of that board's plane should be known a priori. This is called as calibration step. We remove the need for calibration by use of force sensing. The robot is mounted with a 6-axis Force/Torque sensor at its wrist. To draw an edge on the whiteboard plane with roughly known board's position and orientation, we can use an unknown contour-tracing approach as given in [8] and [9]. But these approaches can draw in two dimensional world only. We used three-dimensional force controlled contour tracing approach so that we could draw over arbitrarily shaped surfaces. First the drawing pen needs to be oriented normal to the drawing surface, and then it can be moved tangentially over the surface so as to draw some edge. The flowchart for Force-Controlled drawing is shown in Fig.4.1. For whiteboard plane, the pen needs to be oriented once and the same orientation would work for the complete portrait since the normal does not change over a plane whereas continuous orientation corrections are needed while we draw an edge over an arbitrarily shaped unknown surface. The correct orientation of the pen can be computed from the forces being experienced as explained below (neglecting friction).

For our experiments, we kept the drawing pen aligned with z-axis of the Force/Torque sensor (see Fig. 4.2). Now, if the pen is not in the normal orientation with the drawing surface, we will get a net contact force normal to the surface as shown in Fig. 4.2. So, if we can align the z axis of force/torque sensor with the net force vector (to avoid the gravitational force components, we have used gravity compensation as given in [10]), the drawing pen will become normal to the surface. This can be done as given in [11] and explained under.

Suppose our drawing pen is aligned with z-axis of the force/torque sensor and the net force unit vector $\vec{u}$ has components (a, b, c) where,

$$a = \frac{F_x}{\sqrt{F_x^2 + F_y^2 + F_z^2}},$$

$$b = \frac{F_y}{\sqrt{F_x^2 + F_y^2 + F_z^2}},$$

$$c = \frac{F_z}{\sqrt{F_x^2 + F_y^2 + F_z^2}}$$

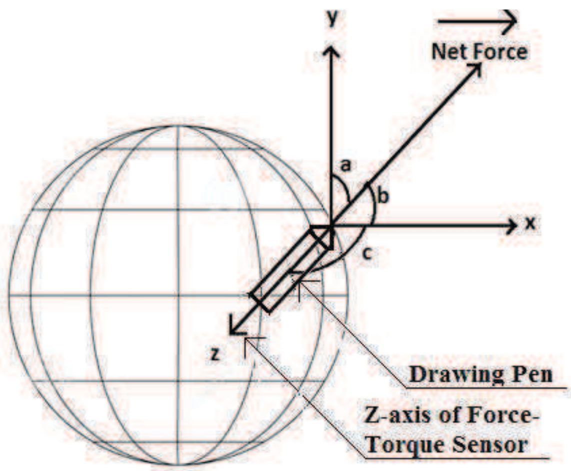

Figure 4.2: Calculating Drawing Pen's orientation from Forces Sensed

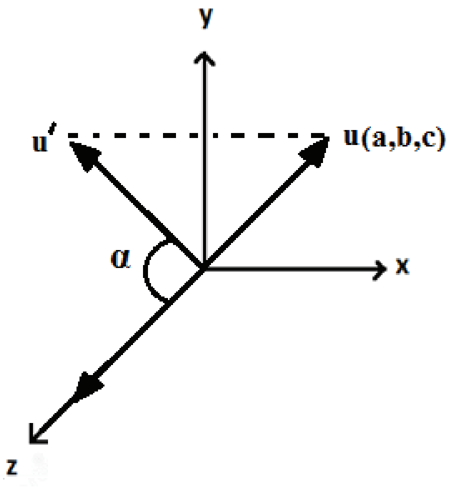

Figure 4.3: First step in aligning Drawing Pen with Net Force Vector

Where,

$$F_x = Force\ in\ X,$$

$$F_y = Force\ in\ Y,$$

$$F_z = Force\ in\ Z,$$

Now, if we want to align $\vec{u}$ with z-axis, we need to first rotate it about x-axis by angle α (see Fig. 4.3). The rotation matrix R_x for this transformation is given by:

$$R_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c/d & -b/d & 0 \\ 0 & b/d & c/d & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Where,

$$d = \sqrt{b^2 + c^2}$$

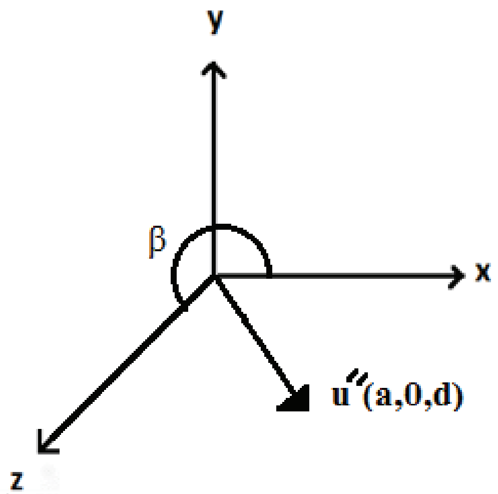

Figure 4.4: Second step in aligning Drawing Pen with Net Force Vector

Now, the $\overrightarrow{u''}$ obtained needs to be rotated about y axis by angle β as shown in Fig. 4.4. The rotation matrix R_y for this transformation is given by:

$$R_y = \begin{bmatrix} d & 0 & -a & 0 \\ 0 & 1 & 0 & 0 \\ a & 0 & d & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

These transformations will align the net force vector with the drawing pen. In order to align the drawing pen with the net force vector, the above transformations were performed in the reverse order. Also, using a single set of force values, the complete alignment was not performed; rather incremental orientation corrections were made using fully active sensing as described in [8]. Finally, when the pen is aligned with the net force vector, there is only the force component in z-axis and the other force components are negligible in magnitude.

This pen alignment needs to be done only once when we are drawing a portrait on a flat surface like a whiteboard whereas the orientational corrections are continuous if we draw on an arbitrarily shaped unknown contour which is not flat.

After the pen is oriented properly, it can be moved either tangentially or using prediction (as given in [8]) over the drawing surface.

Several human portraits were made on a whiteboard using this technique as shown in Fig. 4.5. The total time taken to draw a portrait was around 15 minutes.

We also tried to draw Indian map outline over a spherical globe to demonstrate the ability of this technique to draw over an arbitrarily shaped unknown and a non-flat surface (see Fig. 4.6). The flat image plane two-dimensional coordinates were properly mapped onto the spherical surface as if the two-dimensional image sticker was pasted over the spherical surface.

The full utilization of force-sensing provided us with the following benefits:

1. The whiteboard need not be calibrated or its position need not be accurately taught to the robot before the portrait can be drawn, hence the robot can draw portraits even if the board's position or orientation are disturbed during the drawing.

2. The drawing pen always maintains a constant drawing force with the drawing surface avoiding either a too hard or light contact with it.

3. The portraits can be drawn perfectly even if the drawing board is not perfectly flat, since the force control will always maintain a touch with the drawing surface.

4. The drawing can be done on any kind of surface with any shape or geometry which need not be known to the robot a priori. Therefore we can draw over globes, pots, or any other object.

V. Conclusion

A portrait drawing robot is very enjoyable recreational use of robotics and increases human-robot interaction. We put upon a KUKA industrial robotic arm to this human friendly artistic

Figure 4.5: Collage of Portraits drawn by the Robot

application. Although there are several such robots which can draw human portraits, this paper equips the portrait drawing robot with the ability to sense contact forces. This enables the robot to draw over a non-calibrated flat surface

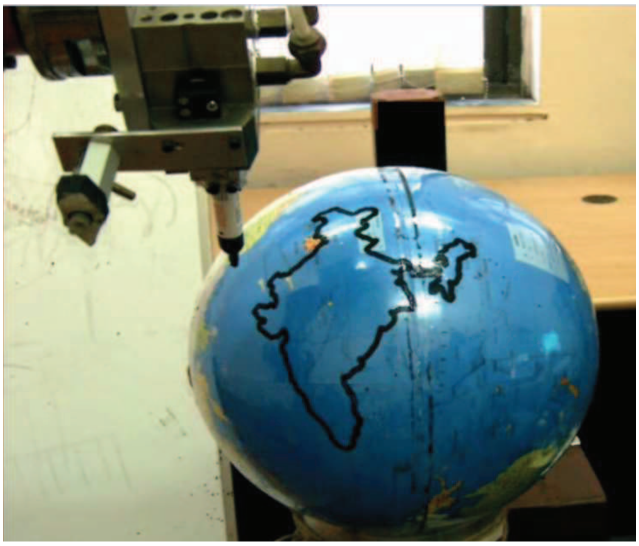

Figure 4.6: Drawing on a Spherical Surface

as well as other surfaces of any shape. The calibration is a time-consuming task and the same calibration does not work even if the drawing board is slightly disturbed. Moreover it is quite difficult to calibrate arbitrarily shaped surfaces which do not have a perfect constant geometry. The force-controlled robot caters to all these problems. It can draw without any calibration and hence it can easily draw if the drawing board is disturbed in position or orientation even in between drawing. Also it can draw over any surface like spheres, cones, flower pots or any arbitrary shape. Humans also maintain a constant force while drawing portraits and hence the robot should be equipped with force sensing, as suggested in this paper, so that it always maintains a smooth and continuous contact with the drawing surface.

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