Haptic robot and human psychophysical studies: A complementary framework to decode haptic perception

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Abstract:
In psychophysical experiments, humans have been shown to characterize unknown objects by adopting stereotypical exploratory strategies. For example, humans are sensitive to subtle surface features and curvatures by actively tracing their fingers on contact surfaces, called contour-following. By examining the signals generated by a biomimetic tactile sensor during similar exploratory movements made by a robot, we developed hypotheses about how these signals could be used simultaneously to modulate the exploratory movement and to characterize the object. The predictions of these hypotheses are tested by psychophysical measurements of the exploratory movements and capabilities of human subjects, which can then be compared to those of haptic robots using algorithmic strategies based on the same hypotheses.

Introduction:
Human haptic sensing is good at extracting precise spatial information about an object by making a highly stereotypical exploratory movement called contour following, in which hands maintain contact with the contour of the object, apply a smooth and nonrepetitive movement within a segment of object contour, and stop and shift direction when a contour segment ends [1]. Most attempts to extract contours using robots have tediously created clouds of contact points in 3D space; Allen et al. used force feedback in the arm to trace contoured surfaces [2].

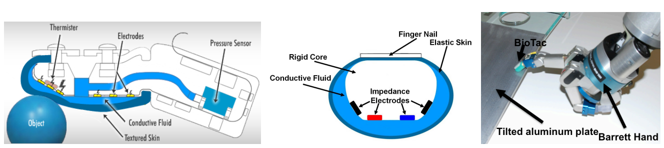

Figure 1: left: Schematic diagram of the BioTac® biomimetic tactile sensor; middle: a cross sectional view of BioTac®; right: The BioTace is controlled to slide on a tiled aluminum plate.

We have developed a haptically enabled robot with Barrett arm/hand system whose three fingers have been equipped with novel biomimetic tactile sensors, call BioTacs®. Each BioTac (Fig. 1 left and Fig. 1 middle) consists of a rigid core housing an array of electrodes surrounded by an elastic skin that is inflated with an incompressible and conductive liquid. When the skin contacts an object, this liquid is displaced, resulting in distributed impedance changes in the electrode array on the surface of the rigid core. The impedance of each electrode tends to be dominated by the thickness of the liquid between the electrode and the immediately overlying skin.

Similar to the apical tuft of the human distal phalanx, the core of the BioTac has a flat portion that tends to be oriented parallel to surfaces to be explored. It is equipped with four identical electrodes that should generate the same impedance values as contact force increases normal to this plane (Fig. 2 left) [3]. Even slight rotations from parallel alignment with a contacting surface produce large asymmetries in impedance, which can be used to achieve very fine control of the orientation of the fingertip. When the BioTac is sliding tangentially along such a surface, however, friction force between the elastic skin of the BioTac and the contact surface causes asymmetric deformations of the skin, resulting in increased impedance of the electrode toward the leading edge compared to the electrode near the trailing edge of the sliding motion. We hypothesized that by adjusting the orientation of the fingertip that humans and robots could compensate this skin distortion so that they could still use this symmetry to control orientation precisely. The question then arises as to how humans and robots might disambiguate the effects of the exploratory movement from the coefficient of friction and the orientation of the surface of the objects being explored (Fig. 2 right).

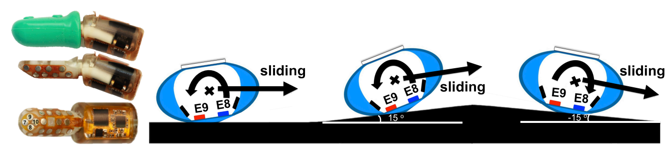

Figure 2: left: Flat portion of the core has two pair electrodes: horizontal pair electrodes E8 and E9, longitudinal pair electrodes E7 and E10; right: The asymmetric skin deformations caused by friction can be compensated by adjusting the orientation of the BioTac on tilted surfaces with tilt angle of 0 degree (flat), 15 degree, and -15 degrees, respectively

Method:
A. Robotic experimental setup
The haptic robot was controlled to slide the fingertip of the BioTac along the tilted (-20° to 20° in steps of 5°) surfaces (polished aluminum lubricated with dry talcum powder) with linear velocity 3cm/s, angular velocity 0.06cm, and normal contact force 1.5N (Fig. 1 right). Normal and tangential force were extracted from the complete set of electrode impedances as described in [3]. The asymmetric deformations detected by E8 and E9 (the electrodes near the leading and trailing edges of the sliding motion, respectively) were used to control the orientation of the BioTac so as to equalize the measured impedances.

B. Psychophysical experimental setup
An acrylic block (1" x 6" x 6") was manufactured into a contoured surface with three flat segments, a 20º incline, and a -30º incline, shown in Fig. 3 upper left, and Fig. 3 bottom. The surface was covered with three different textures, including smooth rubber sheet, porous cloth, and smooth

graphite sheet, which have coefficients of friction around 1, 0.8, and 0.5, respectively. In each trial, blindfolded subjects performed contour following exploratory movement along one of the three textures on the contour surface with their index finger. Horizontal position and roll angle of their index finger were recorded by a magnetic motion tracker taped on the back of the middle phalanx (in Fig. 3 upper left). The acrylic plate was mounted on a 6-DOF force plate, so that the three-dimensional forces were also recorded during the experiment. After subjects became confident with the shape of the surface, the blindfold was taken off, and they were asked to draw the shape of the contours to scale on a piece of paper, shown in Fig. 3 upper right.

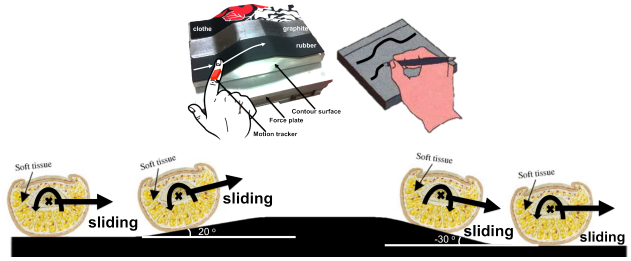

Figure 3: upper left: Experimental setup of the psychophysical contour following experiment; upper right: Drawing of the schematic picture of the contour shape; Bottom: Cross section view of the fingertip sliding on the contour surface with tilt angles of 0 degree (flat), 20 degree, and -30 degrees, respectively.

Results:

A. Haptic robot testing

When the orientation of the BioTac was continuously adjusted while sliding the BioTac on contact surfaces, the impedances could be kept essentially equal regardless of the tilt of the plate or the frictional force. Fig. 4 left illustrates the performance of the servo-controller for an aluminum plate tilted +15° from the horizontal plane. This method was successfully implemented to compensate skin distortion on surfaces with tilted angles from -20° to 20° in steps of 5°. As shown in Fig. 4 right, the line with slope equal to 1 indicates that the rotations on the robot are exactly equal to the tilted angles of the plate. The blue dots are the actual rotation on the robot corresponding to the tilted angles of the plate. The discrepancies between the actual rotations and tilted angles of the plate reflect the compensation for the asymmetrical skin deformations resulting from frictional force.

B. Human subject testing

Rotations of subjects' index finger to the opposite direction of rotations caused by friction force suggest that humans may adopt our hypothesized strategies to mitigate the asymmetrical deformations of the skin. Typical examples are shown with the tilted arrows and corresponding shaded boxes (such as 3-4s and 5-6.5s) in Fig. 5 top. The rotations of subjects' index finger on -30º, 0º, and +20º surfaces are measured and plotted against the tilted angles of the contour surface in Fig. 5 bottom. The discrepancies between blue dots and slope line are consistent with this hypothesis. Because the chosen posture of subjects' hand in this study almost reached the limitation of their wrist pronation, they failed to rotate more than the 20º incline.

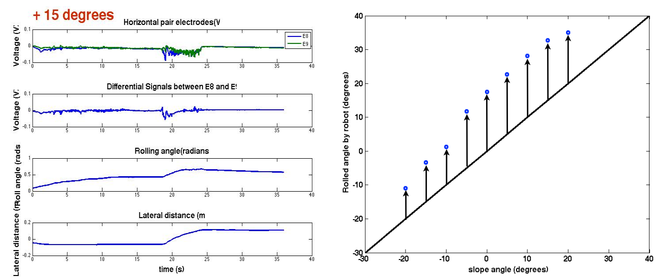

Figure 4: left: Typical behaviors obtained from sliding on 15° tilted surface; right: Orientation control on the haptic robot compensated skin distortion on surfaces with tilted angles from -20° to 20° in steps of 5°

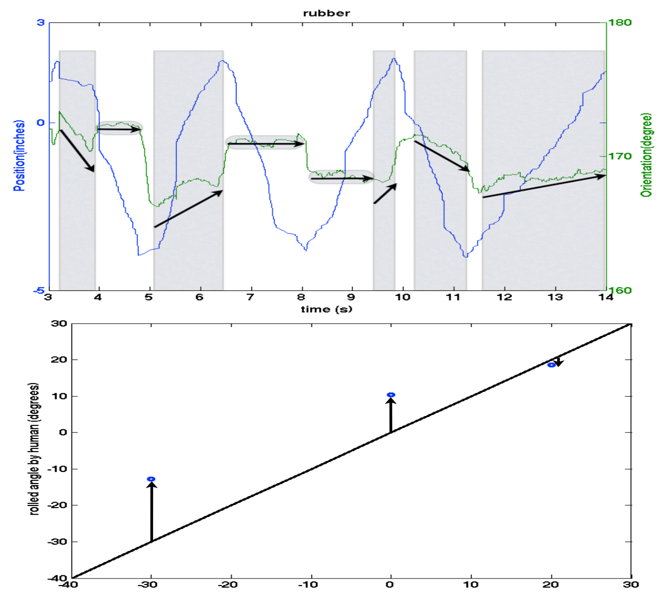

Figure 5: a. Typical behaviors of the human contour following is shown with the position (blue) and orientation (green) of the index finger; b. the rotations of subjects' index finger on -30°, 0°, and +20° surfaces.

Discussion:

In the pilot psychophysical study, preliminary results showed that all three subjects rotate their index finger against friction force while sliding their fingers along contour surfaces with various orientations and homogeneous textures. We are designing a systematic human test to study human strategies to disambiguate orientations and coefficients of friction by including contour surfaces with various orientations and inhomogeneous texture. Then we will design algorithms for exploration of the same contour surfaces by the haptic robot and compare its performance to that recorded from human test.

References:

[1] S. J. Lederman, and R. L. Klatzky, "Hand movements: A window into haptic object recognition," *Cognitive Psychology*, 19, 342–368, 1987.

[2] Allen, Peter K., and Paul Michelman. "Acquisition and interpretation of 3-D sensor data from touch." *Interpretation of 3D Scenes, 1989. Proceedings., Workshop on.* IEEE, 1989.

[3] Z. Su, J. A. Fishel, T. Yamamoto and G. E. Loeb. Use of tactile feedback to control exploratory movements to characterize object compliance. *Frontiers in Neurorobotics*, 6(7) 1-9. 2012.