Haptic shape cues, invariants, priors and interface design

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Introduction

Perception is often discussed by reference to cues as separate sources of information for the perceiver [1]. With vision and audition, the list of such known cues is quite extensive [2, 3]. For example, visual depth perception in humans is thought to rely on monocular, oculomotor and binocular cues. Monocular depth cues include motion parallax, color contrast, perspective, relative size, relative height, focus, occlusion, shading, texture gradient, shadows, interreflections, and others. Oculomotor cues include accommodation and convergence. Binocular cues include disparity-based stereopsis. Such collections have been also identified for other object qualities such as size or color. With audition, say for object localization, there are analogous notions, such as interaural time difference, interaural intensity differences, or spectral cues related to head-related transfer functions, in addition to monaural cues [4].

These cues are tied with the manner in which the sensory apparatus – physically and computationally – has evolved to account for the ambient physics. For example, sound localization obeys fundamental constraints related to the propagation of sound such as wavelength and speed of propagation. Nature has developed marvelous mechanisms to cope with these constraints and at the same time take advantage of them.

It is thus natural to propose that for touch, like for vision and audition, such physically and computationally specific cues must exist and can be identified. This chapter is about discussing some putative tactile cues that refer to shape as one of the object attributes that a perceiver could be interested in.

To this end, the notion of invariant will be used to identify a collection of possible tactile shape cues, and priors necessary to the processing of haptic shape are suggested from the analysis of experimental evidence. Examples of how these notions can be applied are described by looking at two specific haptic detection tasks and how stereotypical movements can be interpreted.

Displays may be thought to operate like 'mirrors' of the perceptual system. The colors channels of a LCD display 'mirror' the color channels of the visual system. The fast repetition of frames – a sampling process – 'mirrors' the computational spatiotemporal interpolation performed by the visual system – a reconstruction process. Examples such as those abound. For haptic interfaces one may adopt a similar view point and examples of how this approach can be applied are discussed later.

Before exploring these topics, general observations are made to illustrate the fundamental differences between direct touch and tool-mediated touch.

Observations on the mechanics of touch

In this chapter we discuss the case of touching rigid and stationary shapes. By this, it is meant that the touched objects do not deform nor move significantly compared to the deformation and displacements of the touching object. It is also needed to assume that when a finger slides on an object, the tangential deformation caused by slipping can be neglected. More general cases will be mentioned when needed.

Tools and fingers

It is commonly observed that haptic interaction can happen in one of two possible ways [5, 6]. Perceivers can interact with objects using tools or with direct finger contact. Forks and chopsticks, surgical instruments, or switches are examples of what is meant by tools. In these cases, the question arises of what are the haptic cues that used to extract information about particular object qualities. As far as shape is concerned, this question turns out to be more difficult to discuss when tools are used rather than bare fingers, as discussed next.

Transformations induced by tools

During haptic exploration with a tool, the information that can be extracted from an interaction is entirely contained in the displacements of the tool, whether they are large movements or small oscillations. The exclusive medium of information transmission are the movements of the tool [7]. Resting a pen on a table tells nothing about the table [8], but when there is movement, the tool first transforms the tool-object mechanical interaction into radically different mechanical events at the periphery of the perceiver [9]. There, what is potentially available is the motor activity that gives rise to the interaction and the resulting deformation of tissues in the fingers and limbs. From the perspective of the perceiver, this corresponds to a second transformation. In order to recover a given attribute, say shape, we may follow this path in the reverse order. Mathematically we could say that if f associates a shape to the movements of a tool and g the movements of a tool to the deformations of tissues that are sensed, then the brain has to invert $g \circ f$ to have access to shape, which is compute $f^{-1} \circ g^{-1}$.

Evidence that the brain is able to invert the second transformation – the tool-hand interaction – can be obtained from the observation that, by and large, similar sensations are experienced when the same tool is used against the same object but with different grips, each creating a different version of the second transformation. We may call this effect a grip-related perceptual constancy effect. Then, the first transformation caused by the tool can be inverted to recover relevant aspects of the tool-object interaction, those related to shape for the case in point. Only then can the sought-after object attribute be recovered from the properties of the tool, since the interaction depends on the tool as much as it does on the object. Here, unlike grip-related perceptual constancy, tool-related perceptual constancy is less likely to succeed, especially if the tool is inadequate such as having a curvature that is commensurate with that of the touched object.

Using intermediaries

When using a tool, the perceiver is faced with two hard, cascaded problems to solve since the variations introduced by the intermediary have impact on both these transformations. Factors that enter into the complete equation include the relative curvatures of the tool and the object at the place of contact, the relative compliance of the materials in contact, their internal structure, the structural dynamics of the tool and the nature of the interface between the tool and the hand as well as the grip used.

This analysis is general and applies also to interaction with complex mechanical devices such as switches, knobs or piano keys. In the later example, the impact of the hammer on the string is actually 'felt' although there is no direct mechanical path between the finger and the string since the hammer is in free-flight at the time of impact! [10] The impact can only be felt by inverting the dynamics of the escapement in order to anticipate the velocity of the hammer as it hits the string. A simpler example