# Haptic Shape Cues, Invariants, Priors, and Interface Design

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## 1 Introduction

Perception is often discussed by reference to cues as separate sources of information for the perceiver [8]. With vision and audition, the list of such known cues is quite extensive [5, 11]. 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, in Section 3 the notion of invariant is used to identify a collection of possible tactile shape cues and in Section 4 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 in Section 5 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 in the Section 6 of this chapter.

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

## 2 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.

### 2.1 Tools and Fingers

It is commonly observed that haptic interaction can happen in one of two possible ways [23, 28]. 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.

### 2.2 Transformations Induced by Tools

During haptic exploration with a tool, the information that can be extracted from the 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 [47]. Resting a pen on a table tells nothing about the table [18], 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 [27]. 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, that is compute $f^{-1} \circ g^{-1}$.

Evidence that the brain is able 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.

### 2.3 Using Intermediaries

When using a tool, the perceiver is faced with two hard, cascaded problems to solve since the variations introduced by the intermediary has 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! [1] 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 that we have studied are surgical scissors [14]. It was seen that the design of the scissors and the tissue properties both have profound effect of the information available to the surgeon. Similarly, experienced surgeons "invert" the scissors to appreciate tissues properties, the result of which guides the next incision, since surgical cutting is the result of many small fast cyclical cuts.

### 2.4 Implications for the Design of Interfaces

Given the limitations of current technology, haptic interfaces are able to replicate real mechanical interaction with only a large degree of imprecision. One can only wonder why force feedback interfaces work so effectively [17]. This must be attributed to the brain's ability to deal with an extraordinary range of possible intervening transformations. From the analogy that displays act as mirrors of the perceptual system, one may conclude that the practical realization of force feedback displays appears to be much easier to achieve than the realization of direct contact cutaneous displays. With direct finger contact, the tool is the finger itself, so the brain benefits from a lifetime of its use and of incorporation of its properties. There must be much stricter rules that the displays must obey.

### 2.5 Force Feedback

It is useful to reflect briefly on the notion of *force* since it is central to the concept of force feedback. First, recall that a force does not have a physical existence. It is a mere abstraction used to describe the action of one particle on another in terms of a vector. We can also use the notion of force for systems of particles that are assembled in a solid. In the later case, we can also describe forces of contact in addition to the forces acting at distance. If we consider a perceiving body, say a finger, then when we speak of force, we simply describe the action of another system of particles that acts on it to change its state, lumped into three numbers. This generalizes to torques and tractions. With the method of Lagrangian dynamics, we can in fact do away with the idea of force and think only of the trajectories of generalized coordinates [12].

When reproducing a virtual object, we may therefore regard the function of a force feedback interface to be that of causing the displacements and deformations of limb(s) and finger(s) that would be equivalent to the displacements and deformations experienced when interacting with an original object. Experimental evidence of the value of this view is provided by the success of acceleration matching techniques, equivalently movement-matching techniques [47, 24].

For the purpose of this paper, although we leave aside the problem of the analysis of the cues available with tools, we retain from this discussion the possibility of describing the cues arising from direct finger contact *entirely in terms of deformations and displacements*. Thus, in the rest of the chapter the word 'force' (or 'traction', or 'pressure') will no longer be needed.

## 3 Mechanical Invariants

With direct finger contact, since there is no tool transformation involved, we can devise a more systematic approach to the analysis of cue generation as they relate to shape.

### 3.1 Notion of Perceptual Invariants

Invariants have for a long time played a central role in the study of perception [10]. There is a strong connection between the idea of perceptual cue and the notion of invariant [30, 44]. In fact, behind each depth cue listed in the introduction hides one or several invariants. Invariants can arise from three sources [33]. They can arise from mathematical properties, they can arise from physics, and they can arise from the structure of the sensory apparatus, in that they have a biological origin. The properties of straight lines, circles, or symmetry groups are examples of sources of mathematical invariants. That gravity accelerates free-falling objects at a constant rate in a uniform direction, or the speed of sound, exemplify the sort of invariants we might expect from physics [31]. The near-orthogonal geometry of the semicircular canals in the inner ear or Listing's law that governs the eyes to rotate around a common fixed axis are examples of the sensory structures that create invariants which are presumed to enhance the computational efficiency of perception [2].

### 3.2 Specific Shape Invariants

There is a number of physical phenomena related to the mechanics of contact which, collectively, provide a rich source of invariants that are highly relevant to tactile shape perception. Within limits, these invariants are generic to any touched shape. Some are briefly discussed next.

### 3.2.1 Static Invariants

Contact mechanics dictates that when two objects are in contact, no matter how hard or how soft they are, they share at least one surface of contact that grows from an initial point [21]. It is a fact of geometry that it is only when the contacting objects are convex (one could be flat but not both) that the contact surface is guaranteed to be a connected component. As long as one can ignore the effects of the fingertip viscosity and hysteresis, the invariants that result may be said to be *static* since they to not depend on history nor speed.

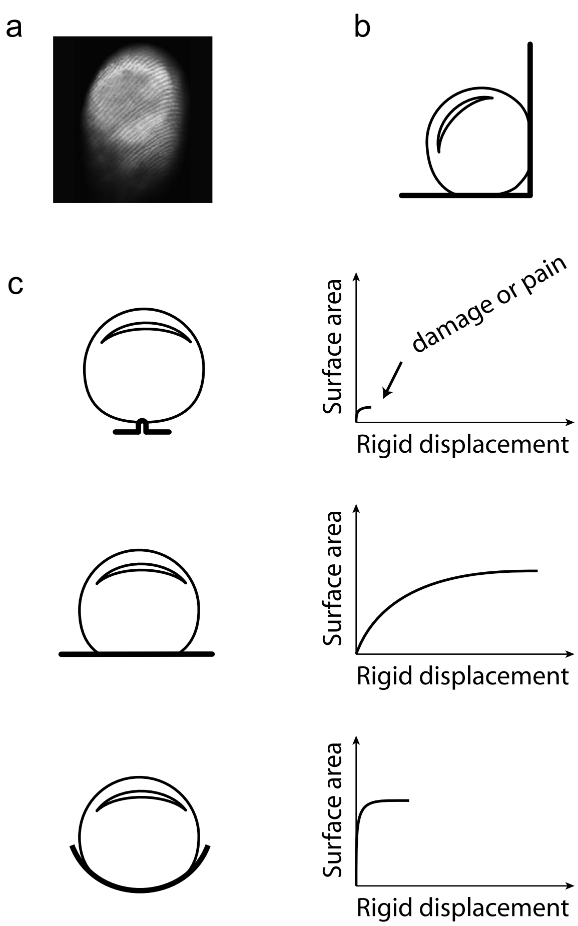


Figure 1: Static tactile invariants. View of a finger contact surface imaged through a desktop scanner (a). A sharp inside corner causes multiple disconnected contacts (b). Dependency of the contact surface relatively to the rigid displacement of a finger (c).

A first aspect of the surface-forming phenomenon which is special to the mechanics of a finger is related to the spread pattern of this surface from an initial point [40, 34]. The finger mechanics cause the size of a contact surface to define an anatomically-related tactile yardstick of about one centimeter (this can be seen by grabbing a glass and looking directly at the contact), which changes by a factor no larger than, say, 1.5 for a flat surface, see Figure 1a. Let's call that invariant S1.

Since the fingertip's sensitive area is a convex surface, if the contact areas are disconnected, then the touched object must have at least one sharp concave region. It is something that can be verified by touching the inside corner of a box, see Figure 1b. More generally, not only the size but the shape of the surface contact is characteristic of the local curvature of touched surface. In particular, the eccentricity or deviation from circularity is directly related to ratio of the principal curvatures of the touched object. Thus, a second invariant and its many variants, call them S2 collectively, is identified.

The surface-forming phenomenon creates yet another powerful sensorimotor invariant, S3, that correlates the curvatures of the object with the growth curve of the contact surface [42, 13, 3], see Figure 1c. When the object curvature is high, say a rod or a Braille dot, the surface grows fast but plateaus at a low value. If the touched surface is flat, the growth rate is at its slowest and plateaus at a higher value. If the touched surface is concave, then it grows fast but plateaus at a high value. At the limit, if the curvatures almost match, then the contact surface is instantly created and the finger rigid body displacement is almost impossible. Of course there is an infinite family of surface-forming curves, each characteristic of the curvature of the surface relative to that of the finger.

### 3.2.2 Kinematic Invariants

In mechanics, one distinguishes local deformation from global deformation [21]. This is expressed by St Venant's principle. This principle states that the effects of different but statically equivalent loads are not distinguishable at distances greater than the dimension of the contact area. For example, if one grips a brass rod in the jaws of a vise with the aim of bending it, the shape of the contact areas (seen by the marks left by the jaws) has no effect on the overall shape of the bent rod. This is the source of powerful invariants and has consequences in almost all aspects of mechanical sensing.

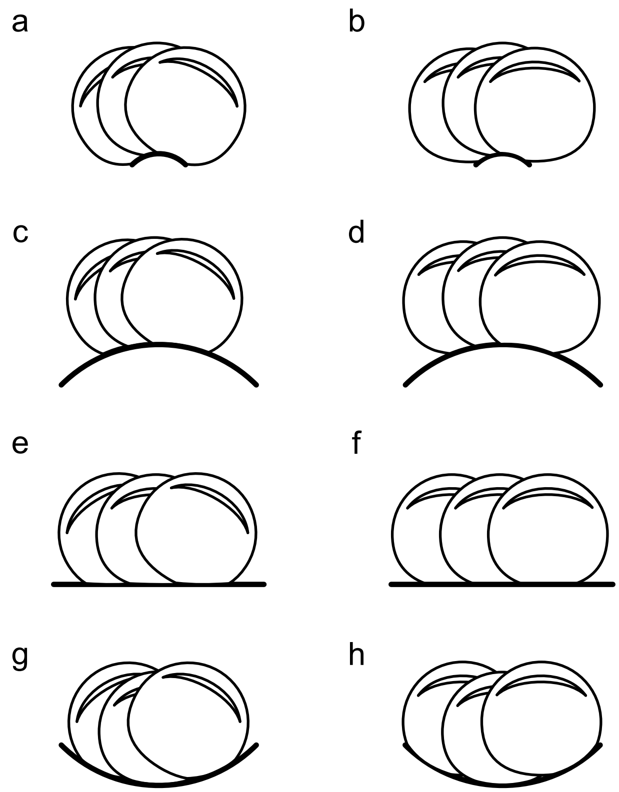


Figure 2: Kinematic tactile invariants. When a finger rolls on a surface, invariant K1 holds that the relative radii of curvature determine the velocity of the contact surface relatively to the angular velocity of the finger (a), (c), (e), (g). When a finger slips, K2 expresses that for a convex object, the lower the curvature of the object, the lower the velocity of the contact on the skin (b), (d), (f). For a concave object the relationship is inverted (h).

For shape perception, this principle has the effect of mechanically separating the sources of information about a touched object into two neatly segregated categories. There is what is available inside the contact in terms of the strains developing at the surface of the skin and in the subcutaneous tissues, the details of which have absolutely no effect elsewhere. Conversely, the net displacement of a contact area, regardless of the details of its shape, provides a second category of source of information. To identify more specifically shape-related invariants and hence possible shape cues, let us consider the information that is available from the velocity of a contact surface on the finger. In considering velocities, we may call these invariants *kinematic* invariants.

The mechanics of the relative motion of two bodies in contact requires that each infinitesimal portion of the two surfaces is in one of two states [37]. Because of friction, each pair either sticks or slips. Upon initial contact the whole of the contact surface sticks. Under sufficient tangential load, the whole of the contact surface slips. With a highly deformable body such as a finger there is a transient regime during which the slipping region grows from the periphery to eventually invade the whole region [26, 43]. This and many other possible patterns are likely to be another rich source of invariants which, unfortunately, cannot be discussed here.

Leaving the transient regime aside, new invariants can be identified. Mechanics requires that when there is no slip, and of course no pivoting, there is pure rolling motion between the finger and the object. In other words, the rigid-body instantaneous velocity of the finger (a global deformation of the perceiver's body) relatively to the object is constrained by a relationship between the velocity of the contact region on the fingertip (a local deformation) determined by the relative curvatures of the finger and of the object.

Specifically, for a given angular velocity of the finger, the smaller is the curvature of a convex touched object, the slower is the velocity of the contact region, see Figure 2a,b. At the limit, for a flat surface, see Figure 2e, this velocity is essentially the effective radius of the finger times its angular velocity. If the surface is concave, Figure 2g, there is amplification up to the point where when rolling the finger on a concave surface with a radius that tends to that of the finger, the contact surface velocity tends to infinity. In a nutshell, for curvatures ranging from an infinitely curved convex surface to a concave surface of the same curvature of the finger, then the ratio of the finger angular velocity to contact surface velocity varies from zero to infinity. When the surface is flat, this ratio is the finger radius. We call the relationship linking angular velocity with contact surface velocity as a function of surface curvature invariant K1.

Now, let's look at the same cases but when there is slip. Slip must occur, for instance, when exploring an object while the orientation of the finger is kept constant. The scanning velocity must be considered and a very different type of relationship is created. For a convex object, see Figure 2b,d, for the same scanning velocity, the lower is the object curvature the lower is the velocity of the contact surface on the finger. At the limit, if the object is flat, then this velocity is zero, Figure 2f. If the object is concave this velocity approaches infinity as the object curvature approaches that of the finger. We denote this invariant K2.

#### 3.2.3 Generic Invariants

The reader will also notice that the relative signs of the finger velocities and of the contact velocities changes from a convex to a concave surface in the case of sliding motion, but not in the case of rolling motion. Said another way, with suitable coordinates, the sign of the product of the velocities indicates the sign of the curvature of the touched surface, a very powerful invariant indeed denoted G1. It is generic because it holds for any magnitude of the velocities and any magnitude of the curvatures. It is known that humans can detect slip velocity accurately for many types of surfaces [9].

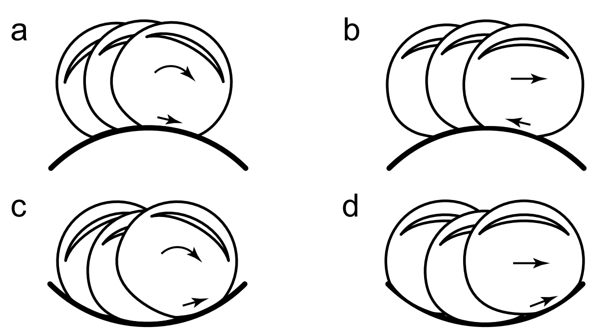


Figure 3: Generic tactile invariants. Comparing a rolling strategy (a), (c), and a sliding strategy (b), (d). When rolling, the direction of the velocity of the contact surface on the finger is unrelated to the shape of the object, only the magnitude is, as was seen in Section 3.2.2. When sliding, the relative directions of the velocities depend on the sign of the curvature of the object.

## 4 Experimental Evidence of Haptic Shape Priors

It is clear that when a perceiver has the experience of an object, complete information cannot be available instantly or may never be available at all. So even if information can be integrated over time to build knowledge about a scene or an object, the perceiver must rely on prior knowledge.

### 4.1 Notion of Perceptual Prior

In general, a *perceptual prior* is knowledge used by the brain to make a judgement when sensory evidence is lacking or if the likelyhood of a property to hold is high enough to override contrary indication. In vision, "light-from-above" and "object stationarity", are well studied examples of priors [11].

In this section, we discuss indirect evidence of haptic priors that coincide with the assumptions made at the start of Section 2. For this, we use the results of two experiments where observers experience illusory shapes based on a highly simplified set of perceptual cues [6, 38].

### 4.2 Shape From Contact Movement

The objective of a device called the 'Morpheotron', see Figure 4a, is to show that the brain can effortlessly take advantage of a single, segregated shape cue [15]. It has a plate constrained to rotate around a point located inside the perceiver's finger, see Figure 4b, and allows for free exploration in a horizontal plane. The machine eliminates proprioceptive cues since the rigid movements of the finger are independent from the plate orientation. By design, under servo position-control, the flat plate rolls on the fingertip and its movements do not affect the finger rigid-body displacement. Under these conditions, invariants S2, S3, K1, and K2 are not available to the perceivers. Yet, they are able to perform in a concavity/convexity detection task at a level equivalent to when exploring real objects [6].

From what source can subjects derive the experience of shape if the static invariants report a flat surface, if the kinematic invariants are destroyed, and there is no proprioceptive cues? Perceivers are likely to use a prior assumption of stationarity. Re-

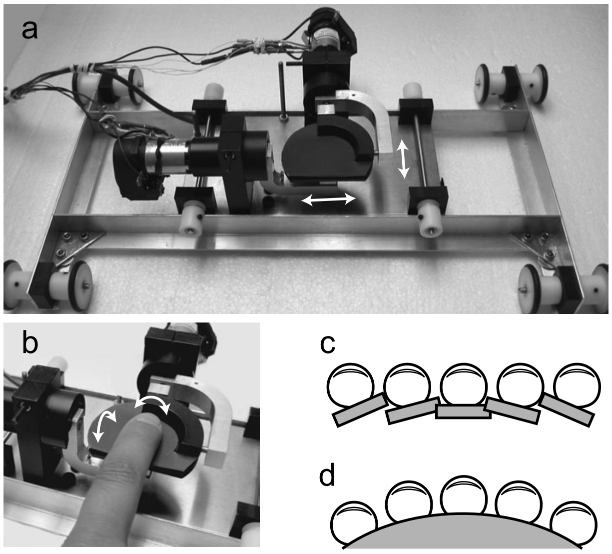


Figure 4: The Morpheotron. A plate free to move in a horizontal plane (a) rotates under servo-control control around a point located inside the finger (b). The contact moves on the surface of the fingertip (c). The form represented in (d) is typically experienced. Please see [6] for the various conditions in which this can happen. Please consult reference [16] for practical means to experience similar sensations.

call that in Section 2 it is assumed throughout that the touched object is stationary, that the object does not deform, and that the finger deformation due to sliding can be neglected. But when observers touch the plate of the Morpheotron, either they are not aware that the plate actually moves (because of the testing conditions), or if they look, the prior that a touched object is stationary is sufficiently strong to override visual report of movement. In these conditions, the stimulation depicted in Figure 4b,c is sufficient to give the sensation of the shape represented in Figure 4d [15].

Neither K1 nor K2 are available in their native form, nevertheless, information similar to that given by K2 is made available by the device if the touched virtual object is assumed to be perfectly slippery and immobile, thus exposing the existence of three priors, that of “object stationarity”, call it P1, of “perfect slip”, call it P2, in addition to “object rigidity”, call it P3.

### 4.3 Shape From Tangential Fields

This experiment is best described by reference to Figure 5a [38] (See also Chapter ??). There, a finger is represented in the act of exploring a protrusion on a surface. In terms of the cues that we have discussed so-far, a protrusion may be characterized as four consecutive changes of curvature, from zero curvature, to negative, to positive, to negative, back to zero. We could therefore invoke the entirety of the static, kinematic, and generic invariants discussed earlier to express the information potentially available to the perceiver. In addition, if the protrusion is large enough to require detectable limb movements, proprioceptive cues are also available.

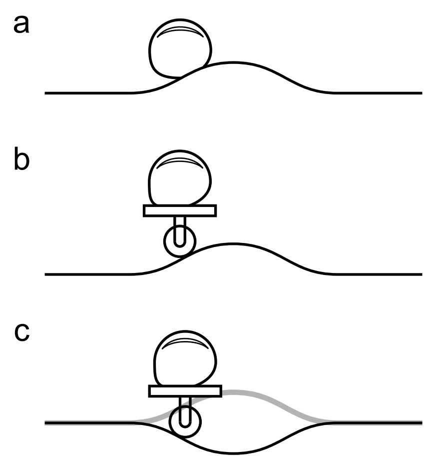


Figure 5: Shape by tangential fields. A finger scanning a protrusion produces many cues (a). A plate and a constraining mechanism eliminates all but two cues (b). Experimentally, proprioceptive cues arising from rigid-body motion can be separated from tactile cues arising from local and global deformation of tissues (c). Please see reference [16] for practical means to experience similar sensations.

Similarly to what was described in the previous section, the principle of the experiment is to eliminate most of these cues by suppressing the corresponding invariants. The apparatus, depicted in Figure 5b, eliminates all static and kinematic cues by using a flat plate constrained to follow a cam. For the observer to push the plate, say up the hill, the finger must deform laterally. In effect, the protrusion is felt, presumably as a result of a combination of proprioceptive and tactile information, originating in the skin, tendons, muscles and other places of the perceiver's anatomy that are sensitive to strain.

At this point, we see that if the perceiver feels the protrusion, the only information available are the priors P1, P2, P3, the later being violated by the apparatus, plus deformations corresponding to the direction of movement. Perfect slip, P1, is especially important since without it deformation could be attributed to, say, varying surface friction and not to shape. We can suppose the efficacy of a fourth perceptual prior, P4, which would require that the friction of a surface does not vary.

The experiment shows that, under appropriate conditions, the information available from proprioception can be overridden by that of other sources, including that of the four priors that we have identified. To demonstrate this, the apparatus, using a combination of sensors and actuators, causes deformations that corresponded to exploring a shape as illustrated by the grey line in Figure 5c but with rigid-body displacements corresponding to the black line [38]. What the perceiver typically feels is the shape represented in grey rather then that in black. It can be further shown that these sources of information are cues that are integrated according to a Maximum-Likelihood-Estimation model for cue integration [7].

While the figure represents deformation in the finger only, there is anecdotal evidence that redundant information is available in other ways since the illusion occurs equally well when using other parts of the hand such as the back of the hand, the wrist, or the hard knuckles [38].

# 5 Applications

In actual everyday manipulation and exploration, the conditions that we have employed to characterize some invariants, the priors, and their attending shape cues, rarely occur in the simplified forms described so-far, and many more indeed could exist. For example, tactile information can be combined with proprioceptive inputs. This can be shown by eliminating cutaneous sensitivity by anesthesia [45]. In another example, the static relative location of the surface of contact in a pinch grasp is shown to determine motor behavior when lifting an object [20]. This later example shows that the presently considered single-finger tactile shape cues can be generalized to multiple fingers.

In the next subsections, the notion of shape invariant will be exemplified, first in the context of stereotypical movements. Such movements have been described for the detection of a specific of objects qualities [25]. Then, a special but interesting task, that of the detection of flatness, will be discussed in the light of the shape invariants and associated cues.

## 5.1 Examples of Stereotypical Movements

Consider the task of sizing a coin. A static grasp is certainly not an optimal strategy. Yet, there is more information available in a static pinch grasp, see Figure 6a, than that coming solely from the separation between the two fingers. Invariant S3 can be invoked: a higher curvature corresponds to a smaller contact surface. In addition, there are typical movements that may employed to detect the curvature and hence the size of the coin in question. A version of invariant K1 may be called upon by rolling the coin between two fingers as indicated in Figure 6a. However, it can seen in this case that K1 is ineffective since the velocity of the contact region is independent from the coin's radius. On the other hand, a version of invariant K2 can be triggered by holding the coin between the thumb and the third finger, and using the index to explore its curvature. This is shown in Figure 6b. It is likely that the later movement is more efficient and more often used than the former.

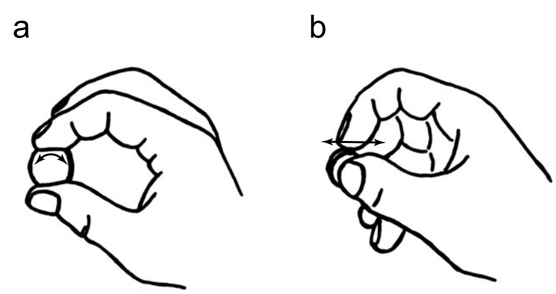


Figure 6: Unsuccessful attempt to use kinematic invariant K1 (a). Invariant K2 can be invoked although the index finger does not have to have a fixed orientation (b). Its kinematics are presumed to be available to relate the contact surface velocity to that of the index in a version of invariant K2.

### 5.2 Detection of Flatness

The notion of tactile flatness is natural to us. Yet, for an observer, on what ground can flatness be decided? Humans are known to be able to detect very shallow protrusions and hence very small curvatures that cause surfaces to deviate from flatness [29]. The invariants we have discussed can all be used to detect flatness. Let us take them one by one.

For a flat surface, the final size, invariant S1, the shape of the surface, S2, and the growth pattern of the surface of contact, S3, are all characteristic. We cannot expect the corresponding cues to be highly reliable but there is evidence that static touch can detect flatness, even with one single finger [13]. Kinetic invariant K1 is a possibility, yet an unlikely one, since its sensitivity to flatness is not great in the case of rolling a finger on a flat surface. On the other hand, invariant K2, available when sliding, is a very appropriate one since, mathematically, the only surfaces that can give rise to zero velocity of contact surface on the finger are the Reuleaux surfaces, that is, the flat, spherical, cylindrical, revolute, helicoidal, and prismatic surfaces [35]. In addition, its precision can be increased by using multiple contact areas within the hand. In particular three fingers are ideal since a three-finger touch will constraint the hand posture appropriately. It is easy to find other cues that eliminate all possibilities but a flat surface. The generic invariant G1 is not applicable in the case of a flat surface. It is the combination of these, and probably other cues that signifies flatness to the observer. By these observations we can justify why the two, and most likely, the three-finger scanning posture is typically preferred to appreciate the flatness of a surface, see Figure 7.

The conceptual analogy with visual straightness is interesting. Visually, an invariant for straightness comes from the mathematical property that a straight line is invariant under very general transformations that resist those introduced by the visual system and that is independent from any coding [33]. This also coincides with the fact that light propagates in straight line as well (provided that the propagation milieu is homogenous). A special case is when looking in alignment with a flat surface or a straight edge to make them vanish. This is analogous to the sliding velocity being exactly equal to the scanning finger velocity in the special case where the finger(s) contact surface velocities vanish to zero. Here too, the haptic invariants are independent from any transformation and from any coding.

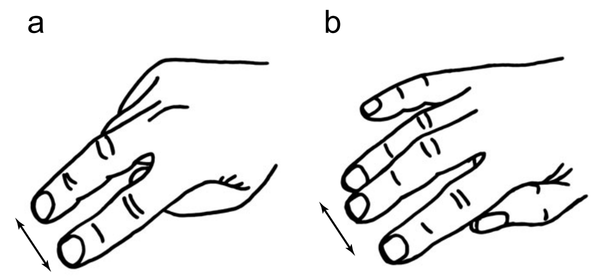


Figure 7: Appreciating flatness. Scanning with two (a) or three (b) fingers are typical strategies that can leverage invariant K2. The tree-finger strategy is most appropriate since it determines the correct number of freedoms and constraints.

# 6 Devices to Generate Missing Cues

Since the cues that we have discussed so-far are eliminated when using tools or intermediaries, designers of haptic interfaces have attempted to devise systems that could produce them. In this section we look at four of these devices and discuss the invariants that they can potentially preserve.

### 6.1 Slip Displays

What if a device was devised so that "perfect slip" prior was replaced by actual physical experience? Then it could be possible to have a haptic interface that could produce invariant K2 efficiently. Generating slip is not a new problem. In human studies, commanding a drum to rotate and cause slip under the finger pad is the traditional method to deliver slip [9, 39, 32]. But of course, there is a desire to command omni-directional slip for general-purpose applications in mechanical virtual environments. To date, the preferred method to achieve this is a ball constrained between motorized traction wheels [22, 46], but other approaches may exist.

### 6.2 Fingertip orientation displays

Similarly, designers have been working on techniques to generate the static and kinematic invariants which are eliminated by force feedback devices in much the same way a tool eliminates them through two cascaded transformations. Of course, designers will always be facing a fundamental tradeoff. The larger is the number of shape cues that can be delivered by a device, the larger is its complexity. In mechanical engineering terms, complexity can be measured in terms of number of actuated degrees of freedom. For the Morpheotron, only two are needed.

The first practical realization of a device that could introduce the missing tactile cues is probably a system described in 1993 by Hirota and Hirose. The authors articulated their goal clearly: "In this concept [of force-feedback], force is considered to be an output from the virtual object to the user. However, it is possible to adopt a different approach where, instead of force from the virtual object, the existence (or surface) of the object is simulated" [19].

Recently, several new devices have been described which explored various design niches. The system that comprises the largest number of such actuated degrees-of-freedom, termed "encounter-type", has nine degrees of freedom, three per finger for three-digit grasps [48]. Its design is driven by anatomical considerations regarding the mobility of the human hand. Another approach is to add a mobile spherical tactile element sliding inside a thimble attached to a force-feedback device. The result is a system with four actuated degrees of freedom [36]. The contact location can be changed according to the movement of the finger which is otherwise stimulated using a force-feedback strategy. The authors show that the addition of this extra element combined with the force feedback give the users discrimination performance comparable to that achieved in real conditions, as long as the finger is constrained to fore-aft exploratory movements. Finally, a device that enables the exploration of arbitrary surfaces in three dimensions is described in [41]. It has five actuated degrees-of-freedom and combines force-feedback with kinematic cues delivered by a flat plate rolling on the fingertip. With this system, users can achieve the detection of very low curvatures, down to 2.3 $m^{-1}$ [41].

## 7 Summary

Here is in list form the steps that were followed:

- Individual perceptual cues have been identified for vision and audition. For touch, the same should be possible. We look at shape only.
- Display technologies may be thought to mirror the perceptual system of an observer. Therefore the knowledge of cues is useful to design systems which can economically provide a desired percept.
- Priors are necessary for perception. For tactile shape, object rigidity, stationarity, as well as perfect slip are such possible priors that, for analysis purposes, are first assumed to hold.
- There is a fundamental difference between between direct and tool mediated touch. Tools introduce cascaded transformations which must be inverted by the brain.
- Force feedback devices with which the brain must assume the existence of a tool are easier to realize than devices where this assumption is lifted.
- The notion of force is not needed for analysis. Only notions of displacement and deformation are needed.
- Like in vision and audition, perceptual cues are linked to invariants that have mathematical, physical, and biological origins. The same should hold for touch.
- Static invariants were identified that are related to the contact surface: its final size (S1), its shape especially connectivity and eccentrity (S2), and the growth law as a function of rigid displacement (S3).
- Kinematic invariants are associated to rolling. The angular velocity of the finger is related to the velocity of the contact through object curvature (K1). They are also associated to sliding. Then, the velocity of the finger is related in a different way to the contact velocity also through curvature (K2).

- Generic invariant (G1) relates the relative direction (or sign) of finger and contact velocities when sliding.

- These invariants owe their existence to the physics of contact such as Hertzian surfaces, St Venant's principle or the properties of friction. They also arise from the near spherical shape of biological fingertips and from their viscoelastic properties in addition to the mathematics of contacts such as convexity, connectivity or limit cases.

- The need and the existence of at least three priors object rigidity, stationarity, and perfect slip can be evidenced experimentally.

- Stereotypical movements can be related to invariants and to the cues they provide.

- Special cases such as flatness detection are related to invariants that have conceptual analogies in vision.

- Haptic devices are being developed which can uphold these invariants and hence provide relevant shape cues.

In conclusion, it is noted that visual or audio displays can take many forms, from store-front LED banners to IMAX theaters, from telephones to wave-field synthesis systems. As long the information delivered is relevant to the task at hand and the signal types and noise ratios match the perceptual mechanisms at play, the display will operate successfully. Perceivers excel at taking advantage of any available cues. The same applies to haptic displays.

In this chapter we have looked at some of the cues that are relevant to haptic shape perception of low convexity objects. There certainly exist many others, but these provide a solid fundation from which more complex ones can be created, particularly by involving several fingers rather then one.

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