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http://cdr.stanford.edu/touch/workshop/

## Section 3.9

# Application-Centered Haptic Interface Design

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A haptic interface is a particular kind of window through which a user may experience or manipulate something else. The purpose of this section is to explore the value that the touch sense can provide in different contexts, and to offer perspectives and principles for the creation of haptic interaction models for specific applications.

We assume the perspective of an interface designer considering haptic feedback as one potential interaction medium. This designer needs first to create an interaction model by which the application can most effectively be perceived and controlled by the intended user, and that model must be submitted to a critical and unbiased task analysis. When (and if) haptic feedback emerges as part of this model, the best morphology and mechanism for the haptic interface device as well as its connection to the rest of the application can be more readily specified and created, using insights into hardware design and psychophysics discussed elsewhere.

This is a "top-down" design approach, which begins with a need (to provide an interface to a given application) and aims to discover the solution from a suite of available interface technologies and methods. At the same time, a good understanding of where haptic interaction adds value should help in identifying the applications for which haptic feedback is a good fit – the "bottom-up" approach. Section I examines different aspects of physical interaction in the real world; Section II suggests design principles for haptic interfaces which we hope are just a beginning to an expanding understanding by the field.

## I Relating Haptically to the Physical World

Consider the yielding fuzz of a peach in ripe perfection, the smooth constrained glide of a crafted wooden drawer, the precise handling of a fine steel knife. Add to the list your own favorite handheld tool, a well-worn garment, and the food you most like to eat. The way it feels - under your hands, on your body, in your mouth - may well be a strong component of your pleasure in it, or why it works so well. When you consider the tools, textures and tastes that irritate and frustrate you or get in your way, you may find a haptic explanation there as well.

It is tempting to romanticize touch; to wax nostalgic as its role diminishes in a world of microcomputers, virtuality and black plastic pushbuttons. What is its real value? Most would agree that humans have evolved for millions of years to use their fingers and limbs and skin to make discriminations, manipulate objects, create music and share some of their subtlest communications with other mammals. However, the need for these skills and abilities may diminish in a computerized society with high-tech careers, Internet shopping and sampled sound. This is a world where we may work all day from a desk and maintain personal relationships electronically, and where peaches don't feel ripe even when you *do* squeeze them. Will those who have grown up playing computer games instead of climbing trees, taking apart bicycles and throwing real balls, share with their parents the desire or even the ability to touch? Is touching a gift whose atrophy imperils pleasure, sanity and self-sufficiency, or is it a quaint appendage that will slip away to a genetic shadow, barely missed, the way of our olfactory organs and a dog's fifth claw?

It is productive to consider separately what is possible, useful and desirable with respect to our haptic sense, in the natural world and ins the synthetically augmented. The answers are necessarily indeterminate and personal, and largely guesswork and vision for now. Offered here is a framework for your own valuation: guess at what a haptically impoverished world would mean to you in functional and aesthetic terms, and imagine another in which the CPU is directed towards sensorial gain, rather than deprivation.

### Taxonomies of Physical Interaction

Touch can be analyzed from multiple directions. The following initiates a mapping of the way people use touch, beginning with a discussion of its unique qualities. The landscape to be covered includes motivation for physical interactions (Why), the physiology of the touch (How), and the kinds of things we touch (What).

#### Special Qualities of Touch

##### *Bidirectionality*

The haptic sense is coordinated and physically, neurally co-located with motor functions, such that touch is sometimes described as "bidirectional" to encompass intention, manipulation and gesture. Much of haptic perception relies on active exploration, which in turn is a form of gesture; and these integrated pathways allow fast reflexive motor responses to haptic stimuli.

##### *Social Loading*

Touch is intentional, invasive and committing, and carries weighty social implications. By reaching out to touch, we reveal our intentions, enter others' personal space and violate taboos. We expose ourselves to physical danger as well as pleasure and information. Cultural semantics add variables to the affective and communicative functions of touch. Consider a handshake: there is the fact that a handshake has been proffered, what it means and how it is received. Who is allowed to and how often and how long it may last; when a nod or a kiss would be more appropriate, or more meaningful.

#### *Gesture and Expression*

Some believe that verbal language evolved first from visual gesture, and is entwined with gestural touch. Through touching, we can convey both functional signals, such as an attention-getting tap on the shoulder; and emotion and expression – a sad caress or an urgent, frightened clutch. We create and perceive felt gestures through the same locus; and because of its inherent intimacy, this kind of touching can be salient and immediate.

#### *Multi-Parametered*

Parameterize the information available to you – and to your fellow shaker – in the handshake: you register your greeter's grip strength, through pressure sensors in your skin and tensile transducers in your muscles and tendons. You discern moisture and temperature (the clamminess of his palm, as well as of your own), texture (smooth and soft, or tough and callused with ragged nails), and frequency and duration – how rapidly she pumps your arm, or tries to escape from yours. This information is integrated with input from other senses to form a complex impression: He's nervous, she's glad to see me; he works with his hands, he is a dandy, she is strong-willed. She finds me attractive – or repulsive. He wants something from me.

#### *Resolution and Associability*

Touch is infinitesimally precise in the control and discrimination it affords, yet vague compared to audition and vision in its facilitation of memory and association of absolute and relative resolutions. The finest scratch on a glass surface triggers a tactile reaction, and we can discern subtly different grades of sandpaper. But how many different sandpaper grades can you memorize and name when they are randomly presented to you, compared to hues of color?

### Why: Reasons for Touching or Staying Away

We initiate or sustain a touch with a number of intentions. People are generally more cautious about what they touch than what they will look at, indeed, the fact that they may have a choice must influence an interface's design. A large part of the haptic interface designer's task is thus in anticipating, managing and accommodating the perception that a potential user might have about the interaction: what it is for, and what the experience will be like.

#### *Motivations*

We touch because we intend to:

- *Do* a task
- *Probe* an object for its state or qualities
- *Communicate* a message
- *Poke* something to elicit a reaction
- *Verify* that an action is completed
- *Enjoy* aesthetic pleasure or comfort
- *Fidget* to relieve tension
- *Connect* physically or emotionally with another person or other living thing

#### *Inhibitions*

Most often, we avoid a particular touch through a perception that it would be dirty, gross, painful, forbidden or too intimate. Beyond this, there are the generally "haptically challenged" – often culturally associated people who do not find touching natural, informative or pleasant.

#### *Information Available from Touching*

Touch is the principal contributor to a number of high level, integrated perceptual functions:

*Assessments* of an object's dynamic and material properties. The particular information we seek (for example, texture versus weight) influences how we approach and handle the object [7].

*Verification* of engagement and completion. This is available as the discrete and satisfying "ka-chunks" from a button snap and an automobile shifter slipping into gear.

*Continuous monitoring* of ongoing activity and gradual doneness. The surging rattle of a vacuum cleaner sucking dirt, a pepper grinder's crunch and a pencil sharpener scraping wood relate progress and completion.

*Building mental models* for invisible parts of a system. We form hypotheses of a function, and probe to test them. A preconceived model influences both perception and the manner in which we touch.

*Assessments* of other people. A handshake is both a social gesture and a testing of the other's dominance in a social hierarchy.

### How: Kinds of Touching

This enumeration and organization of the spaces and variables related to the sensorimotor and gestural aspects of touching illustrate the sense's range and variety. Some variables are discrete, complementary or nonexclusive. They can apply to other sensory modalities, or characterize multisensory experience. We omit the infinite variety of actual sensations – e.g. qualities of temperature, texture, force, and moisture – to focus on deconstructing larger contextual attributes.

*Physical Attributes*

| | |
|---|---|
| **information direction**<br>manipulate ↔ perceive | With a vacuum cleaner, one manipulates direction and speed and perceives the rattle of dirt being sucked up. |
| **continuity**<br>continuous ↔ discrete | Handles control, while buttons discretely trigger; perceptually we distinguish between fused, fluid feels and distinct ones. |
| **rate**<br>static ↔ rapid | Motion between skin and object or of a held object reveals different information and provides gestural quality. |
| **rhythm**<br>steady ↔ erratic | A regular motion or texture recedes; variation in rhythm may be both salient and disorienting. |
| **freedom**<br>constrained ↔ free | Motion constraint affects the degree of control left to the user, and the attention and skill demanded. |
| **effort**<br>strong ↔ light | The amount of force or work transmitted influences things like grip, physical preparation and the fineness of perception. |
| **resolution**<br>precise ↔ fuzzy | A discrimination or action may be exact or approximate, for example connecting a bat with a ball versus stroking a cat. |
| **passivity**<br>active ↔ passive | The net energy transferred from the touched environment to the user tells of the environment's "aliveness". |
| **affect**<br>expressive ↔ mechanical | Emotional and aesthetic variety is demonstrated by the manner of playing a musical instrument and by stroking, poking and slapping. |

*Connection*

| | |
|---|---|
| **location**<br>focussed ↔ whole body | A touch can occur in one focussed locale, like a fingertip, or use your whole body. The cold shock upon entering an air-conditioned room on a hot day, and the brush of clothing are both haptic stimuli. |
| **multimodality**<br>multisensory ↔ haptic | Many actions require the coordination and synthesis of many or all the senses. Sometimes touch is used in isolation, as in adjusting a car thermostat without looking when the radio is turned up. |
| **mediation**<br>mediated ↔ direct | One can touch through a tool (feeling paper texture through a pencil) or directly (stroking the paper with a finger). |
| **grounding**<br>portable ↔ fixed | Some objects we carry and use relative to our own body (a hand tool), while others are fixed (a faucet, a table top, or a steering wheel). |

*Attitude*

| | |
|---|---|
| functionality | (aesthetic ↔ functional ) |
| familiarity | (familiar ↔ novel) |
| privacy | (private ↔ public) |
| intention | (deliberate ↔ accidental) |
| dominance | (aggressive ↔ submissive) |
| value | (precious ↔ worthless) |
| attention | (attentive ↔ automatic) |
| assurance | (tentative ↔ confident) |
| anticipation | (fearful ↔ eager) |
| emotion | (tender ↔ angry) |
| pleasure | (distaste ↔ delight) |
| accomplishment | (frustration ↔ satisfaction) |
| expectation | (fulfilled ↔ betrayed) |

### What: Things We Touch

The attributes of touching can be projected onto innumerable targets. We touch objects: manual controls, tools, clothing, furniture, beloved or sentimentally endowed objects. We touch other living things, acknowledging their consciousness of us and our touch – for most of us, animals rank lower than people on this scale and higher than plants. We touch ourselves with endless variation, intent and awareness, to check, examine, itch, fidget and caress.

In the past, we thought of touching in terms of objects or beings. Synthetic haptic feedback makes possible virtual touching: physical interaction with computer-resident information or remote environments mediated by a computer-controlled haptic interface. Many of the same qualities and attitudes will hold true, but the touching is usually more ambiguous, both through the display limitations and the potential one-to-many correspondence between physical display and virtual information.

## Possible: Old and New Mediums of Tangibility

### Old-Fashioned Tools and Textures

Once upon a time, a thing was what it was. Physical objects usually exhibit a one-to-one correspondence of form to feel, although one object might be employed in multiple ways. The design implication was to customize a tool for a job. The result, illustrated by the contents of a craftsman's toolchest, is variety in shape and many variations on a theme. Individuals often modify a tool to fit their own needs. Some tools are rarely used, but occasionally essential.

Textures on physical objects and surfaces serve many functions, some dependent on their non- or slowly changing nature. They provide friction for grip, slickness for motion, aid recognition through their distinctiveness, and indicate wear. Textures may be created deliberately or as artifacts of production or use; they may be informative or designed to enhance dexterity.

### Communicative Touch

Touching is generally informative, but communication implies a consciousness and abstraction that an inert environment cannot provide. When there is both a sender and a receiver (whether deliberate or unconscious at either end) we will call it communicative touch or gesture. Body language, observed by another, is an example of this; so are a caress, a slap and a handshake. While inert environments can have explicitly designed expressive qualities able to engender an emotional reaction (consider stroking fur, silk or a chalkboard), they lack the dynamic and intention present when two active beings communicate through touch. The beings might be human, animal or machine, as long as they or their model of interaction convey a changeable, contextual message.

### Haptic Language

Most people seem to understand haptic language – the lexicon and syntax of affective communication through touch – intuitively and effortlessly, absorbing its grammar in youth when they learn other languages. But its linguistic codification is another matter; and its extension to a form that a machine could recognize and recreate with a constrained expressive palette is an even greater challenge. Neither innate fluency nor our ability to learn new elements has been well studied.

What is this grammar? It will probably borrow elements from visual gesture and dance. Gesture is an ancient and universal form of communication: some believe that verbal communication emerged not from vocalization but from manual gesture [2], and there is evidence for transcendence of gestural language across cultures [5]. Study of the informal visual gesture accompanying narrative speech suggests that it exhibits many of the structural and semantic properties of verbal language, in a different form; and that it is an essential, rather than redundant, element of narrative communication [10]. Touch shares many attributes with visual gesture; and since touching often involves physical motion, visual gesture is already an intrinsic part of it.

A haptic language might also have a direct lexical relation to other sensory mediums. Synesthesia – the poorly understood hot-wiring between senses wherein a stimulus to one elicits a percept in another [3] – is a rare condition, and its connections are not semantically meaningful. Everyday experience leads one to speculate the existence of a more general kind of synesthesia that translates one sense comprehensibly to another: the visual excitement generated by a hot color like red, for example, to an abrupt, racing, hot haptic sensation.

Linguistic description and organization are necessary for machine recognition of haptic gesture, while imaginative algorithmic and mechanical design will allow a machine to sense, interpret and create it. Visual gesture is one of many related fields: choreographers have developed elegant descriptive systems to help classify, create and teach their varieties of physical gesture [4]. Voice and image processing will feed the computational aspects of this problem, including recent work in audition to extract affect from spoken language [12].

### Tagged Objects

A new means of applying physical handles to the electronic world is the "tagged object", an inert physical object that is electronically marked [1]. The physical and electronic environment responds to these objects in ways that seem magical by the old-fashioned metric of thing-ness. They always *feel* the same, and might look nearly identical (some visual changes are simple to achieve, like flashing LEDs) but mean different things to a computer through their identity or state or the contents of their memory.

There is a tension between the abstract and semantic possibilities for the tagged object's representation. A designer might choose to make the objects similar in form so they may be arbitrarily re-used; or to make their shape and feel reflect their particular function or identity. In the former case, confusion can arise because the lack of physical distinctiveness. In the latter, generality of function is compromised.

### Synthesized Haptic Feedback

"Haptic feedback" – the subject of much of this book – generally implies computer control over the tactile or kinesthetic properties of a physical interface, permitting realtime representation of a virtual or remote environment rather than a specific, constant handle.

However, power-supplying actuators are not the only means of generating a changeable haptic interface. For example, a passive computer-controlled brake can also serve this function by varying its dissipation of a user's input energy, but with advantages of stability and potentially lower power consumption. Even more exotic is the *parasitic* haptic display, which will absorb and store a user's own energy and offers it back in the form of active haptic feedback at a later time.

Most design attention has focussed on kinesthetic and vibrotactile active haptic displays because of their more immediate applicability to known applications. However, these afford only a small range of the haptic sensations available in the real physical world. *Multihaptics* refers to the seamless and spatially overlaid integration of different haptic modalities, including the display of temperature and moisture and a larger variety of textures and shape displays. A design challenge, it is likely to have the greatest value with more communicative haptic interface applications and models.

### Mediating Haptic Interfaces

To date, most haptic interfaces have concentrated on directly exploring or manipulating static or dynamic virtual or remote environments; information is transmitted in both directions, but communication as we define it here does not occur. A haptic interface that *mediates* between two persons or a person and a machine, rather than directly translate, can assume new roles [8]. These include raising the level of a person's direction and perception of his computer-controlled environment, introducing affect to electronic environments and providing more personal connections between people separated in space.

## Useful: When Active Touching Helps

What are the general activities where we can expect haptic feedback – thoughtfully and holistically designed active and passive manual interfaces – to be valuable? On one hand, we have considered the unique affordances of the haptic sense, and on the other we can look for situations where other sensory channels are overloaded or otherwise unsuitable. In almost all of these considerations, however, haptic feedback is generally most effective when associated with other sensory modalities and must be designed in conjunction with them.

### Reconfigurability

Whereas a manual interface without actuation or computer control (for instance, a computer mouse) can also provide benefits of physicality and continuous control, either actively or passively actuated haptic interfaces can change their feedback in response to the environment they display and control. This might be as simple as the ability to alter the number of detents around a haptic knob to reflect different densities in the controlled media; or as sophisticated as a 6-df robot used to interact with a complex dynamic virtual environment.

### Handles for Continuous Control and Monitoring

*Control handles* provide continuous, analog user guidance or intervention. While conventional input devices such as a knob or a mouse also allow continuous control, haptic feedback can reduce motor or visual strain when the manipulation is exacting or prolonged. Further, it can offer selective, suggestive guidance with a cue that the user can smoothly and variably over-ride.

*Expressive control* of a variable or process usually employs continuous input, for example in sketching a visual image or musical melody. Haptic feedback can further enhance this by mediating the input with a dynamic interaction model, increasing the variations possible within a given medium and providing an avenue for stylistic experimentation.

*Low resolution, background monitoring* is a good candidate for haptic feedback. Changes in a landscape – features and discontinuities – are more salient than absolute values in both temporal and spatial domains and don't require memorization or recognition.

*Teaching, training and guiding* of manual tasks and gestures can be facilitated by "intelligent" haptic systems able to diminish the teaching cue as a student learns.

### Buttons for Discrete Control and Information

*Differentiation and identification* of discrete objects, surfaces and boundaries is aided by recognizable, associable tactile properties, either static or dynamic. These "buttons" may be static physical artifacts, or they can help dynamically, for example, to relieve the semantic loading placed on visually indistinguishable tagged objects. Active haptic textures also serve this function well, e.g. in distinguishing objects in virtual environments.

*Imposing discretization on otherwise continuous input* can relieve the strain imposed by using a generic device to do everything. An active haptic mouse allows a user to feel the edges of windows and pull-down menus without falling off [6].

A user can be *notified* of events unobtrusively and with an informative range of values. For example, wireless devices with haptic capability impart an incoming call or an alarm more discretely than the prevalent audio alarm.

A device's *failure* or an action's *confirmation* is understood via haptic interaction in real mechanisms. These subtle cues can be incorporated into sophisticated electronic interaction as well to make the experience more powerful and pleasing.

Touch is a locus for *reflex-rate user reactions*, measured in milliseconds. Certain kinds of manual tool control share this need, and haptic feedback could be used to elicit and transmit the user reaction from computer-supplied stimuli at these rates.

### Affect, Comfort and Communication

Haptic feedback can add *social context* to a socially sensitive or impoverished situation: for example, computer-mediated connections between people or between people and computers in professional, personal and entertainment domains. Communicating affect or personal presence in a variety of ways may enhance such situations, and augment the sense of a shared experience. As we learn its language and build on its strong social and personal-space connotations, haptic and gestural feedback could be a central means to this.

Much of our natural touching gratifies urges purely of aesthetics and comfort – for example, stroking attractive surfaces and fabrics, and fidgeting with articulated objects. As mechanisms and natural materials give way to digital circuits and plastic, opportunities for such indulgence become scarce. Gratuitous addition of nice-feeling haptic qualities can immeasurable enhance the pleasure of interaction.

### Other Areas of Value

The techno-literati are not just wired; they are wireless and portable**.** *Wearable controls and information displays* are active research areas, and good manual controllers will play a key role in their ultimate usability. Currently haptic feedback in wearable devices is challenging because of the size and power requirements of most conventional haptic actuation techniques, but with creativity and constraints there are ways around this.

*Biomedical and prosthetic applications* include augmentation, filtering and otherwise supporting manual activities by the variously disabled; and in fact, are among the first areas of haptic feedback research [11]. With the growing prevalence of keyboard-and mouse induced repetitive strain injury, this research area may hit mainstream.

The *representation of virtual objects and sense of remote telepresence* is perhaps the most widespread haptic application today, and covers the emerging gaming industry. Heavily examined and implemented elsewhere, it is nevertheless worth noting that many of the observations above still apply and could serve both to see where the expensive telepresence systems used are really helpful, and to see how to increase their value.

## Desirable: Restoring the Physicality Lost in Electronification

An important new opportunity for haptic feedback comes with the computerization and electronification of interactions which historically we carried out face-to-face or manually. Because of their personal and affective affordances and capability for continuous control, haptic interfaces may be the way to restore both improved usability and humanity to these interactions.

### Dealing with Complexity

While it can be argued that the world has always been getting more complex, the Information Age has brought entirely new rates of technological change. The volumes of information and things and devices they must deal with routinely overwhelm people. Is there a way in which physicality in electronified interfaces can help?

Things are complex for a variety of reasons. For example,

- There are too many.
- They are confusable and hard to distinguish or remember.
- They are easy to lose.
- It takes too many steps to do it.
- It isn't clear how it works.

Some of these problems are exacerbated with electronic technology, which tends to propagate discrete button selection (the ubiquitous up-down arrows), hide functionality, rely on menus and tiny touchscreens, and be wireless and buried in the couch. They rarely help the user form a useful mental model of the system being controlled.

A suite of well-designed embedded physical interfaces, including active and passive haptic displays and active tangible objects, can help with different subsets of these problems. For example, context-sensitive active haptic feedback in a knob on a handheld controller permits a single analog input to be clearly redirected, if the result of the control action is consistent in the environment and in the haptic feedback. Feeling a virtual representation or "map" of an electronic system's operational model can help a user understand how it works. Haptic feedback can offer clues as to what a user's options are, through constraints and gentle guidance. Tactility can be used to differentiate arrays of buttons. Sequences of discrete steps can be merged into a single fluid continuous control gesture. Active objects can transport electronic tool use away from the desktop computer.

### Aesthetics in Manual Interfaces

After functionality is addressed, there is the matter of pleasure. Manual interfaces to electronic devices can be inelegant or unpleasant for many reasons, and this can contribute indirectly to lessened usability. This list begins with minor culprits, curable with explicit attention to passive feel. The more intrinsically noxious should be newly conceived in interaction model as well as details of input and display, and could engage more sophisticated haptic tools. Here we discuss some desirable aesthetic attributes of manual interfaces.

*Pleasant tactility* makes one want to touch, and then hold or stroke an object. Choice and placement of texture, compliance and other material properties all contribute, as does object shape. Together with visual aspects, they lead a user to grasp and interact as intended, assuring a more satisfying experience.

*Satisfying motion and dynamics* often feel best when they are most informative; membrane switches and rattling buttons don't tell you what you've done. Context dictates the ideal dynamics and haptic events, but they should strike a balance between perceptible and too hard, and correlate to the device's function.

*Ergonomic principles* should always be respected; any frequently or continuously used manual interface should avoid cramping, clutching, nerve pressure and heavy use of weak fingers.

*Inherently continuous tasks* become natural when controlled with continuous input. Up/down arrows may be an unnatural way of controlling volume or video fast-forward rate; but a fine way to jump from one radio station preset to another.

*Inherently discrete tasks* are most comfortably executed with discrete input – the small incremental strain of selecting a GUI menu item with a mouse builds up. Force feedback can impose discretization in arbitrary needed locales.

*Intimacy with the controlled system* is a trait of the most dextrous tools, giving a user the sense of being inside an object rather than directing it from the outside through superficial and indirect means. Latency between command and perceived response is another kind of distance-producing artifact.

*Muscle memory* is an ancient source of manual skill now re-deployed into principally cerebral realms. Frequent, patterned tasks – unlocking a door, traversing a file system, penning a chain of Graffiti characters – can be structured into stylized or abbreviated gestures, reducing cognitive load and tedious extra steps.

*Personalization* makes a device special and suggests ownership and value. The latest Palm is sleek and lovely and just like everyone else's; the iMac's gummi-bear hues

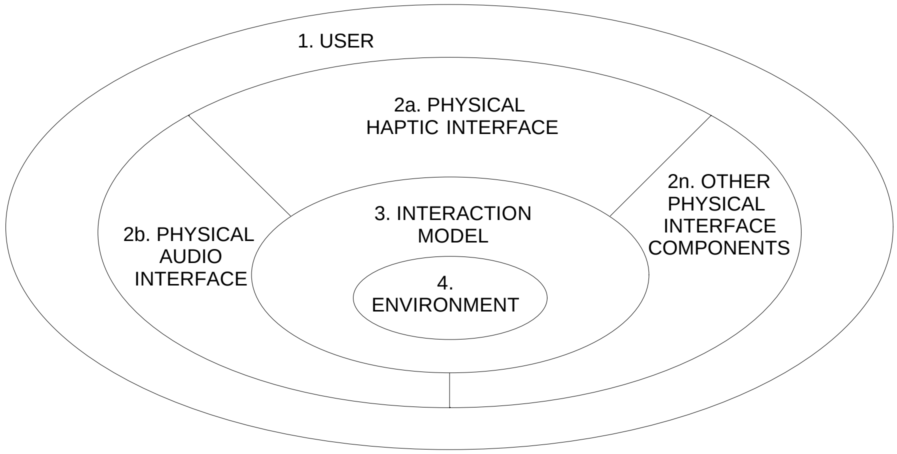


Figure 1. A simple generalized model for multi-sensory interaction with an environment.

address this in one limited way. Old-fashioned tools become personal when worn to fit the owner's hand, or modified to suit a need or style. Haptic feedback is an opportunity for adaptation: e.g., to give an impression of others who have used an instrument, the way donning a broken-in baseball mitt conjures a sense of its owner.

## II Creating Models for Haptic Interaction

The previous section organized experiential evidence of the integral role touch plays in our relation to the physical world, and suggested how touch is underutilized in human-machine communication. We proceed to outline a high-level interaction model structure and some insights into forms of haptic interaction that arise out of recent work. At this early stage of application conceptualization, some families of haptic interfaces are sparsely populated; but we anticipate that this map will reveal holes as the field matures.

### A General Model Structure for Haptic Interaction

Figure 1 illustrates a simplified, generalized view of a haptic interaction as a multi-layered structure, with the user on the outside, the manipulated environment at the core, and layers of physical interface and interaction models in between. The key features of this representation are firstly, acknowledgement of the integral multi-sensory aspect of most haptic interactions; and second, the explicit presence of an interaction model (Layer 3) between the physical hardware (Layer 2) and the environment being manipulated or perceived (Layer 4). The latter allows an arbitrary relation between user and environment, direct or abstract.

While there are forms of mediation of the user-environment interaction that do not fit into this general structure, it covers the majority of cases and is a useful platform from which to discuss haptic and multi-sensory interaction design.

*The Environment*

The environment is whatever the interface is intended to observe or manipulate; for example, a CAD representation of a physical mechanism or a solid-body model. It could be the lighting and temperature of rooms throughout a house, your account balance at an ATM machine, a video or audio stream, a database, or a Windows screen. The environment is distinct from the interaction model and its components and may be represented in arbitrary ways, unrelated to its own form. For example, if the environment is a 3D model of an oil derrick, the literal interaction model of directly touching and manipulating its moving parts is just one of many possible.

*The Physical Interface*

The physical interface (Layer 2) is comprised of the mechanical transducers and displays that accept input and provide output to the user for all the sensory modalities. For a graphical interface, this could be a CRT; for an auditory interface, a speaker or headphone. The haptic physical interface is the mechanical I/O for the haptic display and motor control. Its display and control mechanisms need not be co-located, although they often are. There will often be other input devices that are haptic in nature, e.g. a keyboard and mouse.

*The Interaction Model*

The interaction model, detailed in Figure 2, relates user input to the environment for synthesis and communicates its state to the various displays. Each sensory mode has its own sub-model that generates its specific display. Likewise, each input modality (touch, voice, etc) is processed in the sub-interaction model layer, producing signals that are integrated before transmission to the environment. The sub-models illustrate how each user-input and -output modality may fill an arbitrary and re-

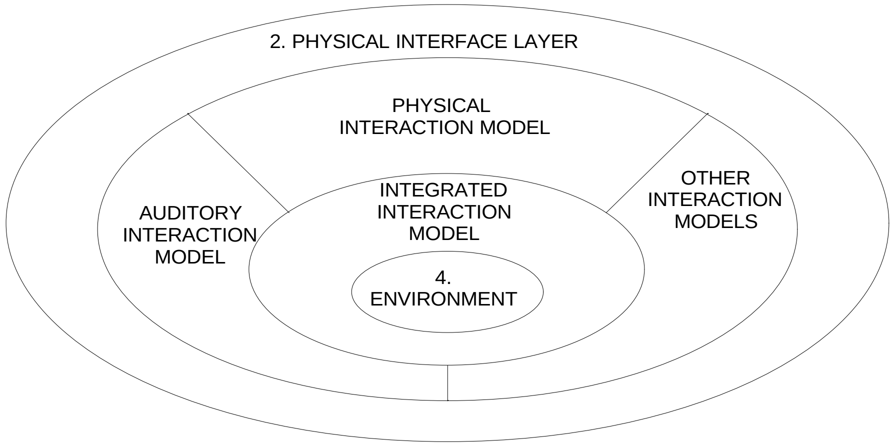


Figure 2: Detailed model for Layer 3 (Physical Interaction Model).

assignable role relative to the integrated interaction model.

### Abstraction in User-Environment Mediation

Haptic mediation between a user and an environment can be pitched at different levels of abstraction.

1. **Direct Manipulation**. At the most literal level, an environment can be rendered, probed or palpated through an interaction model that mimics the environment itself. The haptic interaction aims to directly "feel" the environment or signal, with minimal interposed abstraction outside of rendering techniques.

2. **Container Manipulation**. A simple, relatively automatic hierarchical layer of abstraction is interposed between environment and user. The user feels containers or bins of the raw signal or model; for example, bumps corresponding to successive frames of a video signal, as opposed to the raw bits and bytes coming down the line.

3. **Annotation**. Editorial content is added to a signal or model environment in the form of annotations, which a user can perceive haptically. The annotations are generally linked to discrete locations or components of the environment, rather than becoming a general property of the interaction model.

4. **Mediating dynamic system**. The integrated interaction model and/or its subsidiary sensory-mode interaction models comprise an arbitrary, abstract dynamic system used to manipulate and observe the environment. This interaction model might structurally bear no direct relationship to the structure of the environment. For example, the interaction model for a video environment might be a spinning virtual mass. The user interacts with the video by spinning up and braking the mass, whose rotation is linked to the visual frame rate.

This last and most abstract interaction model will often offer the most options for powerful, intuitive control of many kinds of environments which might not be easily represented in more literal ways. The fact that its structure is not tied to the environment structure gives the designer great freedom, but may also entail greater challenge to make the interaction intuitive.

### Other Challenges for Haptic Design

As with other mediums of interaction design, it is common to employ metaphor to find useful abstractions and generate intuitive tangibility in computer-mediated processes. For haptic manipulation, many of the relevant metaphors will relate to conventional manual tools, actions, materiality and objects.

#### Tension between Discrete and Continuous Control

Haptic feedback can be useful for both discrete and continuous regimes of manual control, but it will generally be most valuable when the latter is required. When a task has components of both (e.g., the need to discretely change mode or content of an environment as well as continuously manipulate that content), designing the affordance for both and the transition between them to be intuitive and seamless can be nontrivial [9].

This tension can also be an opportunity for a revised interaction model. For example, in the case of browsing streaming media such as video, the environment's gradual transition from a discrete (individual frames) to a continuous control regime based on frame rate could be related to the "freezing" of granular elements into a rigid body. In the frozen regime, the rigid body can be shoved, spun up like a flywheel, and perhaps stretched as a coherent elastic body. Alternatively, the discrete phase might be seen as frozen, then "melting" into a fluidic continuous phase. Fluid metaphors such as spraying and pouring would then come to mind.

#### Displaying Interaction Potential

A requirement of any good interaction model is that it makes clear to a user not only *how* to switch an activity or elicit a behavior supported by the model, but that the potential of doing this exists at all. A haptic interface might render this more challenging than is usual, because it lacks the "easy out" of menus and toolbars and visual icons. At this stage, it also lacks the history of past interfaces and expectations, in the way that any user knows that "ctrl-V" will past clipboard into a Windows application.

The strong use of metaphor and suggestibility in physical design as well as simplicity are good tools to use here at least initially, since they invite using the interface in the same way as the implied physical object. As custom and familiarity with haptic interfaces grow, it is reasonable to expect that a language and set of conventions will surround them and make this problem easier – or if the conventions are not ideal (e.g. the QWERTY keyboard), perhaps more restrictive also.

### Customization and Embedding of Simple Physical Haptic Interfaces

The challenge of creating intuitive haptic interaction using abstract models is aided by physical design consistent with the interaction model and other sensory displays. For example, a spinning-mass interaction model for video browsing is intuitive when the video is displayed with low latency, and the haptic display looks and tactually feels like a wheel. If the haptic display looks like a pen-probe or a mouse, it may be harder to figure out.

This diverges from the more prevalent view in commercially available haptic displays, that for excellent reason seek to provide general-purpose access to graphic displays and game monitors. However, these displays are often expensive as well as highly generalized. When the requirement of generality is relaxed, a cheaper, simpler special-purpose haptic display can be created with a handle crafted for a given task. We expect this approach to become more prevalent with the spread of embedded controllers.

### Tight Sensory Coupling for Perception of Control

Some of the best-feeling haptic synthesized haptic interactions seem to derive not from the specific qualities of the haptic feedback, but from the low latency by which it is linked to environment manipulation and other sensory displays. We call these "tight-coupled" displays, and value the sense of power and control they offer the user. Tight coupling can be achieved in various ways, for example through the use of realtime software architectures, high interprocess communication rates and code customized at a low level [8].

Some applications particularly justify the maintenance of low latency communication among interaction model elements; for instance, musical and drawing controllers, which rely on expressivity and crispness of response. However, the effect is generally satisfying enough that we hope it will become a minimal standard of performance for multi-sensory display.

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