Aladdin:
Exploring Language with a Haptic Door Knob

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ABSTRACT

As part of an ongoing exploration in using the haptic (touch sense) medium to enhance interaction with embedded computation and render it more expressive, we built Aladdin, a door with a haptically active knob. We chose a door as the basis of this work for its quality of mediating a real social threshold and for being a commonplace manual control which provokes a range of expectations. The haptic display combined torque and thermal outputs, and we used it in intimate relation with an auditory display in order to extend its expressive range. We used Aladdin to implement a set of narratives that developed its possibilities; and during this process, postulated a framework to describe a haptic language and used it as tool to design and discover haptic experiences.

KEYWORDS: haptic user interface, tangible, tactile, kinesthetic, embedded, expressive, language, manual control.

I. INTRODUCTION

The trend of networked microcomputers moving into the spaces we inhabit and the appliances we use when away from the desk offers many benefits; but it can also levy a cost through impersonality and constraints in the ways which people can communicate with them. “Smart” interfaces embedded in the world now and in the near future, like ATM machines, refrigerators which track the pantry’s inventory or automobile environment controls, promise immediate access to services and seamless connection of our personal data. But a natural consequence is that computers increasingly absorb or mediate more personal exchanges with clerks and service-people, tools and places and even family. Computers are good at conveying precision and quantity and at processing discrete options, but they articulate expression and qualitative distinctions awkwardly. They are less amenable than are humans to subtle forms of directives and inferences, and as such do not access a range of communicative qualities intrinsic in our relation to the real world. Many people find the result an impoverishment in their daily lives.

This paper will describe a project which explores using our haptic (touch) sense as a channel for a more expressive and aesthetically satisfying mode of communication with this kind of embedded computation. The haptic sense includes perception of force, texture, temperature and moisture. Among all the senses it is uniquely bidirectional, coupling manipulation with sensation in the same location. Active haptic feedback – implying computer-controlled modulation of haptically sensed qualities like force or texture through a mechanical display – provides an effective channel for some kinds of information and cues. It is particularly useful in situations where there is a need for continuous or dexterous manipulation; where other perceptual channels are unavailable; where there is a desire to notify with discretion; or the desired communication is affective or imprecise.

There have been decades of study of haptic perception, and increasing attention over the last dozen years to the engineering of interfaces which use it to explore and manipulate virtual models or remote real environments. While it would seem that active haptic interface design should be well suited for expressive or abstract communication, little research or development has addressed this challenge.

Here, we focus on a set of research questions underlying the use of a haptic medium for expressive communication:

- *Embedded Physical Interaction* – lodging active haptic displays in architecture and objects with the aim of making the technology behind the interface more engaging.
- *Multihaptics* – extending the haptic display palette beyond the customarily used elements of force and vibration to others like heat and dampness, bringing physical interfaces closer to the richness of skin and limbs connecting with the real physical world.
- *Multisensory* – merging haptic feedback intimately with displays for other senses, to enhance the expressiveness of the whole experience.
- *Haptic Language* – moving beyond literal representations and direct manipulation to convey expressive and narrative qualities.

To this end, we built Aladdin, a door with a haptically enabled knob, and used it to enact a set of narratives which explore the roles it could fill. The knob displays both torque and temperature to a user's fingers and palm, allowing us to consider multihaptics; and an auditory display is tightly integrated with the haptic feedback to so we could try narratives which rely on the storytelling strengths of both sound and feel. We used all of these technical capabilities to push the limits on the range of expressive qualities we could achieve, through the crafting of the narratives' feel and sound. We were able to demonstrate these experiences to a few people, and recount some of their reactions. These suggested that the interface's location was surprising but could be compelling; and that the tight coupling of haptic display with sound and the use of a thermal display did indeed enhance the interaction's expressive capabilities.

In this process of designing Aladdin, generating stories for it which seemed interesting, and then trying to translate them through hardware and code into compelling experiences, the need for better understanding of how people perceive and interpret haptic sensations became ever clearer. Afterwards, we attempted to encode our insights by constructing a preliminary framework, outlined at the end of this paper. In the future, we believe such a tool will help designers of expressive haptic interaction to describe the haptic qualities they desired, employ it to discover new expressive elements and ways of relating them, and find a path to more easily implement them.

II. BACKGROUND

Embedding Haptic Displays in the Everyday World

Most commercial haptic displays and academic research are currently oriented towards desktop applications. Readers are most likely to be familiar with commercially produced displays such as the 6-dimensional Phantom [Phantom98], often used for manipulating three dimensional graphical CAD models; the Immersion force-feedback game joystick, or tools like the PenCat [PenCAT98, Rosenberg97] for two-dimensional navigation of graphical user interfaces. More research-oriented applications include surgical simulation Madhani98], and aids for manufacturing and design [Colate96, Hollerbach96, MacLean96]. There has been less attention to the integration of active haptic displays into everyday manual controls [Gillespie94, MacLean96] and it has been largely devoted to simulating systems that exist in the real world. Our vision is to employ active haptic feedback as an expressive element in customized interactions within everyday spaces, rendering numerous points of connection with the digital world more pleasurable and effective.

Embedded haptic displays raise new issues. How will people react to "live" objects in their environments, and will the initial oddness become accepted? Can movement through mediated touch be as engaging and fun as other modes of expression, making it a good candidate to soften the edges of the electronic world? What will be the true added value of embedded haptic displays, and will it be enough? These questions are best answered by putting a haptic display in the real world and seeing what people do with it.

Multihaptics: Torque and Temperature

While there are innumerable variations in configuration and technology, with few exceptions [Ottensmeyer97, Caldwell97] haptic displays have controlled force or torque and vibration to generate their illusions. This is because these modes are both the easiest to construct – which is not to say they are at all straightforward – and most immediately useful for the sorts of applications thus far pursued. Force displays aid a user in interrogating shape and manipulating virtual objects; vibration can be used to imply forces and textures on virtual surfaces. Other haptic sensations such as temperature and moisture are even less exact and problematic to create. Most importantly, with more conventional applications it is not clear what they would add.

Here, however, we wanted to push the expressive range of our haptic vocabulary, and adding the ability to synthesize a new, subjective and imprecise kind of haptic sensation was very useful. We picked temperature; having toyed with displaying moisture in various ways in the past with unsatisfying results, we decided to leave it for another time.

Multisensory: Coupling Sound with Haptic Feedback

From the outset we were interested in pushing the link between audition and haptics. Sound is an inextricable part of the haptic experience – for example, the scratch of a pen on textured paper is both a felt and heard perception. Haptics researchers have long realized that the synchronization of a sound with a haptic event influences its believability: a haptic wall, for example, can be made to feel stiffer or softer by the sound that accompanies it [Rosenberg94].

We wanted here to go further, and explore a range of ways in which sound and haptics can work together: by giving them different but complementary roles in a narrative and synchronizing them at key points, and by letting one control the temporal flow of the other.

Need for an Expressive Haptic Language

While haptics research steadily improves underlying display technology, it has become apparent to us that for active haptic feedback to become a useful and socially communicative medium we need to discover its language. There are realms of potential haptic applications which sheerly technological advances will not bring within reach; but they may be realizable now with the most ordinary mechanisms if we can grasp how the thing must speak. Here, we are interested in understanding how to manipulate salience and interpretation and expressiveness in a medium making use of the haptic sense, and Aladdin's creation was spurred by a desire to attempt this in a provocative context.

There has been past work in beginning to identify the design space of physical user interfaces, e.g. [Fitzmaurice95, Ishii97]. A large part of this design space applies to embedded haptic interfaces. However, it does not go far enough for our purposes: focussed on physically inert objects, it allows local microprocessor intelligence or light but not active haptic activity. Here, our principal interest is in the quality of that haptic activity, and the fine-grained manner in which it relates to the rest of the interface experience.

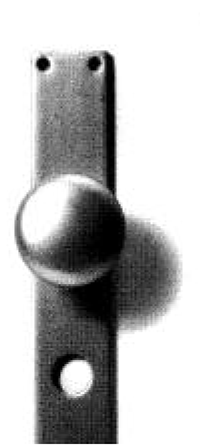
Part our recognition of the value in attempting to codify elements of haptic language came as we created the narrative threads we would use to give Aladdin contexts for exercising this expressiveness. The narratives were attempts to exercise different aspects of the door in compelling ways: the door in one, The Party, gives you a chance to get accustomed to the mood of the room you are about to enter. The doors in The Well House and The Seductress offers information on the state of the room. The Malleable Knob transforms in response to the flow of people through the doorway during the day.

Simply listing the adjectives we chose to tell these stories verbally, before any attempt to implement them, suggested the breadth and specificity of sensations we wanted – curvaceous, fluttery, leaden, feverish. What haptic affordances would you need to translate these to feels; and how would you then layer and connect them? This lead us to generate the haptic lexicon and syntax that we describe in a later section, borrowing from more studied modes of communication and grounded in an awareness of haptic psychophysics.

III. THE ALADDIN SYSTEM

Why a Door?

We chose to build a door, rather than a haptic light switch or radio dial, because as both an architectural feature and a social boundary it seemed it would be fertile ground for investigating our questions. A door is a barrier between two spaces, and the area surrounding a door represents a boundary zone for leaving one space and entering into another. It is a place for social interaction, and when the door is shut, a place to wonder about what's happening on the other side. Its handle seems a natural location for an expressive and communicative element; in fact, home owners and architectures already use door knobs to convey character and style.



System Overview

As envisioned, Aladdin would be a door to a real space with a haptically active knob, computer control of its latch and knowledge of the door's angle of opening. The sound to support the narratives would come from different sources as needed – behind the door, from the knob, or out of the door itself – and the door's behavior would respond to presence and activity sensed in the room beyond as well as to a user's handling of its knob.

The engineering prototype built here and shown in Figure 1 has a large subset of the functionality we imagine in a final version. Prior to building a full-sized door mediating access to a real space, we needed to address the technical issues in haptic embedding and some elements of the ensuing interaction experience. Our prototype is a half door and room activity is not monitored; high quality sound comes from speakers at head level in the door's wall. We implement all of the other desired capabilities in this prototype – a knob with a multihaptic (torque and thermal) display, door angle sensing and latch control.

Figure 1: The Aladdin engineering prototype, shown here with the thermal knob, is a half-door with a fully functional knob, latch control and door angle sensing, and an auditory display.

The deviations from ideal did restrict this prototype's use as a platform for a social experiment. Since it is a half rather than a full door, a user can feel the knob, open the door and listen, but without being able to pass through it is not obvious to regard it as a threshold. Secondly, the door is not the entrance to a real space, depriving it of a context; and since a real space is not sensed, the narratives used in our preliminary experiments are manufactured rather than real-time. We were nevertheless able to get some sense of user reaction and use them to generate new ideas for how it or other embedded haptic interfaces might be used; these will be discussed in a later section.

The unique features implemented here enabled our study and development of haptic language:

- the embedding of a haptic display in an architectural element;
- multihaptic display of torque and temperature in one location;

- a custom realtime software architecture for tight coupling of displays to multiple senses;
- an auditory display providing finely grained control over sound content and filtered effects.

These features are described briefly in the following. For more detail on Aladdin's construction, please refer to [MacLean 99b].

Embedding: Functional Layout

Figure 2 shows the prototype's functional layout. A custom-built half-door on a pedestal is conventionally hinged and opens fully. Its angle of opening is sensed with an encoder in one of the hinges, and it is locked with a computer-controlled solenoid latch. Its knob is the active haptic display with two components: torque feedback occurs through actuation with position readback on the knob's turning axis, and thermal display is provided in the body of the knob using a thermoelectric module. The auditory display is a pair of speakers mounted at head level on either side of the door. Power and signal lines are routed from the computer and power supply in the pedestal, up into the frame and through the hinge to reach the knob.

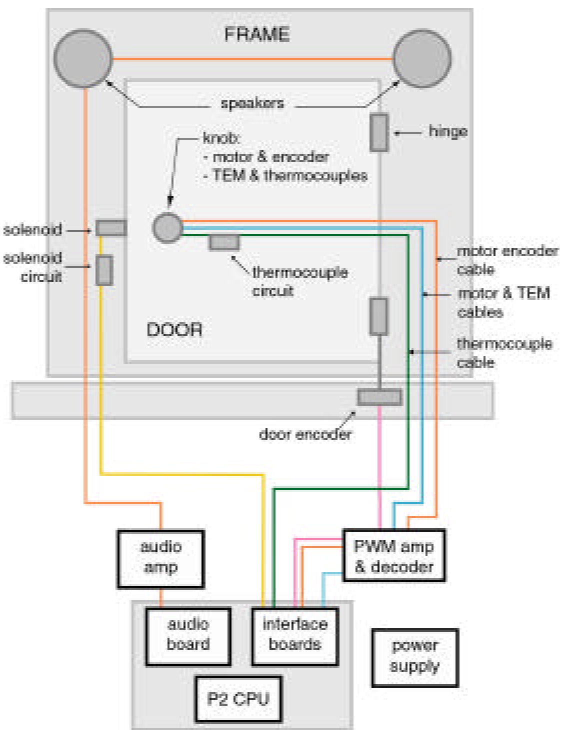


Figure 2: Prototype operational schematic.

A single Pentium II CPU orchestrates all sensing and control while traversing a programmed interactive narrative, with transitions and branches triggered in response to a user's actions – e.g., when he first touches the knob, how hard he pushes against a resistance, or how quickly he turns it at a key moment.

With the exception of designing the thermal display, described in the next section, building these display and sensory elements into the door was a straightforward albeit nontrivial job. However, we simplified the problem substantially by permitting ourselves a convenient pedestal computer housing and a custom-built door: to retrofit such a system into an existing door set in a wall (truly embedding it) would be much more involved. For example, we did not have to tear into existing walls to access the installation. We were able to use a desktop computer, which speeded development and reduced the number of elements we had to locate within the door and walls themselves. Likewise, we did not in this prototype concern ourselves with power requirements and point of supply; but in a real installation, would want to minimize additional power needs for reasons of cost, cooling and ecological impact.

Multihaptics: Torque and Thermal Displays

Aladdin's haptic output is produced by a torque applied to the knob's rotational axis combined with a temperature-controlled knob surface. The display can be configured either with the thermal knob or with arbitrary and much simpler non-thermal knobs which permit greater freedom in shape and range of motion. The knob can also be controlled when untouched, as a visual or gestural display.

Figure 3 is an exploded CAD drawing which shows how the mechanical elements fit together. [1] is the thermal controlled surface. [2] is the heat pump, source of thermal output. [3] is the TEM's rear heatsink. [4] is the heat pump's power and signal conduit. [5] is the DC torque motor. [6] is a cutaway of the front door surface. The entire knob downstream of the motor shaft (elements 1-4) turns as a single rigid unit.

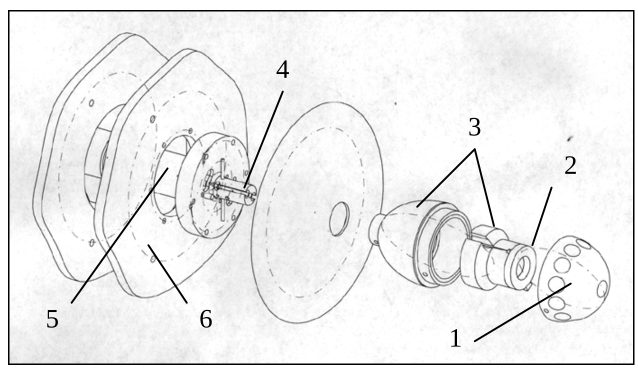


Figure 3: Exploded drawing of thermal knob, actuator and cutaway mounting in door.

Torque Display

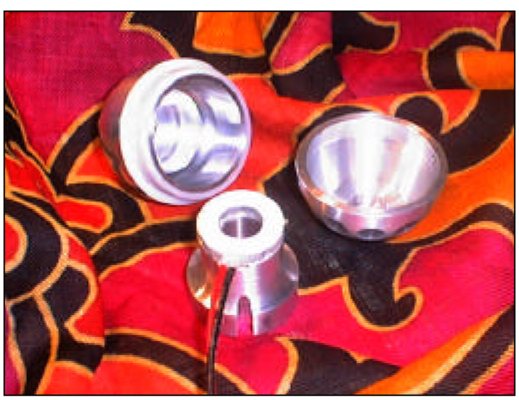
Torque feedback occurs through a direct-drive DC motor with a position encoder, conventionally controlled at 1 kHz ([5] in Figure 3). The principal challenges in locating it within a door were disguising its length, which was wider than a normal door thickness; and routing electrical connections from the computer located in the pedestal's base, through the hinge to the motor. The motor's length was accommodated with curved spun plates on both sides which were effective in making the whole knob assembly appear normal.

Because of their different inertia, we had to use different control gains when using the aluminum thermal knob or the other knobs we tried, which were constructed of wood or foam. Even with altered gains, the heavier thermal knob was more difficult to stabilize than the others and thus the haptic performance was sometimes lower when combined with temperature output. Since it seems important to keep the thermal display on the moving part of any interface that employs a temperature display, this situation will continue to be a constraint and needs to be revisited.

Thermal Display

The thermal element is the most experimental aspect of the haptic display, since this medium has been less used than force/torque or vibration in past haptic research. We used an annular thermo-electric module or TEM as a heat pump and integrated it directly into the handle (Figure 4a). A TEM operates as a reverse thermocouple, creating a temperature gradient across its surface in response to a voltage; one surface can thus be made colder than ambient temperature, but the other surface then becomes warmer. The warm side must be cooled by either air flow or heat sinking to prevent the TEM from burning out. This posed a challenge, since we wanted the user to feel only one temperature, rather than the two juxtaposed; and we could not locate an efficient finned heat sink on the knob since this could hurt the user if the knob were to slip in his hand.

(a) assembled to show surface detail



(b) disassembled to reveal the touch surface, thermoelectric module and internal heatsink.

Note: better photo will be included in final version

Figure 4: Thermal display in haptic knob

The solution was a compromise. The TEM is buried near the tip of a thermally conductive aluminum body with thermocouples on the front side for closed loop control, a second thermocouple on the back to alarm the control computer of eminent burnout, and a smooth (less effective than finned, but safer) heatsink on the proximal knob surface ([3] in Figure 3). Unavoidably, part of the heatsink surface can be touched by a user's hand; but we designed the shape and dimpled features of the knob (Figure 4b) to encourage a fingertip grasp which would fix on the front, controlled surface. The distal, temperature-targeted region of the thermal knob ([1] in Figure 3) can be driven to about 15 degrees F above and below room temperature within 15-30 seconds, extremes which register as clearly "hot" or "cold" without burning or frosting a user's hand. Since we had in mind for temperature to correlate to slow room environment changes, this was an adequate response time.

The other design complication was in getting power and thermocouple signals on and off the knob. This was accomplished by limiting rotation to 180 degrees so that the wires could be routed through a conduit in the shaft ([4] in Figure 3).

Knob Shape Design

The knob's shape and texture are critical to the experience's success. In addition to the thermally active knob, we used a number of differently shaped and textured non-thermal knobs for some of the narrative contexts, experimenting both with effective display and protection of both user and motor. The latter included attention to orienting the user's grip with the knob's shape and texture; minimizing the load on the motor through choice of encouraged grip; avoiding external protrusions and asymmetry of shape which might abrade or cut the user's hand; and enhancing perception of deliberate motion with visual asymmetry.

Tight Coupling: Realtime Software Architecture

Our software architecture is designed to enable tight synchronization between haptic sensing and display and other continuous media such as audio and video, providing the sensation of direct control and rich, dynamically configurable behavior, and is used in numerous applications in our lab. In addition to achieving a particular kind of performance, we wanted to make it easier to author complex and interesting haptic experiences. We use the QNX realtime operating system to guarantee response times at the rates we are interested, sub-millisecond for the haptics process while also permitting multiple clocked threads and interprocess communication. This OS is also embeddable, which will ease the transition to lower-profile implementations at a later time.

The architecture, at present existing as a software API and template code to provide structure for new applications, has the following key elements:

- Multiple processes running at different refresh rates.
- Two-way communication via shared memory, message passing and remote serial/Ethernet protocols.
- Bulk of computation on the haptics side of the model for tightest feedback with user.

Figure 5 indicates the general structure of the architecture we used here. Although shown in its own block to illustrate its functionality, event management – e.g. transitions in the narrative, cued in response to user actions – are in the Aladdin implementation handled within the haptics process, because it runs fastest (1 kHz) and has earliest access to the sensory information on which transitions are based. The audio control process (or video control process, in other versions in our lab) is treated as a client since it does not trigger control events. This location of "master" control within the haptics process, rather than a slower-running graphics or audio process, is where our model departs from most current convention for functional distribution in multi-process haptics control code. It is a direct consequence of our priority on tight coupling; and made possible by employing virtual models which are not computationally intensive.

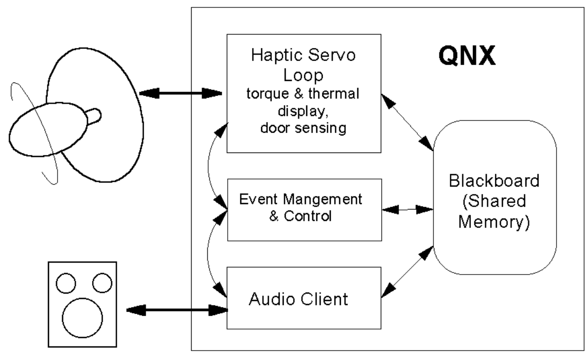


Figure 5: Software architecture, illustrating the primary processes (haptic and audio managers) and shared memory.

Other features of our architecture include run-time targeting to different or multiple devices, cross-platform development and a simple callback model for registering haptic and non-haptic processes and establishing the shared memory and other communication protocols. The callback model allows the authors of haptic experiences to focus solely on the haptic coding and ignore the details of timing, filtering and other computation.

Further details of the software architecture may be found in [Maclean99a].

Auditory Display

The auditory display is crucial to the Aladdin narratives. It relies on tight realtime coupling between the haptic and auditory displays; small audio buffers are swapped directly by the main control CPU before routing through an audio board. The buffers are updated at 88 Hz and the audio process communicates with the main control process at the same rate. This results in low latency in modifying the auditory signal in response to manual user interactions. This rate is limited by the CPU; but while 88 Hz is well below perceivable audio frequencies (44 kHz), we have found it an acceptable response time for modifying an audio event.

A number of effects (volume, speed of play, equalization, distortion, reverberation) can be applied to the audio output in realtime. Together with the auditory and haptic content, they are expressive design handles available for use in crafting the overall interaction. For example, turning the knob against a textured resistance might cause an audio feed to become less distorted, giving the impression that the knob brings the sound into focus. In the current implementation, a great deal of aesthetic pre-processing is done on the audio material, which is taken from a variety of sources. In later prototypes, much of the audio may be processed with dynamic filters from live pickups inside the room.

IV. NARRATIVES AND REACTIONS

Here we describe the narratives implemented on the Aladdin door, and discuss the reactions we obtained from some colleagues who used it.

Narratives

The Party

On approaching the door you hear faint, distorted sounds from activity in the next room. As you turn the knob it grows lighter and the sounds get louder and start to clarify. Finally, as you open the door it becomes clear that the sounds are coming from a party in the room you are about to enter.

This narrative emphasizes the transitional zone surrounding a door. By turning the knob you can focus or tune into the sound space behind the door. The combined effect of the haptic and auditory phrase is to prolong the moment and give you time to adjust to the mood of the room. The weight of the knob forces you to pause and focus on the unraveling of the sound, almost as if you were moving from slower to normal motion.

The Well House

While on holiday in Korea a colleague noted that the door to his hotel room made sounds to indicate that a) on exiting, the lights and heating had been switched off and b) on entry, the room had not been disturbed. He found this to be simple, yet effective feedback, which reassured him that the room was "at rest". He also noted that this feedback occurred when and where he was most likely to wonder about the state of the room.

Picking up from this we looked at creating a remote sense of presence by making the doorknob become hot when someone was inside the room and cold when nobody was inside. We also experimented with how comfortable the knob felt when it was being turned - where the suggestion of angular movement and resistance indicated the degree to which the room was not at rest.

The Malleable Knob

The door for this scenario would ideally link two public spaces. As people pass through the door and make use of the knob, the movement of the knob and its texture begin to change. Levels of activity through the space are recorded by these changes, such that the knob is continuously being sculptured.

In one realization of this scenario the knob felt firm and crisp at the beginning of the day, matching the expected feel of the heavy looking, aluminum knob, and hot and gummy after a bout of heavy usage. It was interesting to note how far we could stretch the suggested materiality of the knob. The more radical the contrast from the look of the knob, the more the imagination worked to fill in what had been happening and who had been using the knob.

Hide and Seek

You hear sounds coming from behind the door. The sounds seem to suggest a busy hallway with lots of people opening and closing doors. As you turn the knob it starts to resist you, and you hear the sounds of people running. The more you try to turn the knob the more it resists you. Suddenly the knob acquiesces, the door opens and the room is silent – saving a few suppressed giggles. After shutting the door the sound of people moving around starts up again.

This is a game. The sounds of bustling activity are intended to arouse your curiosity. The increase in tempo of the sound track and resistance of the knob as you try to turn it will hopefully arouse you curiosity even more. The double break in the sound and resistance is a point of synchronization, a form of punctuation where everything goes quiet and the sound and haptics come together.

The Seductress

In this scenario the door acts as a seductress and tries to lure people into the room. The seductress reacts to the mood of the room – the more energy and activity in the room the more the character tries to entice. The sound of a female voice cooing "hello" calls to you – the urgency and tempo quickens if she really wants you to come in. Turning the knob is akin to a handshake. The speed, directness and texture of the knob reinforce the urgency and the desire to let you in.

Learnings from Narratives

Embedding a Haptic Interface in a Door

Our attempt at embedding an active physical interface in a doorknob met with varying degrees of success. In The Party, where resistance is used to shift sound in and out of focus, we found that people used the knob as a tool. We had intended that people would turn the knob just once, to get a quick impression from the adjoining room before they enter. Instead, people tended to spend time at the door turning the knob back and forth whilst trying to eavesdrop; they may have been more likely to do this because they could not actually walk through the door. We enjoyed this unexpected reaction, but also realized that the interface did not respect its context and guess that we could not expect a person to linger so long upon entering a real door.

Aladdin worked more suitably for the interactions in The Well House, Malleable Knob and Seductress. Here, users did more often take a quick reading from the knob; we think this is because people had less control over content in these narratives.

Another aspect of embedding the interface in the doorknob was that many people were worried about touching the knob, especially for the first time. At one extreme a user 'jumped' every time she touched the knob. She did admit, however, that she tends to jump whenever the phone rings too. For most people, concern about touching the knob diminished as they got used to it. The addition of sound helped here, especially in The Seductress and Hide and Seek narratives, as sound helps to 'set the scene' and alert people to the possible mischievous behavior of the knob.

Multihaptics

The decision to experiment with multihaptics resulted in us designing a thermal display into the knob. Despite being tricky to integrate it was a successful part of the project. From the standpoint of language, we found temperature to be very salient. People noticed changes in temperature and would comment on them before mentioning other aspects of the haptics. Temperature was the ideal choice for the presence indicator in the Well House. In this narrative we wanted people to get an impression of the room without having to linger to explore other haptic features of the knob.

Multisensory

Our exploration into multisensory interfaces did enhance the expressiveness of the whole experience. Sound played an important part in acting as a decoy to draw people into the interaction, and in contributing to the phrasing of the interaction. People commented that certain sounds and feels irresistibly fuse together; for example, in The Malleable Knob the sound of someone handling wet chamois leather merges with the feel of goo.

Language

Our exploration of haptic language was informed by discussions on how to depict the characters and situations in our narratives. In The Seductress, for example, we chose to suggest one aspect of the character, her snake-like quality. The knob describes a circuitous *path* that takes a varying amount of *effort* to turn depending on how much we want her character to be noticed. Throughout the stages of (a) imagining the feels we wanted, (b) implementing them in code by building a virtual mechanical model, and (c) assessing the final result, we began to speak in terms of these qualitative dimensions of path and effort. These eventually crystallized into the kinesthetic axes we propose in the following section. The axes enabled us both to describe more clearly the sort of feel we wanted to implement, and to establish what we had tried.

V. HAPTIC LANGUAGE

One of Aladdin's trajectories became the building of a language for the knob – a haptic language that would be expressive and sufficiently rich to convey meaning. For example, as we began to envision the Malleable Knob scenario, we found we needed a vocabulary of strong kinesthetic impressions that could be used to represent patterns of activity through the space. We intended that someone using the knob from time to time throughout the day would recognize its feel, notice changes, and perceive larger patterns of evolution.

We were influenced by the work of choreographer Rudolf von Laban [Laban60] and Susan Leigh Foster [Foster86]. In describing movement in dance, Foster constructs a frame of reference for describing quality in movement. With reference to Laban, she divides quality in movement into four categories: space, time, weight and flow. These categories, in turn, have dimensions of indirect ↔ direct for space, sustained ↔ quick for time, strong ↔ light for weight, and free ↔ bounded for flow. All human movement, according to Laban, exhibits constellations of these factors that form identifiable efforts or textures.

A Proposed Map for Haptic Sensation

We felt it would be useful to construct a similar frame of reference to describe haptic sensations and their relation to one another. Our intent is not to produce an exhaustive codification. We wish to loosely codify a lexical palette, and use it to describe, plan, inspire and extend designs for haptic communication. Such a linguistic structure will help us observe what works and what fails when we combine grammatical elements, and extrapolate to new combinations.

While we recognize and routinely leverage the synergistic benefits of multisensory coupling, we will here discuss only *haptic* language, and leave the vast space of haptic-auditory and haptic-visual language for the future.

Dimensions

As with movement, qualities of touch can be organized along a few dimensions. The space spanned by these axes is a rich world of movement and touches. We considered both psychophysical and more subjectively interpreted perspectives for this division, and happily found them compatible. The origins of haptic interpretive distinctions are after all derived from the organization and capabilities of our fundamental sensory organs.

Kinesthetic Axes: *movement and forces*	
Path	[circuitous ↔ direct]
Rate	[quick ↔ sustained]
Flow	[free ↔ constrained]
Effort	[strong ↔ light]

Tactile Axes: *skin sensations*	
Hardness	[soft ↔ hard]
Sharpness	[blunt ↔ sharp]
Vibration	[slow ↔ fast]
Temperature	[cold ↔ hot]
Moisture	[dry ↔ wet]

Figure 6: Two proposed axis sets which together span the perceived haptic space. The axes' names are followed by their dimensions.

We found it most useful to divide our dimensions into two groups, distinguished by their derivation from either the kinesthetic (body forces and motions) or tactile (skin sensations) subdivisions of the haptic sense (Figure 6). Kinesthesia provides physical self-awareness, when the loads and movements imposed on or produced by our body stretch internal tendons and muscles. Tactility is a more direct connection to the outside world, inviting judgements of the texture, softness, heat and moisture in touched objects through deflection and vibration of skin receptors.

As with any space, an infinite number of orthogonal axis sets might be chosen; we found this one efficient in terms of the haptic experiences we sought. Illustrating in terms of The Seductress: the path the knob suggests as it is being turned is curvaceous, a snake-like motion designed to resemble the undulations in the cooing 'hellos' of the vocal track. Its rate is quick but irregular, constrained with only a suggestion. If the user chose to resist the suggestion, the knob would push gently and then try a different approach.

These axes represent perception at a processed and interpreted level, and are subject to illusions which can be exploited to overcome restrictions on the space imposed by a given piece of hardware. Although the Aladdin knob is physically constrained to single-axis rotation, apparently narrowing the usable range of the Path axis, dynamic modulation of Flow can convey the illusion of greater spatial variation. The net impression is of irregular path of rotation.

Ambiguity abounds in our classification. Within the tactile / kinesthetic division, compliance is sensed by either kinesthetic or tactile organs, depending on the degree of deflection. Kinesthetic "constraint" or tactile "hardness" thus refer to regimes along a continuum rather than orthogonal qualities. Similarly, roughness cues are received through a combination of tactile (vibratory receptors) and kinesthetic (knowledge of velocity) paths. There may also be confounding between axes within a domain, or even on a single axis. Moisture can be confused with temperature; we perceive wetness when a film of water on our skin evaporates, cooling it. Extreme hot and extreme cold result in the same initial sensation. Finally, when a surface is touched through a passive mediating agent such as a tool or garment, any of these axes may be distorted, magnified or masked [Hollins98, Katz25/89, Lederman82].

It would be difficult for any framework to accommodate the essentially messy nonlinearities, redundancies and tunings of our sensory apparatus, variation in individuals' past haptic conditioning, or the influence of context. Instead, we find that examining violations to a simple classification such as ours can lead to insight into useful illusions, and to intriguing sensory surprises.

Syntax and Salience

Individual haptic words may be related and arranged with syntactical operations. What grammatical tools are available for creating haptic phrases and stories? What functions may the primitive elements serve with respect to one another? The roots of salience are only crudely understood for complex haptic sensations. Some haptic primitives don't mix well, due to psychophysic or machine limitations; e.g. a clear haptic click superposed on a fine-grained repetitive background texture might vanish. The relative rhythms and forcefulness of sequential haptic patterns or trajectories frame, highlight or mute individual elements.

As with temporal languages, haptic sensations may be layered (superposition), and linked to traverse in time (transition). Their spatial component allows the use of location. Others are more subtle, and increasingly dependent on harnessing to other sensory modes: our narratives have employed punctuation, tempo and thematic variations in conjunction with sound.

Conversations

Touch is an interactive language: we influence what we feel through our own haptic response. This makes the haptic designer's workspace difficult and infinitely rich. One can't prescribe an experience, only suggest and encourage it, and the surprises are interesting as often as they are discouraging.

Some variety in user response arises from personality, some from expectations created through the interface's context (does it look like a handle or a button?), and some from familiarity. The user may actively explore or wait passively for something to happen. He may handle a probe tentatively or aggressively, with a powerful or a delicate grasp. He could rush quickly through the space and feel only dominant features, or slowly and carefully test for subtle qualities. He may be wary of getting hurt, or easily startled.

As with any sort of interaction design, one can encourage some desired behaviors. The handle's shape and materiality can influence how tightly it is held and its surroundings build expectations for what it will do and how it works. Visual features may invite particular kinds of movement. Dynamic haptic behavior often draws a user to explore and play with the virtual entities inside. Desired user behavior can be rewarded with changing sensations.

VI. CONCLUSIONS

We found this partial implementation of the envisioned Aladdin design valuable in answering both engineering questions and some of our larger interest in learning peoples' reaction to encountering expressive physical interfaces embedded in the world. This prototype allowed us to gauge some user reactions and generate more ideas about where the concept might be used. However, to effectively test the concept as a user interface, it is still clear that it must be more appropriately situated as a walk-through entrance to at least one real space used by a variety of people. We hope to implement this in the future since we feel our preliminary results are promising.

Engineering Issues

This prototype demonstrated the feasibility of integrating a haptic display into a commonplace manual control and points out areas that will require engineering iteration. Despite constraints, the mechanical design for the torque display was reasonably straightforward and successful in matching performance of other haptic displays. Building the thermal display was challenging and our solution limited its range of motion to 180 degrees, which in turn limited the haptic behaviors we could achieve; however, the desired control over temperature was achieved.

Embedding Haptic Displays: User Perceptions

We were able to exhibit Aladdin to a number of users and observe their responses to the narratives we implemented; from this we gained insight in both expected and unexpected areas.

We have become attuned to the issue of user perception of "live" interfaces. A consequence of embedding the display in a context beyond the realm of the desktop computer is that users may be startled by its behavior, and on the other hand are likely to use it more frequently and casually. Active haptic displays are new and strange enough that the uncertainty of how the interface might respond can make them unwilling to touch it. It is a research and design goal to alleviate this concern, either by better design or by allowing the user to develop confidence as such interfaces becomes more familiar.

The issue of an interface "respecting its context" came up, when we found users enjoying and lingering to explore a narrative longer than we had expected because of the degree of control they had over the experience. In the case of a haptic knob outside a real space, this might be a problem.

A direct result of putting a haptic display in a door, rather than on a desk, was the realization that it is an opportunity for a different kind of active display when untouched – a visual gestural display. We have only begun to toy with the possibilities here.

Expressiveness of Multihaptic and Multisensory Displays

The ability to manipulate the handle's temperature proved an important extension to our expressive palette, with a high degree of salience to users. In particular, the slowly changing temperature appears to be a good display medium when a user is not expected to spend much time feeling the knob.

The tight coupling of haptic feedback to the auditory display was extremely effective in creating an overall impression. The two mediums often assumed complementary roles, the audio conveying narrative content while the haptic handle controlled or advanced the experience.

Language

Aladdin's greatest utility has been in stimulating the beginnings of a linguistic framework which we used to generate and describe our narratives. The process of codifying the lexicon and syntax offered here lead us to new possibilities, both for constructing primitive haptic sensations and for discovering ways of combining them with each other and with other sensory displays. We better understand the expressive haptic palette available to interaction designers, and can use it to inspire the physical design of new expressive displays.

VII. FUTURE DIRECTIONS

Beyond building and developing a walk-through, room-centric iteration on Aladdin – or embedding a haptic display with similar refinement in a different context – the insights gleaned here can head in some more general directions.

Refining Grammar

There's much to be learned about a haptic grammar starting from here. While we have proposed a framework that structures vocabulary, possibilities for syntax using haptics alone or haptics with other sensory elements are less clear and must be arrived at through attempting more expressive goals. We need to better understand salience, by breaking it down into characteristics such as discernibility and associability; a valuable objective would be a set of general rules for combination of haptic primitives to optimize salience such as we have for graphic design.

Gestural Display

Haptic displays lodged in the world can serve a different, visual function when they're untouched. While we believe that there has been little attention given to developing a haptic lexicon, there is a rich legacy in the use of visual abstractions to convey emotional expression, or affect. Classical animation and caricature comprises the most venerable, widely appreciated and understood of these techniques.

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