Contribution to the study of the haptic enhancement of images on touchscreens

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Antoine Costes

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Introduction

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Touchscreens are part of the daily life for most of us. They display a variety of texts and images for us, be it private documents or random content from the web. We manipulate this content in a very effective way, thanks to touch gestures. We touch them a lot, but touchscreens do not really touch us back. Regardless of what is displayed on the screen, they remain steady under the finger.

This thesis, entitled "**Contribution to the study of the haptic enhancement of images on touchscreens**", presents research results on enhancing image rendering with haptic features on touchscreens. In this work, we investigate how to provide touchscreens the means *to touch us*. The means to produce compelling sensations, to display invisible information, or even to scramble our perceptual certainties.

1.1 Context

1.1.1 From cards to screens

As a young child, I was an illusionist. I used to perform card tricks to my relatives at any opportunity, because I loved to *trick* their perceptions. Above all I loved the feeling of *being tricked* myself, this particular moment where a crack opens up in my reality, to make place to something delightfully odd and baffling, yet tangibly there. I was up to work a lot to be able to share this joy, even for a single moment.

Later on, I discovered interactive technologies and got completely amazed by their endless possibilities in terms of perceptual experiments. I learned programming, became a creative coder, and had endless fun hooking signals of different natures: sound, images, motion, words... in any way that would tell a story, and open a door to fantasy. The early 2010's were exceptionally inspiring in that regard: the Kinect was just released (a few years after Johnny Chung Lee's Wiimote hacks), quickly followed by the Leap Motion and the Myo armband; Arduino cards were starting to spread as well as the "maker" movement; video mapping was emerging as an art form... Sensors, tools and softwares became insanely affordable all of sudden: there were so much things to do, to try, to hack! I designed interactive installations, automated scene lighting props, augmented artworks and musical creation tools. Every time, I was seeking for this particular and "magic" feeling, when the technical setup fades out and leaves place to some meaningful impression, allowing us to let our imagination flourish.

Most of these experimental systems had a visual output (light, images, motion), sometimes a musical one, but rarely a physical one. The more I got into digital technologies, the more I liked them to be tangible, and I eventually got into robotics, then into haptics: after an illusionist career of two decades, I discovered to my surprise that **every perception, touch included, is prone to be tricked**. Which is, somehow, the purpose of **haptic technologies**. I dove into these thoughts during my master internship on motion illusions at Technicolor.

Technicolor is a world leader in multimedia related services and technologies, supporting broad research and development efforts in related fields. Inside the Media Computing Laboratory, new interfaces and future man-machine technologies are studied and developed as they are expected to play a key role in multimedia consumption in the years to come. One particular topic of interest is **the association of audiovisual content with physical sensations** in order to deepen user experience. My internship addressed the production of bodily effects that would enhance multimedia content. Thereafter, we decided to collaborate with the HYBRID team at Inria Rennes on a PhD thesis on tactile sensations coming from images. The HYBRID team investigates body-based interactions in virtual reality through haptic and pseudo-haptic feedback techniques. Despite the high interest and skills of both laboratories for virtual reality, we shortly decided to focus the technological scope of the PhD on touchscreens, for a variety of reasons that we will detail hereafter.

1.1.2 Industrial context

Haptic technologies: a long-awaited future of interfaces

Although they are generally received very positively by the general public, **haptic technologies are hardly penetrating the consumer market**. Force feedback arms and exoskeleton gloves were intensively developed and studied since the mid-90s, but remained limited to a set of industrial applications.

One obvious limitation is their high cost, cumbersomeness, and power consumption. However, the history of the Novint Falcon demonstrates that lowering these three barriers is not enough. This force-feedback device, which targeted the gaming market, met the challenge of lowering the purchase price by two orders of magnitude, and a very limited bulkiness. However, ten years after its release in 2007, the device is still largely unknown from the general public and Novint Technologies stopped their production, although the word "haptic" keeps getting trendier. Every year, dozens of crowdfunding projects try to propose new haptic controllers: despite a steady interest of the public for haptic feedback, novel stand-alone products do not break through into the mass market.

In contrast, embedded vibrators in gamepads and cellphones have become so common that their absence is commonly perceived as a serious lack. Although their signals are relatively crude, they happened to be crucial for many use cases, from virtual keyboard typing to discrete notifications and video game enhancement. They actually constitute the only widespread haptic technology at the moment.

In a nutshell, recent technological history suggests that in order to reach the customers, **haptic technologies need to be embedded into existing products**, rather than designed as additional peripherals.

The advent of the touchscreens

Touchscreens have largely spread out over the last decade and have become one of the most ordinary human-machine interface. In addition to the commercial success of tablet computers, cell phones and laptops also tend to feature a touchscreen. The average number of screens per household in France in 2017 exceeds five [1], so that although the television screen remains the most widespread, audiovisual consumption diffuses to other supports, which are mostly touch sensitive. Therefore, **touchscreens are on the way to be the major display technology for audiovisual content**.

Touchscreens offer a wide range of interaction paradigms, without constrains like wearing a prop or limiting the field of view. They are generally cheap and can be handheld, which make them very versatile. Moreover, the co-location between visual display and touch control makes many interaction metaphors intuitive enough for some babies to try to zoom on paper maps.

However, despite these qualities, **touchscreens still lack of tactile sensations**: no matter the visual content, they feel flat, smooth, rigid and static under the finger. Although they take advantage of finger dexterity, touchscreens do not exploit much finger sensibility, yet.

[1] for more details, see the biannual reports of the "Observatoire de l'équipement audiovisuel des foyers de France métropolitaine" [Observatory of household audiovisual equipment in metropolitan France]

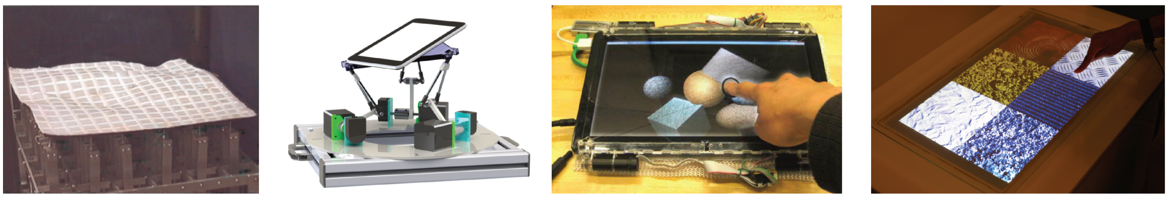
1.2 Surface haptics

Concurrently to the spreading of touchscreens, the interest in their haptic enhancement grew, and became **a new research field called "surface haptics"**. Surface haptics refers to **any system actuating a physical surface** in order to produce haptic effects, preferably **on the bare finger** [28].

In the scope of this thesis, we are mainly interested in the haptic rendering of images on touchscreens. Therefore, we will narrow our study on surface haptics systems which also provide a **co-located visuo-haptic feedback**. The images that we consider can be 2D pictures as well as the visual aspect of virtual objects in a 3D scene.

1.2.1 Main approaches to surface haptics

Long before the development of touchscreens, the premises of surface haptics were laid with the concept of **shape changing surfaces** (see Fig. 1.1a). Ambitious attempts were made to mechanically actuate a surface in order to reproduce any shape in an interactive manner. With the help of video projection, these displays can provide co-localized shape and visual information. In these approaches, the resolution of the rendering is directly linked to the (high) density of actuators, resulting in a very high technical cost.



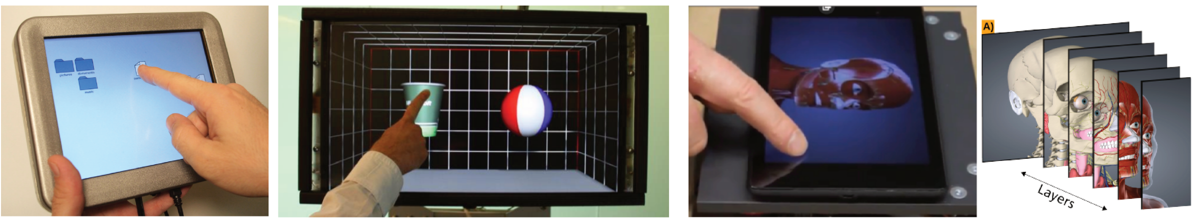
(a) (b) (c) (d)

Figure 1.1 – Main approaches to surface haptics. **(a)** Shape changing surface [67]. **(b)** Actuated touchscreen [51]. **(c)** Actuated digital proxy [156]. **(d)** Friction modulation display [13].

Tablet computers are **highly integrated devices**: they combine touch tracking and visual display, in addition to self-contained battery power and operating system to run software. Therefore it can be very advantageous to use them as part of a haptic rendering setup. For instance, **force-feedback arms or robotic systems can be used to actuate directly a touchscreen**, and provide it with force and motion abilities (see Fig. 1.1b). However, this approach was rather little explored, despite a number of possibilities offered for a reasonable technical cost. Some alternative approaches make use of an **intermediate proxy** acting on the finger with minimal sight obstruction (see Fig. 1.1c). Finally, a huge body of work has been achieved on **friction modulation**, which uses either ultrasonic or electrical vibrations to change the physical contact phenomena between the finger and the screen, and either reduce or increase the overall friction forces (see Fig. 1.1d).

1.2.2 Applications

As tactile screens are used in many different contexts, their haptic enhancement covers a large variety of usages. **Usability of tactile user interfaces** can be improved thanks to haptic feedback, achieving better performance and comfort for common manipulation tasks (see Fig. 1.2a). In particular, there is a huge margin for progress in **assistive technologies on smartphones**, notably screen-reading technologies which are mainly based on auditory feedback for now. The physical display of shape and volume informations enriches the manipulation of 3D objects, be it for **industrial design** or for **3D modeling** (see Fig. 1.2b). The exploration of complex data such as **medical scans** can be eased thanks to a physical movement for navigation, and haptic events to highlight elements of interest (see Fig. 1.2c). Because of its strong contribution to immersion[2] and presence[3] [146, 159], haptics is a topic of high interest for the **entertainment domain**, from video games to multimedia consumption.



(a) **(b)** **(c)**

Figure 1.2 – Application examples for surface haptics. **(a)** Haptics widgets [13]. **(b)** Manipulating 3d objects [164]. **(c)** Exploring multidimensional data [115].

1.2.3 Challenges of surface haptics

Semantic issues: characterizing haptic properties

However startling it may seem, the very **definition of haptic properties** of a material remains an open research question. From a technical viewpoint, there is **no standard procedure to measure a set of properties needed to describe a material haptically**, except for very specific contexts.

Every day, we touch and manipulate a large variety of materials, that we generally distinguish easily without the need of looking at them: **our tactile sensitivity allows us to discriminate almost instantly** a soft and sticky rubber from a cold and smooth metal or a harsh and dry textile. If identifying an object among others in a box can take only a few seconds [87], **verbalizing the criteria on which we rely is much less spontaneous**. In fact, there is no general-case set of descriptors to classify materials haptically, be they verbal

[2]"Immersion is a description of a technology, and describes the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant." [166]

[3]"Presence is a state of consciousness that may be concomitant with immersion, and is related to a sense of being in a place." [166]

or not. For instance, Yoshida had a quite wide approach with 20 adjective pairs [206]. On the other hand, when reducing the scope to a specific family, like banknotes, only two features can suffice for an accurate discrimination [172].

Because of a lack of appropriate vocabulary, we name tactile sensations and material properties with identical words (like “roughness” or “hardness”), although they are totally different things. This confusing polysemy gets even worse in the engineering field, where despite precise definitions, a property like “roughness” can be described by a dozen of parameters and measured by several different methods [65]. As they relate to both physical properties and perceptual phenomena, haptic properties find themselves at the intersection of several fields of study like psychophysics, contact mechanics or surface metrology. Each of these perspectives may contribute, for a part, to the definition of a given haptic property, but they often have conflicting terminology.

To sum up, the haptic description of an object often relies on subjective and context-dependent choices, which impedes the scientific effort of merging analysis and results. There is a need to **clarify on which features we humans rely on when we appreciate or compare surfaces** through touch. This would help to design haptic experiences more finely and achieve better user performance and experience, but also to refine the conception of haptic rendering devices.

Lightweight rendering technologies

On a more materialistic perspective, one major limitation of haptic technologies is the **technical complexity of mechanical actuators**. If traditional force feedback devices are effective for teleoperation and have been largely introduced in industrial and medical applications, they remain often **complex, cumbersome and expensive**. In other words, they are not likely to spread in the consumer market like touchscreens did.

The **challenge of simplicity** applies to haptic technologies from their conception to their end-use, as its impact is considerable on both production costs and use case relevance. Usual vibrators embedded in cellphones and game controllers are a typical example of a successful simple technology, but their expressiveness is also exemplary limited. They illustrate on one hand the relevance of the haptic modality in many cases, and on the other hand the immense underuse of our haptic sensitivity.

Many haptic technologies failed to emancipate from research laboratories because their technical heaviness kept them out of realistic applications. Yet the richness of our haptic perception calls for sophisticated cues. In order to reach the broad dissemination of touchscreens, **haptic technologies need to be lightweight, without sacrificing their richness and quality**. As stated by Chang et al., “haptics are best employed when minimal actuation can have broad and great effect” [27].

Addressing a variety of haptic sensations

As we will detail in 2.3, haptic researchers have proposed a number of innovative solutions in the recent years to provide haptic feedback and tactile sensations to touchscreens. Yet, most of these technologies provide **only a limited range of tactile sensations**, which depends largely on the generated stimulus. In order to address the full richness of haptic perception, several actuators could be combined to deliver specific stimuli of different kinds: forces, vibrations, shape and/or temperature. However the **technical complexity** of such a build-up can be considerable.

Nevertheless, it is noteworthy that an additional stimulus (for instance, shape in addition to forces) does not necessarily adds to the richness of the rendering. Before being transformed into a sensation, sensory cues are merged into a **complex integration process** [39][37]. Hence, the quality and richness of a haptic rendering is less due to the number of stimuli than to their **congruence and complementarity**; which is hard to evaluate directly. Some approaches can be used to estimate the optimal number of dimensions necessary to discriminate between samples, like multidimensional scaling [71]. They provide useful qualitative leads on the perceptual significance of each considered features, but do not provide definitive answers for the technical dilemmas of rendering technologies.

In order to get **an interesting trade-off between technical complexity and richness of the rendering**, the development of haptic technologies requires to **take into account perceptual factors** and to focus on the most meaningful elements of haptic phenomena.

1.3 Methodology and chosen approach

1.3.1 Axes of research

The goal of this thesis is to investigate how to **provide image-related haptic feedback on touchscreens**. To do so, and answer some of the challenges raised by surface haptics, we followed three different axes of research. Those axes and the resulting contributions are illustrated in Fig. 1.3.

Data format and hardware independence

While haptic devices and setups spread widely, little attention is paid to the reuse and compatibility of haptic data, which is most of the time context- or hardware-specific. The very definition of “haptic data” is still a matter of choice for anyone designing a rendering setup, as there is **no obvious, generalized way to provide haptic properties** to a virtual object. Instead, most haptic rendering setups rely on **custom and specific data formats**, with a **strong dependence to hardware**. This lack of standard representation impedes the whole computer haptics pipeline, from acquisition to rendering.

Our first axis of research is to **propose a rationale to define and store haptic data,**

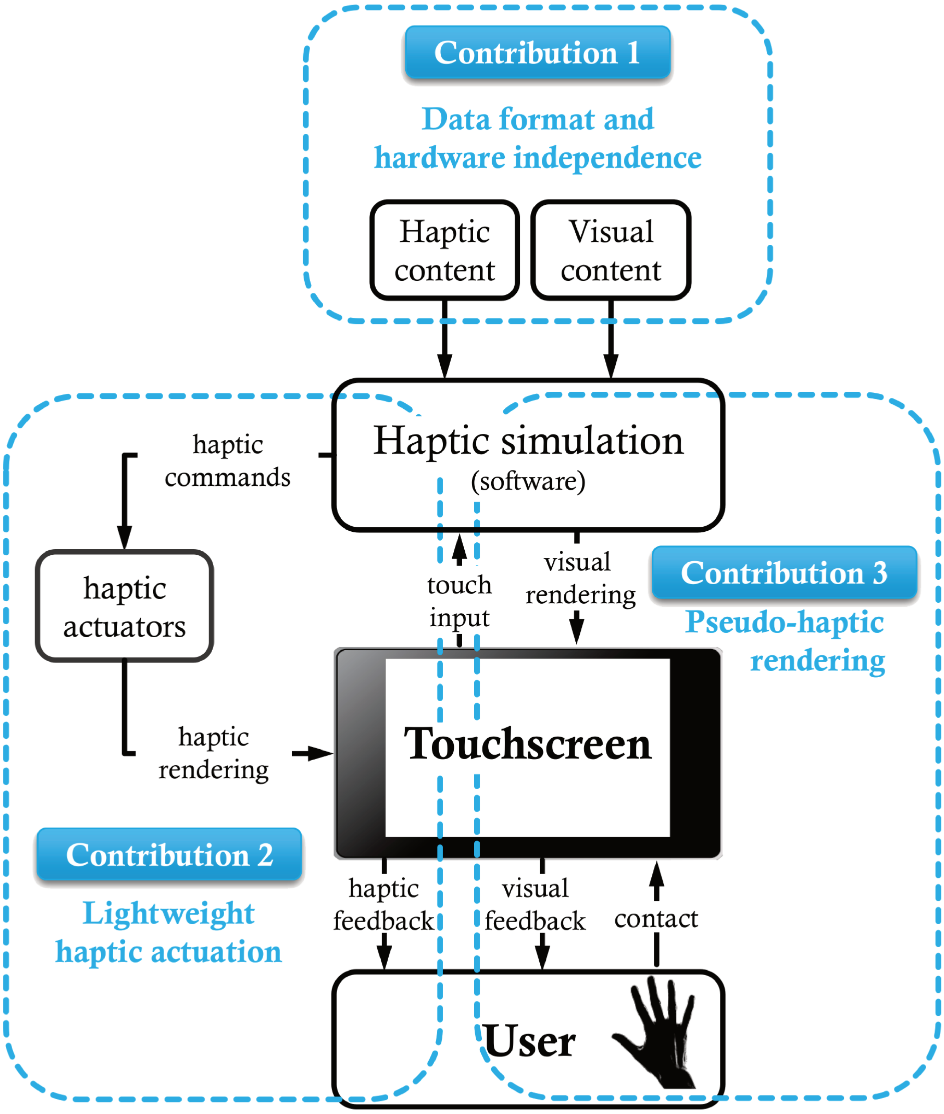


Figure 1.3 – Schematic summary of our contributions to haptic enhancement of images on touchscreens. We first propose a **new format** to embed haptic content inside what we call a **haptic image**. Then we present a novel approach for **lightweight haptic actuation** of touchscreens. Finally, we investigate the use of **visual effects** to evoke haptic properties without the need of mechanical actuators.

and to relate it to a visual image. This representation should be versatile not only for the type of haptic features considered, but also for the choice of the rendering technology.

Lightweight kinesthetic and tactile actuation

Haptic perception is composed of two different sensory systems: the kinesthetic sense and the tactile sense. Each of these sensory systems has it own specialized receptors (see Chapter 2). Approaches like friction modulation or micro-pin array devices provide **tactile stimulation but no movement**, whereas traditional force feedback systems simulate stiffness, friction and other contact phenomena by **constraining the motion of a handle** that acts like pretty much like a probe. Some authors proposed to combine the two types of devices, at the cost of a certain mechanical and functional complexity [77, 201]. On the other hand, the ability of force-feedback arms to be controlled **either in force or in position** was little explored as a mean to provide a variety of haptic effects.

The artificial production of haptic stimuli offers a very large panel of technological sophistication. The technical complexity can be justified to enhance either the quality or realism of a given effect, or the diversity of the generated sensations. However any hardware complication has a very high cost in the industrial context of mass-consumption technologies. Our second axis of research is thus to investigate **lightweight technological solutions that could address a diversity of haptic effects on a tablet computer**.

Visuo-haptic interactions

If the most straightforward way to think of haptic rendering is to reproduce rigorously the mechanical phenomena occurring on contact, one should beware of this ideal. Indeed, contrarily to vision or hearing, the sense of touch cannot be "entirely" stimulated and its artificial stimulation involves inevitable compromises. Fortunately, haptic perception is not that straightforward and allows for some shortcuts, thanks to multisensory integration. In particular, in the right conditions, **vision can increase or even overcome tactile information** in the judgment of haptic properties [145].

Our third axis of research aims at taking advantage of this fact to develop **visual pseudo-haptic rendering methods** which would evoke a range of haptic properties of an image, **without the need of any haptic actuator**.

1.3.2 The haptic image concept

By crossing these three axes, we elaborated an approach which can be summarized with the concept of the **haptic image**, illustrated in Fig. 1.4. The production and design of a visuo-haptic experience can be considered along three complementary aspects: the haptic stimulus, the visual stimulus, and the conditions for them to be merged into a single coherent perception.

The haptic image relies on a technical method called **texture mapping** [53], which consists in wrapping on a 3D mesh various images containing the necessary information for the rendering of fine details. In the context of haptic images, texture mapping defines a direct relationship between visual and haptic data. The method is especially adapted to **heterogeneous haptic data**, storing it spatially in dedicated "maps". The haptic image is suited to the decomposition of haptic data in many simple elements, and thus gives a preference to **haptic rendering methods and devices** offering a **diversity of simple effects** rather than elaborating one single complicated model. Finally, the haptic image is intended to make use of **perceptual interactions and multimodality benefits**.

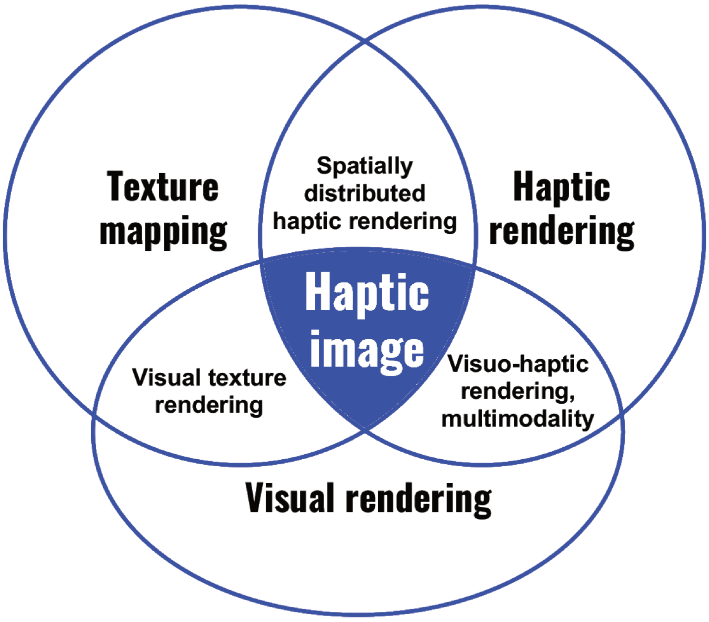


Figure 1.4 – Our approach extends texture mapping to tactile and kinesthetic rendering, and includes cross-modal interactions. It can be summarized by the concept of "haptic image".

1.4 Contributions

The remainder of this manuscript is organized as follows.

Chapter 2 presents related work on surface haptics. First, we present the perceptual mechanisms underlying the haptic perception of surfaces, from the triggering of nervous signals to the formation of subjective percepts. Then, we present how previous research addressed the acquisition of haptic data, which is necessary related to modeling choices. We also discuss recent proposals to share haptic data through publicly available datasets. Finally, we review existing solutions to actuate a touchscreen and provide responsive haptic feedback.

In **Chapter 3**, we propose a new format for haptic texture mapping which is not dependent on the haptic rendering hardware. This format is meant to be seamlessly integrated in audiovisual content creation workflows, and to be easily manipulated by non-experts in multidisciplinary contexts. We show from previous experimental findings that ten elementary haptic features can be used in a complementary way for the rendering of haptic surfaces. We provide a detailed example of a haptic material and the ten associated maps, as well as a general-case specification table.

In **Chapter 4**, we introduce "KinesTouch", a novel approach for touchscreen haptic enhancement addressing four different psychophysical dimensions with a single force-feedback device: compliance, friction, fine roughness, and shape. We present the design and implementation of a corresponding set of haptic effects as well as a proof-of-concept setup. Regarding friction in particular, we propose a novel effect based on large lateral motion that increases or diminishes the sliding velocity between the finger and the screen. A user study was conducted on this effect to confirm its ability to produce distinct sliding sensations. Finally, we showcase several use cases illustrating the possibilities offered by the KinesTouch to enhance 2D and 3D interactions on tablet computers in various contexts.

In **Chapter 5**, we propose an pseudo-haptic approach called “Touchy”, where a visual cursor is introduced under the user’s finger, to evoke various haptic percepts through changes in its shape and motion. We present seven different effects inspired from physical models addressing five different haptic properties. In order to validate our approach, we conducted a user study where the effects where matched to real material samples. We also extend the Touchy approach to 3D scenes, and showcase several 3D scenes to demonstrate the use of Touchy in a variety of virtual environment contexts.

Finally, **Chapter 6** concludes this manuscript and discusses future possible studies and improvements to pursue the present work, as well as long-term perspectives and open questions towards the achievement of haptic images on touchscreens.

Literature review 2

Contents

This chapter presents an overview of previous work that relates to surface haptics. Firstly, we review the mechanisms of **haptic perception of surfaces**, and address the definition of haptic properties: the perceived features do not directly match physical properties, but rather arise from a complex integration process. Then, we address the issue of **haptic data**, and summarize the possible approaches for their production. Finally, we present the various **technological solutions** proposed in the previous literature to enhance touchscreens with haptic effects.

2.1 Haptic perception of surfaces

Haptic perception is the process of recognizing objects through touch [86]. It is part of the somatosensory system, which mediates sensations coming from the body tissues (like skin, muscles or viscera). Physical sensations originate from the nerve impulses sent by a variety of receptors, which are distributed in the body and are specific to each sensory system. These receptors are of different types, with various shape, constitution and distribution making them sensitive to specific stimulations.

2.1.1 Sensory systems of the human body

The term "haptic" refers to the combination between two sensory systems: the **kinesthetic sense** and the **tactile sense** (see Fig. 2.1) [149].

The kinesthetic sense (also called kinesthesia), refers to the perception of the body configuration and limb movements [142]. It relies mainly on two kinds of receptors, namely muscle spindles and tendon organs, although cutaneous receptors also contribute to joint angle perception. Primary and secondary muscle spindles, located within the belly of muscles, detect changes in muscle length. The tendon organs, located at the point of attachment of muscle fibers to tendinous tissues, are sensitive to muscle's contraction, which is representative of muscular effort [68].

The tactile sense is mediated by the skin, which is the largest organ of the body: in an average adult it covers almost $2m^2$ and weighs around 4kg. The receptors in the skin transmit pain, temperature, itch, and touch information to the central nervous system.

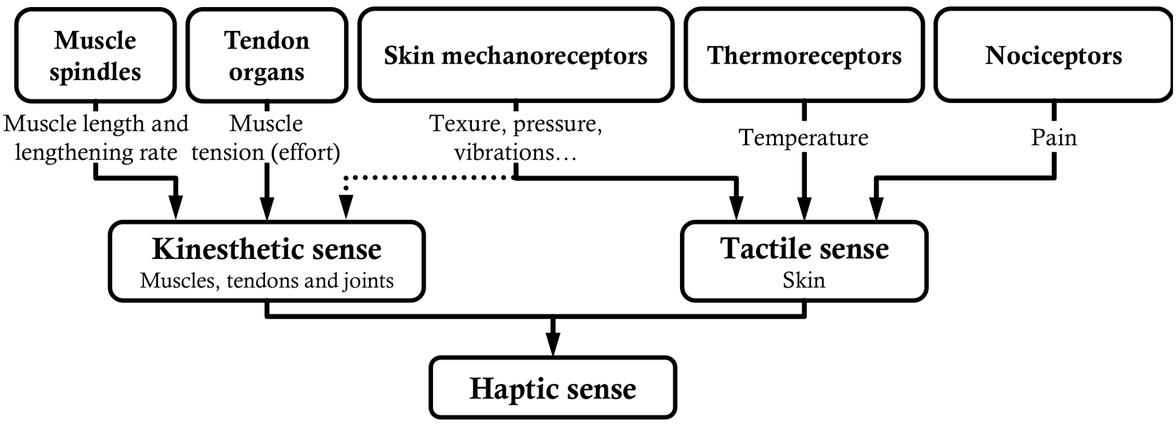


Figure 2.1 – Types of receptors for the kinesthetic and the tactile sensory systems.

There are three types of skin: the hairy skin, the glabrous skin, and the mucosal skin. The hairy skin covers more than 90% of the body surface, while the glabrous skin is limited to hand palms and foot soles. They can be easily distinguished because the glabrous skin features a fascinating sculptured superficial geometry at its superficy, which is at the same time unique for each individual but also deeply structured. The mucocutaneous skin is generally moist and is mostly internal.

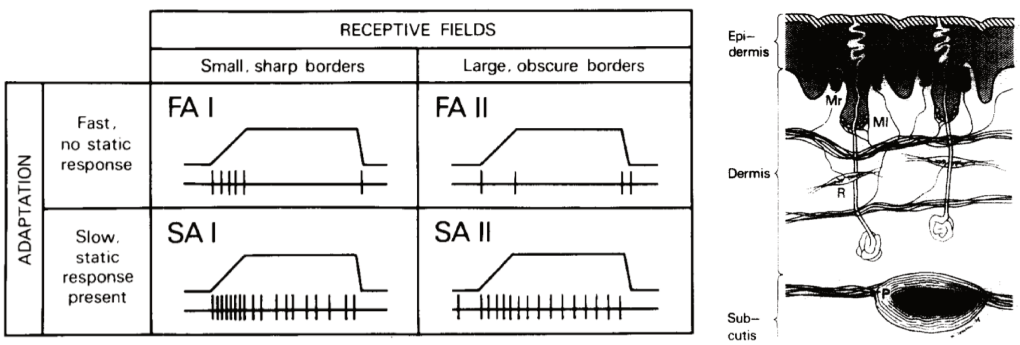
Glabrous skin is obviously specialized for discriminative touch, manipulation and locomotion. It has a a much higher density of receptors (therefore a much higher spatial acuity) than the hairy skin, as well as very different biomechanical properties. It is straightforward to experiment the differences in sensory capabilities between the hairy and glabrous skin. Put a coin on a fingertip, then on the back of your hand: you should clearly feel its weight and temperature in both cases, bot not its embossed patterns in the latter. For the scope of our research, we will focus on of the glabrous skin, as it is the one generally involved into manipulation and active sensing.

The receptors of the tactile sense fall into three categories: mechanoreceptors, thermoreceptors and nociceptors. Although temperature sensing can play a crucial role in tactile discrimination, mechanoreceptors are of higher interest in the present work, because from a technological perspective, surface haptics is much more prone to mechanical stimulation than thermal rendering. Also, the production of any sort of pain is out of our scope. In the next subsection, we provide a brief overview of the main mechanoreceptors related to touch that are found in the glabrous skin. For more details, we refer the reader to [72].

2.1.2 Main mechanoreceptors in the glabrous skin

The low-threshold mechanoreceptors involved in fine touch perception are usually classified along two types (I and II). The type I receptors are distributed superficially (at the interface between the dermis and the epidermis), with a high and variable density, and exhibit a small and sharp activation area, around a dozen of mm^2. The type II receptors, in contrast, are located more deep in the dermis, with a lower but more constant density. Their activation area is large, with fuzzy borders.

In addition to their type, the mechanoreceptors are classified along their firing pattern regime during a sustained indentation of the skin. The "slow-adaptating" ones (SA receptors) keep firing as long as the stimulus last, whereas "fast-adaptating" or "rapidly-adaptating" (FA or RA) receptors only respond to the change rate of the stimulus (see Fig. 2.2a).



(a) (b)

Figure 2.2 – **(a)** Impulse discharge (lower trace) to perpendicular ramp indentation of the skin (upper trace) for each mechanoreceptor type, from [73]. **(b)** Positioning of the Meissner corpuscles (Mr), Merkel disks (Ml), Rufffini endings (R) and Pacinian corpuscles (P) in the glabrous skin, from [73].

According to these two criteria, four different types of mechanoreceptors can be found in the glabrous skin (see Fig. 2.2b), each of them exhibiting a particular anatomy with specific mechanical filtering characteristics (for more detailed information, see [210]).

Table 2.1 summarizes the main differences between the four main types of mechanoreceptors in the glabrous skin. Their sensitivity to vibration frequency is shown in Fig. 2.3. The Merkel complexes (SA-I) are the most sensitive of the four main types of mechanoreceptors to vibrations at low frequencies (0.5-2Hz) [74], and may respond to tissue displacements of only a few µm [64]. They are known to be involved in the detection of local shape: edges, curvature and coarse asperities [74].

	Merkel complexes	**Meissner corpuscles**	**Ruffini endings**	**Pacinian corpuscles**
Receptor type	SA-I	RA-I	SA-II	RA-II
Density	25%	43%	19%	13%
Receptive area	$11mm^2$	$13mm^2$	$59mm^2$	$101mm^2$
Response type	S, dS	dS	S	d^2S
Detected stimuli	local curvature, edges, corners	stretch and slip transients	directional static stretch	vibration

Table 2.1 – Comparison between the main types of mechanoreceptors in the glabrous skin (summarized from [160] and [74]). S refers to a skin indentation stimulus, and dS and d^2S refer to its derivatives.

Meissner corpuscles (RA-I) are the most frequent mechanoreceptors in the human hand (they are especially concentrated in the finger pads) and react rapidly to transients in indentation or stretch, with a maximum sensitivity at 40 Hz. Therefore they are supposed to play an important role in slip detection [74].

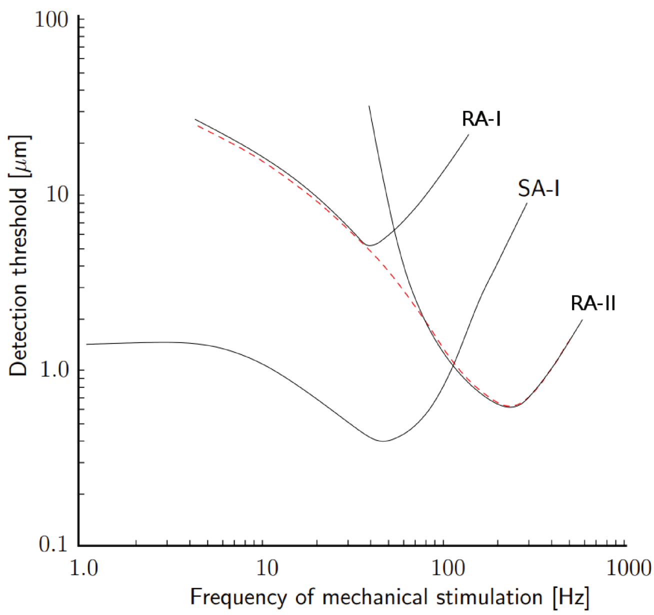


Figure 2.3 – Frequency dependency of the thresholds for sinusoidal stimuli of RA-I, RA-II, and SA-I mechanoreceptors, adapted from [46]. The resulting line (red) represents the perceived sensitivity vibration with a maximal sensitivity of 0.6 µm at about 230 Hz.

The Ruffini endings (SA-II) are the less well known of the list, because they are hard to observe. They have been mostly identified in the hairy skin, and experimental results about their sensitivity are still contradictory; their precise role in touch perception remain largely hypothetical [138]. They are sensitive to sustained stretch, and appear to be concentrated in the borders of the fingernails [21]; therefore they are supposed to detect directional stretch and to play a role in grip manipulation.

In contrast, Pacinian corpuscles (RA-II) are thick lamelar capsules of about 1mm, which are therefore easy to observe and to stimulate specifically. Their firing activity is therefore known with great certitude as correlated to vibrations, with a variable sensitivity depending on the frequency. At its peak sensitivity (around 250Hz), the corpuscle can detect amplitude vibrations as small as 0.1 µm on the skin, while it is located a few milimeters deep, in the dermis [17].

Sensations from the glabrous skin are crucial for manipulation, and people with tactile sensitivity impairment tend to subjectively experience motor deficiency. However manipulation tasks are themselves an important part of haptic perception, and participate even in the conceptual definition of haptic properties.

2.1.3 The hand: a window to the world

As opposed to sight or hearing, the haptic modality is bidirectional and interlinks perception with action. In daily life we experience active touch: the hand comes into contact with objects to examine them. It is trivial to notice that despite a very large variety of motor possibilities, our spontaneous manipulation gestures are strongly stereotyped and follow a number of invariants [41, 94]. For instance, hand rotations are generally made around a fixed axis, and in the absence of an obstacle the hand moves in a straight line towards its picking target. This obvious observation remains yet complex to explain (it is not about effort minimization, for instance), and the question of its formal description remains open after decades of research in various fields, from physiology to robotics.

In regards to the examination of haptic properties, these stereotyped gestures (see Fig. 2.4) were identified thirty years ago under the term “exploratory procedures” (EP) by Lederman and Klatzky [103]. For instance, a subject asked to evaluate how rough or smooth an object is will spontaneously stroke its surface, while they would settle for static contact to assess its temperature, and apply pressure to evaluate its hardness. This classification outlines the coherence between active gesture and sought information, the former yielding a pertinent stimulus to access the latter, and suggests the number of type of haptic information is limited. This pioneer work has deeply structured the literature in the decades that followed, putting the focus on two properties: roughness and hardness (and, in a lesser extent, temperature).

It is noteworthy that a stroke gesture allows not only to appreciate roughness, but also stiction, and that static contact is not only relevant to temperature, but also asperities at the milimeter scale. Surprisingly, it was not before the 2000s that stickiness and macroroughness were mentioned as fundamental properties of haptic surfaces [16, 58, 178].

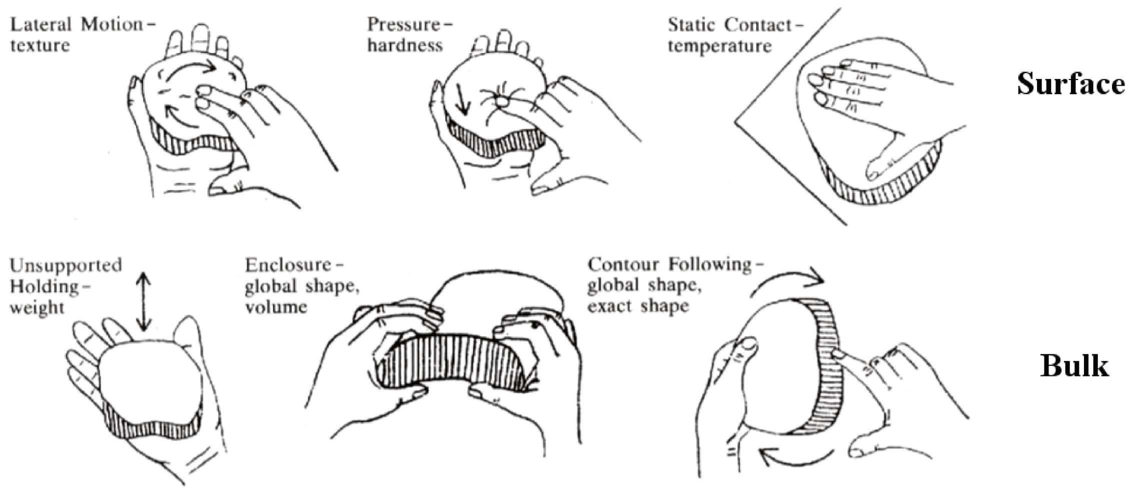


Figure 2.4 – Haptic exploratory procedures, adapted from [104]. The three above relate to surface properties, whereas the three below relate to bulk object properties.

In fact, haptic properties are hardly definable without a context. However when studying haptics it is often necessary to define a limited set of descriptors which provide a quantitative representation of the considered object. The number and the nature of the chosen descriptors are crucial to the quality of the representation (that is, the quantity and fidelity of the information it conveys). The optimization of these descriptors, also called "dimensionality", is crucial both to the understanding of haptic perception and to the design of haptic rendering.

2.1.4 Semantic issues with haptic descriptors

Because they relate both to physical features and perceptual phenomena, haptic properties easily cross multiple perspectives and fields of study. Their restriction to quantitative characteristics leads inevitably to some terminology conflict. The term "roughness" is probably the most illustrative case of this semantic complexity.

Roughness (also called "texture") has been extensively studied in the haptic literature [40], and yet its definition varies widely between authors. Even excluding perceptual aspects, roughness as a physical property is not a simple concept and has a debatable definition (according to the ISO 4287:1997, a dozen of different parameters can be used to assess it). Across this variety of conceptions, what can be safely said is that roughness is a geometrical property of a surface, which relates to some form of spatial frequency.

Regardless of the chosen definition for roughness as a physical property, *perceived roughness* is supposed to vary in intensity according to "physical roughness". Perceived roughness has been firstly hypothesized to be a single quantity depending only on a few geometrical properties of the touched surface, but no convincing model was found despite considerable efforts [100, 101, 102, 105, 121, 175]. It was demonstrated later that the perceived roughness verbally expressed by different subjects would relate to different objective measurements [180], which suggests that a plurality of perceptions is associated to the word "roughness". In other words, roughness entails several components and is hardly reducible to one quantity.

Indeed, a distinction is commonly made between fine and macro roughness. It was confirmed by several studies [16, 57, 58] many decades after it was hypothesized by Katz [79] under the famous name of the "duplex theory". This theory states that fine and coarse asperities are mediated by two distinct perceptual mechanisms, the first one relying on contact vibrations and the second one involving spatial distribution of pressure. It was notably found that contact vibrations are necessary to perceive asperities under 0.1mm [58]. Interestingly, a similar distinction can be found in metrology (ISO 4287:1997), where surface deviations are split on both sides of a sampling frequency: "roughness" refer to high frequency components, while low-frequency components are designated as "waviness".

In order to address such semantic issues, Okamoto et al. suggested to distinguish between different semantic layers (see Fig. 2.5): the perceived attributes of a material, which constitute the *psychophysical layer*, serve as an interface between the "objective" physical properties of the material (the *material layer*), and higher cognitive layers (*affective* and *preferential*) [131]. The psychophysical layer relates to the perceptual representation of the touched object, and defines the scope for perceptual dimensionality, which we will address hereafter.

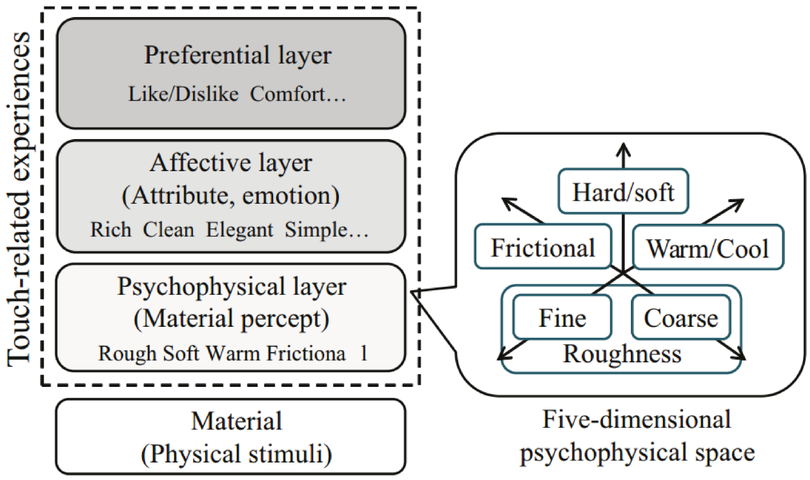


Figure 2.5 – Semantic layers of touch-related experiences, from [131]

2.1.5 Perceptual dimensionality of haptic surfaces

In daily life we touch many surfaces and in many cases, we can identify them in a second without the need of looking at them. On the other hand, it is sometimes hard to get a specific object out of the bottom of a bag without several trials and visual validation. What are the features on which our haptic representation of surfaces is based on?

This question has been addressed in a large body of studies (for a review, see [132]). While these studies are generally consistent about the two most discriminative features being **roughness** and **stiffness** (which definitions are variable though), the rest of their results are quite diversified, yet without strong contradictions. This can be explained by the fact that these studies vary a lot in terms of stimuli choice, psychophysical methods and mathematical methods [200]. Tiest and Kappers demonstrated that if many studies concluded in a 2- or 3-dimensions model, they were valid only for a quite limited range of materials and that more descriptors were required to accurately depict the diversity of real-world materials [179]. Although most studies do not even mention it, **temperature** appears to be a very discriminative feature [75]. **Stickiness** was mentioned in more recent studies [93, 179]. To sum up, there has been little common understanding for decades in haptic research about the dimensionality of touch perception.

The notion of "tactile primary colors" has been proposed by Kajimoto et al., emphasizing the complementarity of the mechanical stimuli which the four types of skin mechanoreceptors are sensitive to [76, 204]. As an analogy with the correspondence between color receptors in the eye and the color decomposition into primary colors, they suggested that a tactile sensation could be decomposed in four elementary stimuli, which would be perceived in a relatively independent manner. Pacini corpuscles react to the vibrations of a rough rubbing, Meissner corpuscles detect the pressure changes due to pressing, Merkel complexes are sensitive to the indentation due to a rough texture, while Ruffini endings are supposed to respond to shear deformations produced by adherence. However, this direct correspondence appears to be very simplistic [154]. For instance it does not explain why hardness can be correctly estimated through tapping vibrations rather than squeezing pressure. It has been recently argued by Saal and Bensmaia that the central integration of tactile afferents in the primary somatosensory cortex does not reflect this submodalities decomposition, but rather higher-level neuronal representations of tactile features across different receptor types [154]. For instance, while the spatial pattern of SA-I activation accurately reflects the shape in contact with the finger, it has been shown that subjects were able to identify letters formed by vibrating patterns which activated RA-I and RA-II, but not SA-I afferents [49].

In a comprehensive review attempting to synthesize 40 years of research, Okamoto et al. proposed to consider **one thermal dimension and three mechanical dimensions**: compliance, roughness and friction (see Fig. 2.5) [131]. This is in accordance with other reviews [88, 178]. Considered in a broad sense, **compliance refers to how the surface deforms, roughness relates to its geometrical features, and friction concerns the easiness of the sliding against it**. Yet, each one of these three reviews outlined the contradictory diversity of experimental findings, suggesting that these four dimensions remain general categories rather than clearly distinct features.

To sum up, the haptic perception of surface is strongly structured by the diversity of skin mechanoreceptors and their respective sensibilities. If its **four main dimensions of compliance, roughness, friction and warmth** have been clearly established in the previous literature, these attributes might appear to be simplistic to describe the fine details of tactile perception. If it is very likely that they could be in turn decomposed in **more elementary components**, these are much more complicated to identify for at least two reasons. On one hand, the number of possible interactions grows with the number of considered features, increasing the complexity of experimental protocols. On the other hand, the coarseness of our vocabulary makes subjective reports vague and their analysis tricky.

Finally, one should keep in mind the importance of the context to define a concept such as perceptual dimensionality. For instance, other properties like wetness, brittleness or cohesion do certainly play an important role in material discrimination. However for technological reasons, they are much less prone to be artificially rendered in the near future, and are thus considered as off-topic of the present work. They would be yet crucial in a food study context, for instance.

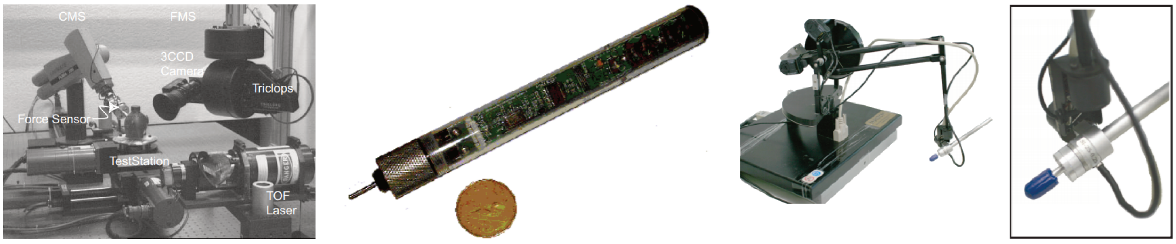
2.2 Haptic data: measurements, modeling and distribution

The use of *haptic data* is one of the scientific challenges raised by the achievement of haptic rendering. Haptic rendering can be defined as the production of sensory stimuli in response to user interactions in order to produce one or several haptic percepts (such as shape, compliance, texture, friction, etc...) [10, 157, 158]. Given the complexity of describing a subjective haptic experience, on which data should haptic simulation rely on? While some systems are able to produce realistic sensations from simple mathematical heuristics, other make use of real-world measurements. Yet, haptic features can be tricky to characterize, and there is no standard way of measuring them, because there are no generalized definitions for them. In addition, the design and fabrication of custom sensors is often needed once the object of measurement is defined. Adequate sensors for haptic measurements tend to be technically complex to conceive and expensive to produce. Their use is diversified and aims at different goals, namely robotic manipulation, haptic evaluation, material identification or realistic haptic simulations. Because each one of these application contexts implies a different use of haptic data, they require very different haptic acquisition approaches.

In this section, we review the different strategies used to produce haptic information from the capture of real objects' features. We also address the question of haptic modeling and its reliance or not upon haptic measurements. Finally, we review recent attempts of making haptic data publicly available, which might be a decisive element for the development of haptics in immersive 3D applications.

2.2.1 From tactile sensing to haptic evaluation

Tactile sensing, defined as the measurement of "given properties of an object through physical contact between the sensor and the object" [106], was developed in the first place for teleoperation systems, because reflecting contact forces is crucial for manipulation performances [62]. Semi or fully automated robotic manipulation also has a crucial need for tactile sensing, for instance to address the challenge of maintaining the grasp of an object with unknown weight and friction coefficient. Yet, these applications were in practice limited to real-time force and torque sensing, and did not ambition any storage of information for later use [106]. However, in the late nineties, the alternative use of tactile sensors to evaluate haptic properties was considered, pointing out many applications in other fields like medicine (especially for tumor detection), cosmetics (for product evaluation), or food industry (for delicate handling and inspection) [106]. For a comprehensive historical review, we refer the reader to [183].



(a) (b) (c)

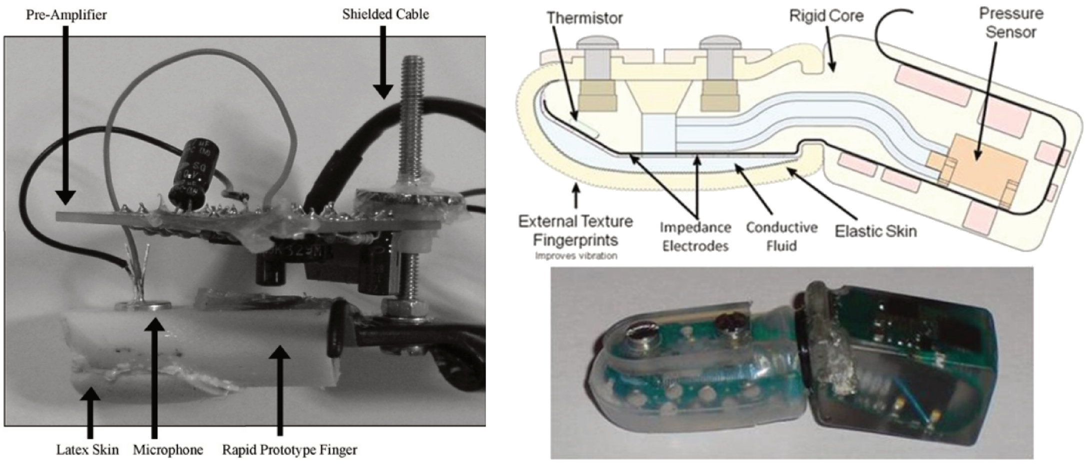
Figure 2.6 – Haptic acquisition devices. **(a)** The ACME facility combines radiometric measurements with tactile sensing in a totally automated environment [136]. **(b)** The WHaT sensor, in contrast, is meant to be used manually [137]. **(c)** The device used in [60] for haptic recording and replay with an implicit data-driven approach.

From that moment, the interest grew for devices able to characterize an object haptically, which is also much valuable for another application field, that is realistic haptic rendering. The idea of "reality-based" haptic models spread widely during the 2000s, with the exemplary ACME system (Fig. 2.6a) [136]. This robotic measurement facility could produce completely automated measurements and be controlled over the network. It included notably a laser range finder for shape acquisition, a stereo vision color system for reflectance acquisition, and a probe with a force and torque sensor for texture, friction and elasticity estimations.

However, a limitation of computer-controlled scanning systems is that they hardly reproduce the mechanical behavior of a human hand. Therefore, despite of their high reliability and reproducibility, they produce contact forces which differ from the one of natural human interaction. In this regard, several handheld probes were proposed instead (see Fig. 2.6b) [137, 153]. They measured contact forces and vibrations, and were usually combined with an optical position tracking system. Methods to map such surface measurements on a 3D mesh in an interactive manner were discussed in [4] and [95]. Battaglia et al. went even further and proposed thimble-shaped wearable sensors in order to measure multi-finger forces during grasping and manipulation [12].

2.2.2 Bio-inspired sensors and material classification

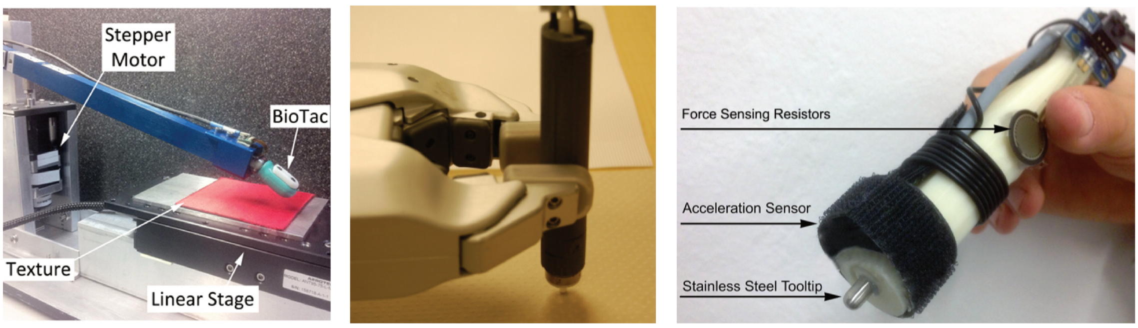
Artificial fingers constitute another trend for tactile sensor design [123, 130, 173, 196]. By mimicking the mechanical behavior of a human finger, they aim at reducing, as much as possible, the effect of artificial mechanical transductions which are typically induced with probes. Artificial fingers also get inspired by human mechanoreceptors [130], and most of them seek for multimodal sensing. An exception is the work of Edwards et al. who had an original approach using an inexpensive microphone only for textural discrimination (Fig. 2.7a) [38]. However artificial fingers are not necessarily intended to capture data for realistic haptic rendering; they rather replace hands for material classification tasks [40]. In particular, the BioTac sensor distinguished itself by featuring a thermal sensing ability, in addition to vibration and deformation (see Fig. 2.7b) [196].



(a) (b)

Figure 2.7 – Bio-inspired tactile sensors. **(a)** Extraction of textural features with an artificial finger and a microphone [38]. **(b)** The BioTac sensor detects contact forces, vibrations and thermal changes [196].

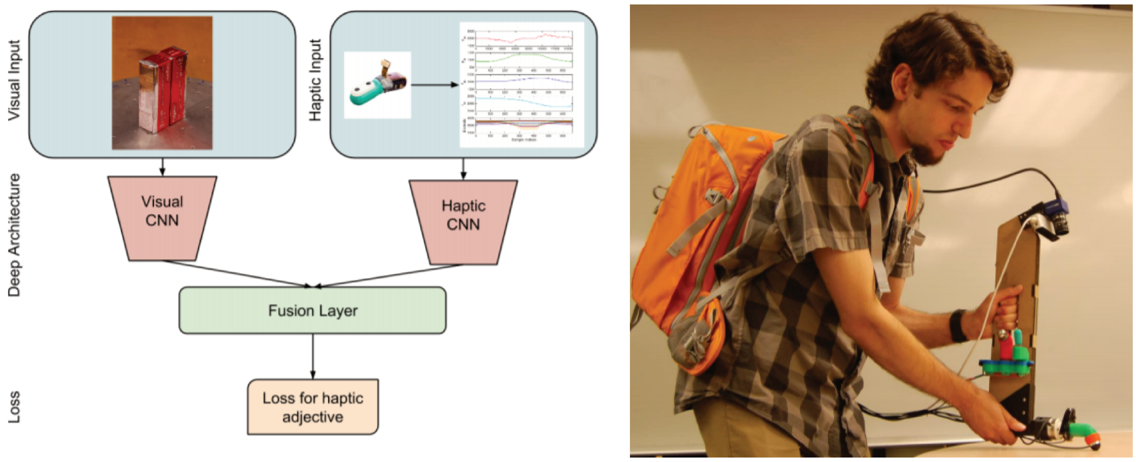
Robotic material classification tasks received a particular attention recently [40, 162, 208]. In this approach, the features extracted from the measurements are not intended to represent intelligible properties of the material nor contribute to some realistic simulation, but rather to be efficiently distinguished by an automated process (see Fig. 2.8). For instance, Romano et al. used support vector machines on features that included normal force, end-effector speed, and frequency-binned vibration [151]. Strese et al. achieved even better results using methods from audio signal processing such as cepstral analysis, without relying on explicit scan speed and force measurements [171].



(a) (b) (c)

Figure 2.8 – Haptic acquisition systems for material classification. The scanning motions can be performed **(a) (b)** robotically [40, 151], or **(c)** during freehand movements [171].

As machine learning techniques spread widely in almost all fields of science, the most recent trend in haptic acquisition is the treatment of unconstrained multimodal data (see Fig. 2.9). Gao et al. applied deep learning over both visual and haptic data to develop a prediction model for robots to anticipate contact with visible objects [48]. The Proton Pack is a handheld surface interaction recording system with an impressive number of sensors [24, 25, 26]. It is intended to produce an ambitious multimodal dataset for autonomous robots to properly interact with their environment. Another inspiring body of work in that domain is the one of Strese et al. who used audio signal analysis in conjunction with machine learning algorithms on both sound and acceleration data [169, 171]. One particularly interesting trait of their approach is that they put effort on establishing a ground truth about perceptual similarity from subjective psychophysical experiments, aiming at matching robotic analysis with the five human perceptual dimensions [167, 170].



(a) (b)

Figure 2.9 – Visuo-haptic acquisition for autonomous robots. **(a)** Visual prediction of haptic features using deep neural networks [48]. **(b)** The Proton system features three interchangeable end-effectors, a force/torque sensor, a microphone, several inertial sensors, a 3D camera and a high resolution color camera for comprehensive multimodal acquisition [24].

2.2.3 Explicit and implicit haptic modeling

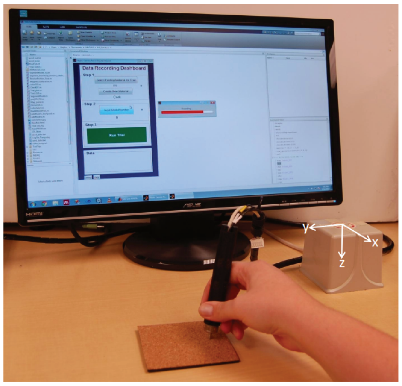
Haptic data are not necessarily at the core of haptic rendering, but haptic modeling is. Haptic rendering can be considered as a *relationship* between given exploratory or manipulatory inputs and given delivered outputs: in this regard, it expresses a model of the contact phenomena.

The most straightforward approaches for rendering consist in using explicit models: approximating the virtual object by an idealized, simplified mathematical model in order to run a physical simulation. The quality and realism of the resulting experience is thus dependent on the proper choice of the physical parameters of the model. The typical example is the use of the Hooke's law to simulate stiffness. Because of their simplicity, explicit models were popular in the beginnings of haptic rendering [11, 120, 209]. The parameters of the model can be eventually fitted through measurements done on real objects [50, 95, 133, 136], which is usually referred as "measurement-based modeling". Explicit models have two main limitations. Firstly, they require some preliminary knowledge on the physical phenomena that are to be simulated. Secondly, outside of simplistic cases, they often require considerable sophistication to provide a convincing result, and can thus be unfit for the real-time rendering of complex, realistic scenes with non-linear behaviors [140].

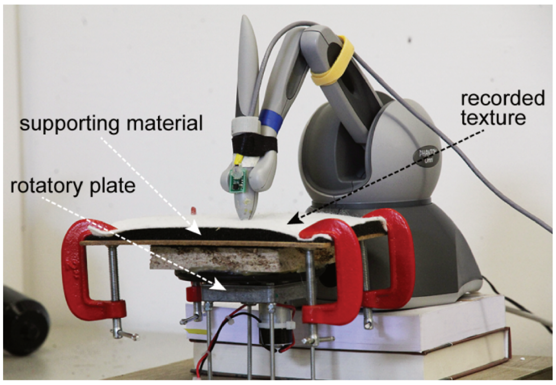
More recently, "data-driven" approaches were proposed as an alternative, in which the rendered forces are computed from an interpolation of sparse recordings of the real interaction [1, 60, 134, 205] (see Fig. 2.6c). A strength of such implicit methods is to make use of precalculations on the recorded data to provide sophisticated outcomes in real-time. In a pioneer contribution, Hover et al. proposed two offline force field interpolation schemes in order to render one-dimensional visco-elasticity [60]. Their method could handle arbitrary non-linear materials with visco-elastic behavior. This work was later extended to the rendering of viscous fluids [61], slipping phenomena [59], and inhomogeneous behaviors [163]. Because of their promising possibilities in terms real-time realistic rendering, data-driven approaches received great attention in the field of medical training and robotic surgery [127, 135].

2.2.4 Haptic databases

A few authors worked on constituting haptic datasets for use by the research community. Publicly accessible databases save the research community time because collecting data can be time intensive and expensive. This ambition is recent, as the very first attempt was the one of Culbertson et al. only a few years ago (Fig. 2.10a)) [31]. They provided one hundred haptic texture and friction models, the recorded data from which the models were made, images of the textures, and the code and methods necessary for rendering on a commercially available device. Each texture and friction model was based on a ten-second freehand recording of the force, speed, and high-frequency acceleration measured with an instrumented probe.



(a)



(b)

Figure 2.10 – Haptic recording for data-driven rendering or material classification. **(a)** The tool measures position, orientation, force and 3-DoF accelerations during a ten-second manual interaction [31]. **(b)** Controlled vibratory acceleration recording. The rotary plate ensures a controlled velocity scanning while force-feedback is applied to control normal force [168].

Shortly after, Strese et al. proposed a set of controlled and freehand acceleration recordings of 43 different textures (Fig. 2.10b)) [168]. Control recordings were done under two conditions, either with constant force and increasing scan velocity, or constant velocity and increasing normal force. Uncontrolled recordings consisted in a set of ten different twenty-second recordings following five lateral movements and five circular movements. The dataset was later extended to 69 textures, including measurements of sound, grasping force, and images [169].

The Proton Pack project envisions the constitution of a comprehensive multimodal dataset [26]. Because of the quantity of data it is able to gather, this work opens a lot of exciting possibilities and challenges in data treatment and analysis. Another ambitious recent work foresees a "universal haptic library", where psychophysical haptic features are matched with visual features, in order to automatically generate a haptic data-driven model from an unknown visual texture [1]. Such an approach tackles the difficulty of producing quality haptic content in large and complex scenes, which is one of the main issue of bringing haptics into immersive 3D environments.

2.3 Technological solutions for surface haptics

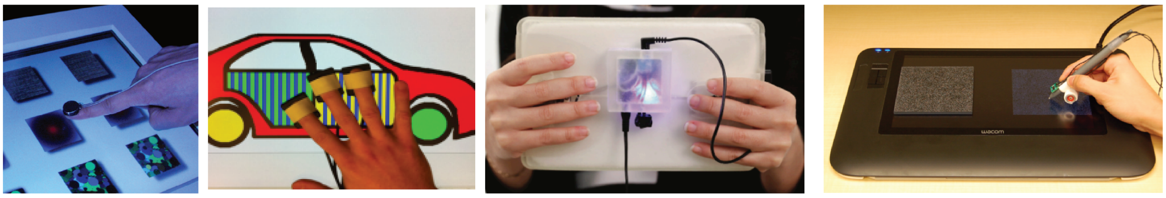
Enriching touchscreens with additional tactile content has become an active field of research in the last decade. Researchers have proposed a wide variety of strategies to provide touchscreens with haptic sensations, and very different technological solutions have been explored.

In this section, we review these approaches according to the type of actuation they imply. The vast majority of them is based on mechanical stimulation, and neglects thermal stimuli. This can be explained by the technical difficulty to combine tactile screen interactions with temperature control. Although some examples exist [147], they are non-colocated and were therefore considered as out of scope for our review.

2.3.1 Vibrotactile feedback

Because of their simplicity of integration, embedded vibrators are very common in nowadays mainstream tactile devices, and they tend to be intensively used for both gaming and GUI interactions enhancement. It is a fact that even a very simplistic haptic feedback can considerably increase the comfort and/or performance of tactile screen interactions (like the vibratory feedback when typing, for instance) [47]. However, the possibilities of usual embedded vibrators for haptic feedback remain limited: because they act on the whole screen as a single source, they produce a similar effect on different fingers touching the screen, and they cannot provide localized or moving stimuli. Furthermore, because they are generally simple eccentric rotors, they operate in a very narrow range of frequencies.

Many researchers have proposed original ways to enrich touchscreens with an additional vibrator (see Fig. 2.11). The vibrator can be placed either on the nail [3], between several fingers and the screen [23], on the device [22, 203, 207] or both on the device and on haptic gloves [66]. In particular, Romano and Kuchenbecker used a high-quality one-dimensional vibration to display compelling texture details through an actuated stylus, according to normal contact force and lateral speed [150].



(a) (b) (c) (d)

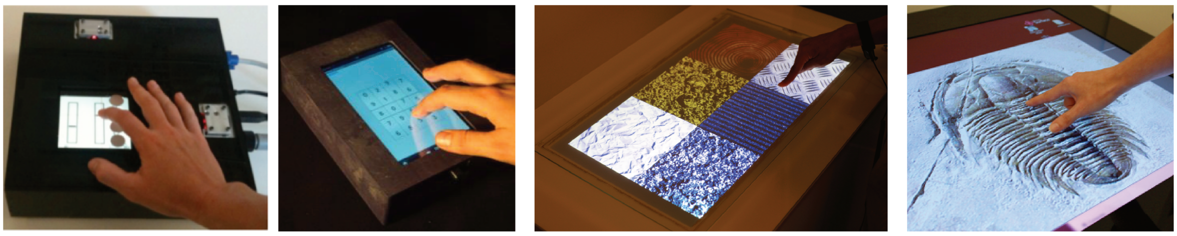
Figure 2.11 – Examples of vibration feedback approaches. **(a)** Finger-nail mounted vibrator [3]. **(b)** Multi-finger 2-D haptic display [23]. **(c)** Intermanual motion illusion [207]. **(d)** High-quality texture vibration rendering [93].

2.3.2 Variable friction

Vibrations can be used as a haptic signal mechanically transmitted to a finger; but they can also be a mean to modify the physical phenomena occurring on contact with a surface (see Fig. 2.12). In particular, ultrasonic frequencies are able to produce a thin film of air between the finger and the vibrating a surface, resulting in a diminished resistance to sliding. This friction reduction technique, first described by Watanabe and Fukui [194], was applied to touchscreens only in the 2010s [111, 125].

Another technique, called electrovibration, consists in amplifying electrostatic forces through high-voltage oscillations [13]. Although the concept was dating back to the 1950s [116], Linjama and Mäkinen were the first to use it on a transparent substrate, compatible with a tactile screen [114].

In both approaches, friction can be modulated to produce texture effects and even 3D pattern features [84, 198].



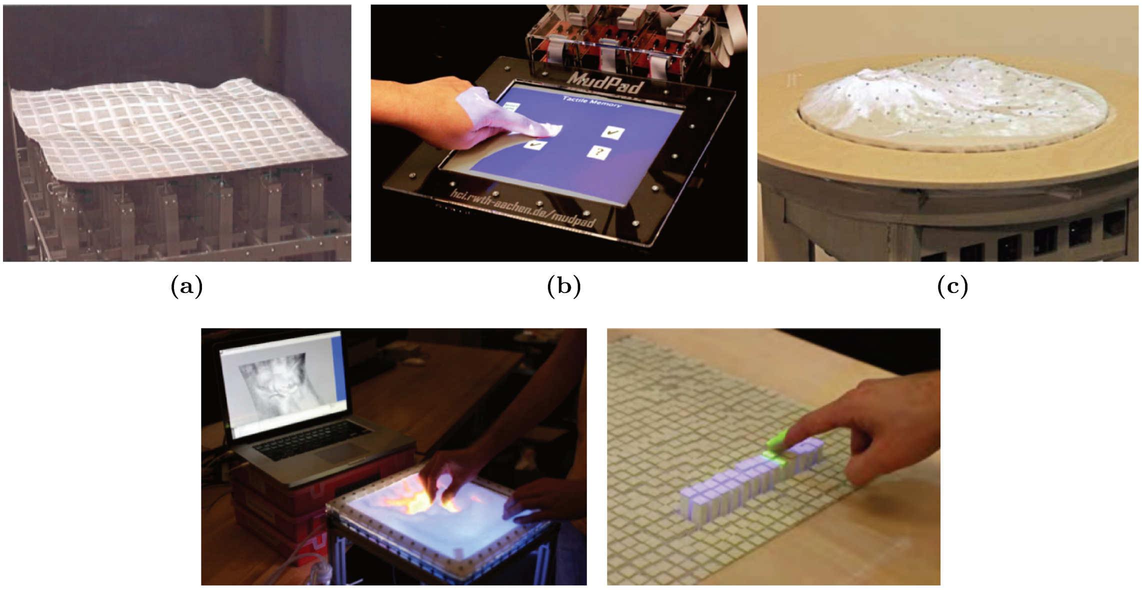
(a) (b) (c) (d)

Figure 2.12 – Examples of friction modulation displays. **(a)** The LATPaD device [111]. **(b)** The TPad fire [125]. **(c)** The TeslaTouch [13]. **(d)** Bump rendering with electrovibration [84].

2.3.3 Shape changing screens

Shape changing screens, as their name indicates, intend to reproduce the shape of an object consistently to its visual display. A pioneer work in that field is the FEELEX project [67], a deformable 24cmx24cmx3mm plane actuated by an array of thirty six linear actuators (Fig. 2.13a). Each actuator is combined with a force sensor, providing interaction with the graphics which are projected on the surface from the top. Since then, a variety of other technological solutions have been proposed to achieve a similar concept. The main technical challenge for shape changing screens is to achieve acceptable performances for both resolution and actuation latency, with a limited bulkiness.

Jansen et al. used electromagnets and magnetorheological fluids to achieve low-latency multitouch feedback, at the cost of a low resolution [70] (Fig. 2.13b). In contrast, Jansen et al.'s Tunable Clay is a malleable screen with a hydraulic-activated particle jamming controlling controlling its global stiffness [43] (Fig. 2.13d). Leithinger et al. proposed a solution with simplified open-source hardware and no sensors in order to make it scalable and affordable [110] (Fig. 2.13c).



(a) (b) (c)

(d) (e)

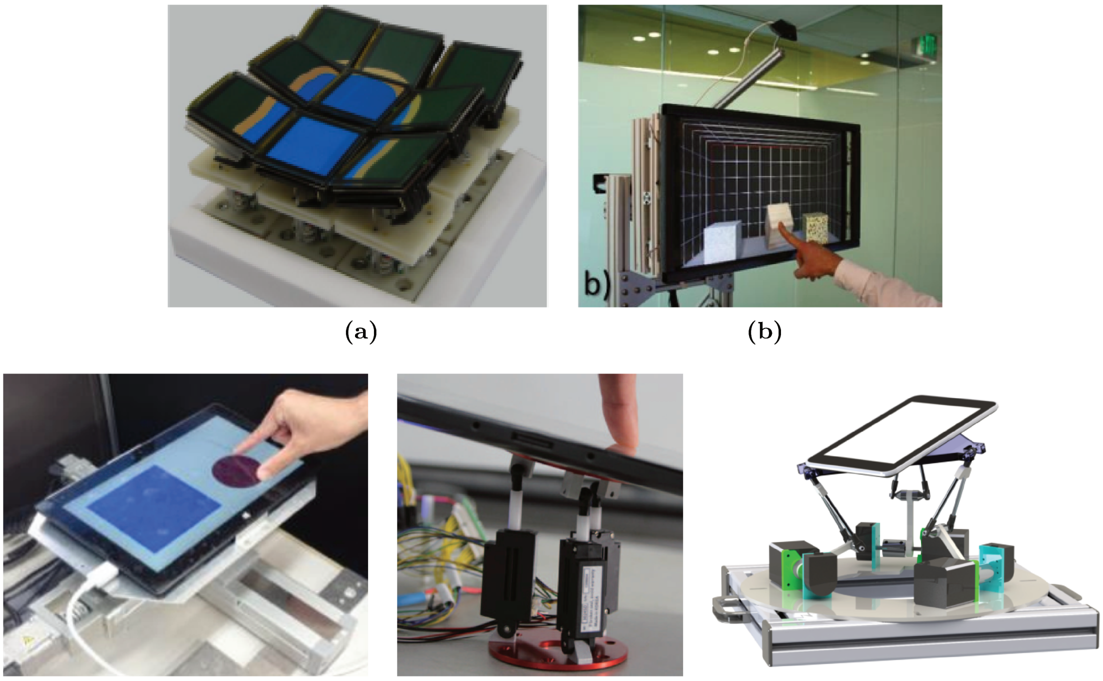
Figure 2.13 – Examples of shape changing surfaces. **(a)** The FEELEX 1 device [67]. **(b)** The MudPad system [70]. **(c)** The Relief 3D tabletop display [110]. **(d)** The Tunable Clay [43]. **(e)** The inFORM system [44].

In particular, the MIT Media Lab did an impressive work in designing a variety of pin-based shape displays and exploring their many applications, like UI dynamic affordance, physical rendering, 3D model manipulation, physical telepresence, music computing [29, 44, 107, 109] (Fig. 2.13e, see [108] for a review).

2.3.4 Moveable touchscreens

As an alternative to the technical complexity of shape changing screens, it can be beneficial to actuate a regular touchscreen with a robotic system providing motion and/or force-feedback abilities. By doing so, one takes advantage of the highly integrated nature of touchscreens, namely a high-resolution visual display with co-localized touch tracking. Yet, only a few solutions were proposed to haptically enhance a touchscreen with motion.

Alexander et al. proposed an interesting system named "Tilt Displays" that is about midway between a shape changing surface and a moveable screen [2] (Fig. 2.14a). It is



(a) (b)

(c) (d) (e)

Figure 2.14 – Examples of actuated touchscreens. **(a)** Multi-faceted shape rendering with Tilt Displays [2]. **(b)** Normal force feedback from the TouchMover device [164]. **(c)** Planar force feedback system [174]. **(d)** Inclination rendering through linear actuators [83]. **(e)** Orientation display by the SurfTics system [51].

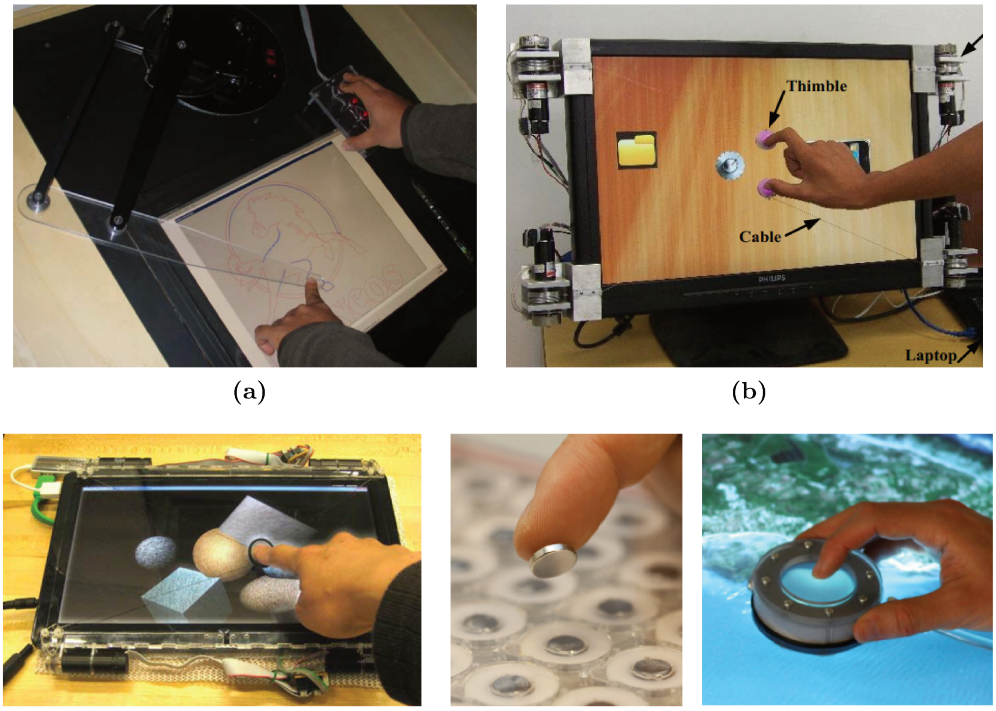
composed of a 3x3 grid of small tilt-actuated OLED screens, and is able to reproduce low-resolution 3D shape or kinetic animations.

The "TouchMover" device is a touchscreen actuated and moved using force feedback in the normal direction [164] (Fig. 2.14b). Its large force and movement abilities (up to 230N and 36cm) allows to simulate inertia and 3D shape of virtual objects, as well as volumetric data manipulation. The second version includes vibrators that allows to render either fine shape details or local content information [165]. Another approach presented by Takanka et al. consists in a touchscreen with planar force feedback and large translation and rotation abilities, simulating contact, inertia, shape and stiffness [174] (Fig. 2.14c).

Rotational movements can also be used to express the curvature of a virtual object on contact point, as proposed by Kim et al. [83] (Fig. 2.14d). Parallel platforms are an efficient way to provide this inclination feedback, as shown in the work of Maiero et al. [115] and Hausberger et al. [51] (Fig. 2.14e).

2.3.5 Actuated proxies

Instead of actuating the touchscreen itself, several authors proposed to make use of an intermediate part. Most of these solutions can be classified along two categories: the one providing a proxy just under the finger (see Fig. 2.15), and the one actuating a transparent overlay covering the screen (see Fig. 2.16). We will not address here the many works involving actuated probes (stylus, pen, stick, etc...), as they imply rather different types of interaction than touching the screen with the finger pad.



(a) (b) (c) (d) (e)

Figure 2.15 – Approaches using an actuated digital proxy. **(a)** Haptic Desktop System for assisted handwriting and drawing [141]. **(b)** The FingViewer enables two finger grasping of virtual objects [202]. **(c)** String-based geometry and texture rendering [156]. **(d)** Principle of the Finger Flux system [195]. **(e)** The HapticLens allows to feel the image's local stiffness [43].

Portillo et al. proposed to use a pantograph above a touchscreen for multimodal handwriting and drawing assistance (Fig. 2.15a) [141]. Ynag et al. had an original approach with a 4-DoF string-based system actuating two digital rings and providing grasp force feedback (Fig. 2.15b) [202]. The system was adapted later on a handheld tablet, with a single ring, in order to provide 2.5D geometry and texture feedback (Fig. 2.15c) [155, 156]. The FingerFlux uses electromagnetic actuation on a permanent magnet placed under the finger (Fig. 2.15d) [195]. It achieves attraction, repulsion, vibration, and directional haptic feedback on and near the surface, perceivable at a distance of several cm. Finally, the HapticLens is a transparent "tangible" allowing to feel the stiffness of any region of an image (Fig. 2.15e) [43]. The hydraulic jamming system controls the density of the chamber, going from liquid to solid consistency.

Some authors suggested to actuate a transparent film covering the whole screen. Wang et al. demonstrated a 2-DoF translational motion "Haptic Overlay Device", intended to enhance GUI interactions on automobile dashboards (Fig. 2.16a) [191]. The inspiring work of Roudault et al. in particular, investigated the uses of a tactile gesture output (Figures 2.16b and c) [152]. Their two prototypes could guide the finger on the screen to reproduce a given gesture like a letter or a symbol, without the need of looking at it.

(a) (b) (c)

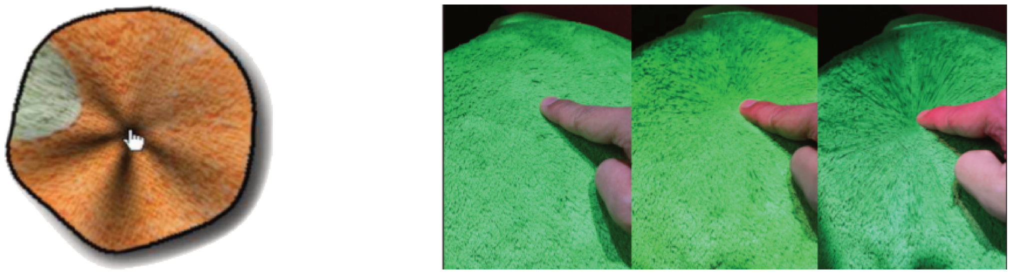
Figure 2.16 – Approaches using an actuated overlay. **(a)** The Haptic Overlay Device provides planar force feedback in two directions [191]. **(b)** and **(c)** Gesture output devices: the overlay can displace the finger to reproduce touch gestures [152].

2.3.6 Pseudo-haptic feedback

Regardless of the technology used, haptic actuators require fine design, additional technology, and available energy to stimulate the skin in order to provide realistic sensations. There are other ways, however, to transmit haptic information; notably thanks to cross-modal interactions. As thoroughly discussed by Biocca et al. in many cases the brain is able to fill the missing components of a perceptual modality to ensure coherent and consistent percepts [20]. Vision is especially prone to enhance or modify the perceptual content of other modalities.

"Pseudo-haptic feedback" refers to a non-haptic feedback inducing or modifying a haptic percept in response to a force or motion input. Its very first use was to replace expensive haptic devices with passive ones [99]. The first contributions on the topic mostly relied on modifying the Control / Display ratio of the mouse cursor in order to generate the feeling of going through a bump or a hole. Additional works explored other haptic properties such as shape for stiffness, speed for friction or mass, trajectory for slope (for a review, see [97]). For instance, Lécuyer et al. compared the choice of modifying the size or the speed of a mouse cursor in order to simulate the reliefs of a texture [98]. Both Mensvoort [187] and Watanabe and Yasumura [193] proposed a comprehensive framework to animate a mouse a cursor with a variety of effects. Pseudo-haptic principles have been used for various purposes like industrial and medical virtual training [18, 30, 113] or improving GUI performance [14, 117].

In the following decade, alternative approaches were explored. Keller et al. induced "pseudo-weight" sensations in drag interactions by making object harder to displace [80]. Watanabe changed the C/D ratio of a scrolling background image instead of the cursor to induce friction sensations [192]. The "Elastic Image" proposed by Argelaguet et al. consists in deforming an image being clicked locally (Fig. 2.17a) [6]. The progressive deformation (which approximately substitute pushing force by time) creates a quantitative softness sensation. With a similar visual effect, Punpongsanon et al. used video-projection and finger-tracking to enhance the perceived softness of a real object (Fig. 2.17b [144]). Ban et al. used visual retargeting to provide illusory shape curvatures (Fig. 2.18) [8].



(a) (b)

Figure 2.17 – Pseudo-haptic softness effects. **(a)** The Elastic Image induces a softness sensation when clicking on an image [6]. **(b)** The SoftAR system provides illusory softness to a real object through video-projection [144].

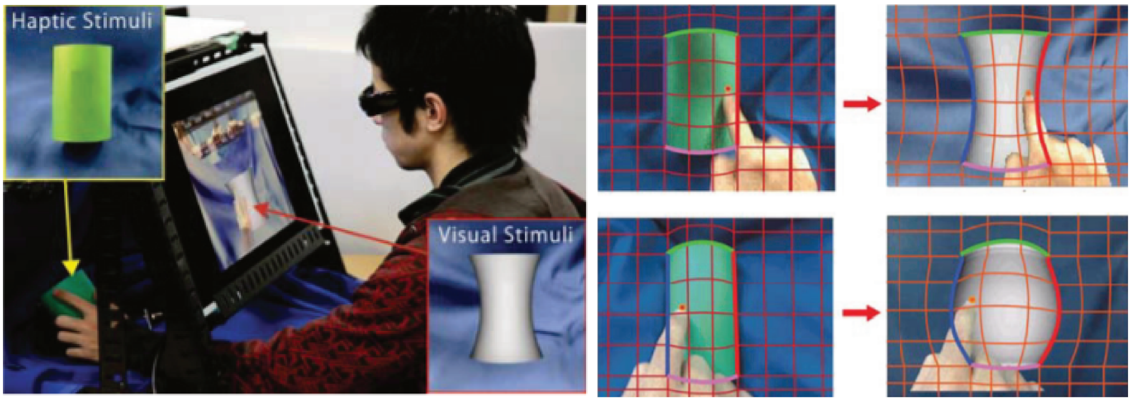


Figure 2.18 – The Magic Pot setup [8]. Although the finger follows a straight line on the object, the visual retargeting induces an illusory curved shape.

Only a few authors applied pseudo-haptic principles to touch interactions. Some of them chose a non-colocated approach, to avoid occlusion and decoupling issues. The TCieX environment, for instance, proposed a variety of remote tactile interactions built on pseudo-haptic principles [126]. The interface was split in two parts: one for control (mostly lateral stroke), one for content display. Kokobun et al. used a separate rear touch interface, and used a mouse-like cursor to showcase the effects of Lécuyer et al. (Fig. 2.19) [89]. Argelaguet et al. proposed a collaborative experience where a virtual object was squeezed between two virtual proxies, which were controlled independently by two different users [5]. This original scenario required the participants to coordinate their inputs, which were done on separate tactile tablets, to squeeze and deform the virtual object. Changes in deformation rate were perceived as changes in stiffness, with similar performance for collaborative and single-user tasks.

Other authors leveraged co-localized touch interactions to display pseudo-haptic effects on touchscreens. Ridzuan et al. changed the visual aspect of the user's finger according to the applied pressure to simulate variable stiffness (Fig. 2.20a) [148]. The approach of Watanabe was adapted to touchscreens in [184] and [128], inducing quantitative sliding sensations (Fig. 2.20b). Fleureau et al. adapted the Elastic Image technique to a digital tablet, with an additional audio feedback to simulate roughness (Fig. 2.20c) [42].

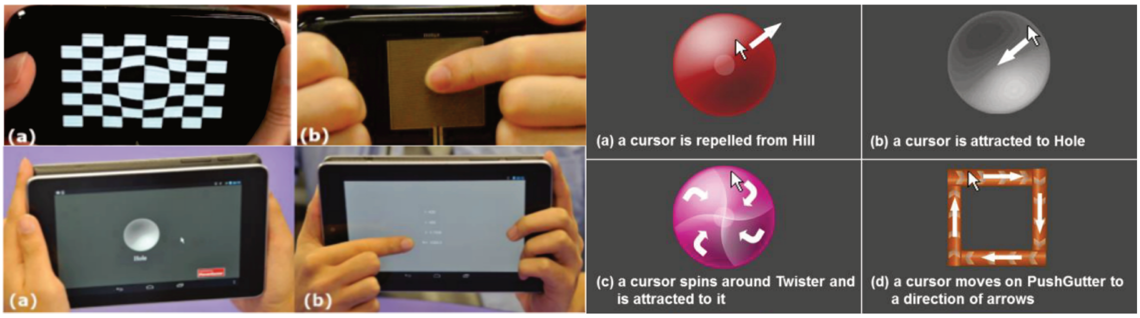


Figure 2.19 – A separate rear touch input avoiding both occlusion and decoupling issues [89]. Changing how the mouse-like cursor moves in response to touch input induces a variety of pseudo-haptic effects.

(a) (b) (c)

Figure 2.20 – Adaptation of pseudo-haptic approaches to audio-visual experiences on touch-sreens. **(a)** The finger is visually elongated according to pressure to induce variable stiffness sensations [148]. **(b)** The sliding rate of the image and sounds of steps in the snow induces sensations of different snow depths [184]. **(c)** The visual deformation evokes compliance on contact while a rubbing sound on stroke simulates texture [42].

Decoupling issues can arise for speed-changing effect applied on a visual cursor placed under the finger: if the position offset between the finger and the cursor is too large, the illusion breaks. Ban and Ujitoko discussed this issue and proposed various visual effects to attenuate this phenomenon [9].

2.4 Conclusion

This chapter provided a literature review on three major topics related to surface haptics. Firstly, the perceptual mechanisms of haptic interactions with surfaces were presented and discussed. While skin mechanoreceptors show specific sensitivities to various tactile features, the choice of descriptors to quantify a haptic experience remains an open question. The experimental evaluation of haptic sensations is easily scrambled by semantic issues. Yet, haptic percepts can be classified along four general perceptual dimensions: compliance, roughness, friction and warmth.

Secondly, we addressed the question of haptic data, which can involve measurements, but necessary relates to modeling choices. Haptic data can derive from mathematical models, measurements of real materials or a combination of both. The few existing haptic databases illustrate both the heterogeneity of approaches for haptic acquisition, and the recent trend of taking advantage of machine learning techniques to extract haptic data from measurements.

Thirdly, we provided an overview of previous solutions for touchscreen haptic enhancement, which span a variety of technological approaches: vibrotactile feedback, variable friction displays, shape changing screens, moveable touchscreens, or actuated proxies. Regardless of their technical complexity, most of them address a limited range of sensations. Crossmodal effects like pseudo-haptic feedback can also complement haptic feedback without the need of a haptic actuator.

Haptic Material: a holistic approach for texture mapping

3

Contents

3D scanning techniques have flourished in the last decade, giving the possibility of digitizing real-life objects in a photo-realistic way. How could and should such virtual objects be enhanced with haptic properties in a **touch-realistic way**? Which features are to be considered, and how to store them in a standard format?

As for today, there is **no obvious, generalized way to provide haptic properties to a virtual object**, and most haptic rendering setups rely on **custom and specific data formats**. Even "holistic" systems [36, 77, 201], aiming at an exhaustive combination of haptic actuators, did not clearly address the question of holistic haptic data. This **lack of standard representation impedes** the whole computer haptics pipeline, from acquisition to rendering. A common, standardized way of storing haptic data would help to unify the approaches, to simplify the processes, to facilitate compatibility between setups, and to spread haptic databases.

Regarding hardware, if the CHAI3D project[1] is an example of unifying achievement regarding force feedback, its extension to other technologies like pin arrays, vibrators and thermal displays remains to be done, and stresses the need for a generic format addressing multi-cues rendering. Such a format would ideally comprise **sufficient information for the rendering of any perceptually meaningful feature**, and rely on standard metrics.

[1] www.chai3d.org

Therefore, in this chapter, we propose and develop **the notion of "haptic material"** as a reference to the similar notion of "materials" in computer graphics. In computer graphics, materials are handy packages with all the data required for the visual rendering of a virtual object. As an analogy, **the haptic material should provide all the necessary elements for haptic rendering**. Once associated with a haptic material, a virtual object should be ready to render through a variety of rendering setups, each of them making use of the appropriate subset of haptic features according to its capabilities.

Our approach relies on **texture mapping**: this term refers to a set of techniques to efficiently display the fine details of a 3D model in a realistic way without the need of a high-resolution mesh [53]. Originally developed in computer graphics, this approach has been advantageously applied to haptic rendering [82], but mostly in a hardware-specific way, with a limited range of haptic features. Following this approach, virtual objects can be seamlessly enhanced with additional haptic properties distributed on their surfaces, that are easy to edit and to visualize. Furthermore, the use of separated maps is appropriate to merge heterogeneous data.

Our format takes in account **ten different spatially distributed haptic features**, which we extract from previous literature in order to cover the possible combinations of four haptic percepts and four rendering cues. The ten haptic features are stored in **haptic maps**, which provide an intuitive way to visualize them and facilitates many tasks related to haptic design. Maps can be sketched with any raster graphic tool and progressively added into 3D scenes for prototyping, and corrected later with precise data from real-world measurements. More generally, our format is meant to be **seamlessly integrated in audiovisual content creation workflows**, and be easily **manipulated by non-experts** in multi-disciplinary contexts.

The contributions of this chapter are:

- the identification of ten elementary haptic features representing haptic surface perception according to both psychophysical quantities and haptic submodalities

- a new haptic material format, which extends the texture mapping approach to these ten complementary features, so to be compatible with a large variety of hardware

In the next section, we show from previous experimental findings that **ten elementary haptic features** can be used in a complementary way for the rendering of haptic surfaces. Then, we present **a new format** which extends texture mapping to these ten features, storing them spatially in ten **dedicated haptic maps**. We provide a detailed example of a texture and the ten associated maps, as well as a general metric for units, ranges and resolutions to be used to interpret the haptic maps, in order to match the largest range of rendering contexts.

3.1 Ten relevant features for haptic surfaces

Decades of research on touch perception showed that pressure forces, vibrations, friction forces and temperature are perceived in a complementary way, resulting in four distinct percepts (for review see [178] and [132]):

- **compliance** refers to the perception of deformation modalities,
- **surface geometry** refers to shape, reliefs and asperities,
- **friction** refers to sliding-related sensations,
- **warmth** refers to perceived temperature differences.

These perceptual dimensions, or percepts, arise from the reception of different types of cues by various body receptors:

- **cutaneous cues**, relating to contact area and skin deformation, are mainly sensed by SA-I, SA-II and FA-I in the region of contact,
- **vibratory cues**, relating to rapid deformation, propagate trough the limbs and are mainly sensed by FA-II receptors in deep tissues and joints,
- **kinesthetic cues**, relating to limb movements and efforts, are mainly sensed by proprioceptors located in muscles and joints,
- **thermal cues**, relating to the heat flux transmitted by contact, are sensed by thermoreceptors in the region of contact.

Despite a tempting correspondence, these four types of cues (also called "submodalities") do not match directly the four perceptual dimensions of texture perception. Indeed, finger pad deformations, contact vibrations and constrained motion are not specific to a given property, but can rather arise from compliance, geometry or friction attributes. For instance, the compliance of an object can be felt and judged either by the vibrations occurring on contact, by the fingertip deformation under pressure, by the movement due to object indentation, or by any combination of those. Thus, the compliance percept arises from three distinct stimuli, depending on the context. Therefore, the three mechanical dimensions can be decomposed according to the three possible mechanical cues, leading to nine haptic mechanical features. The thermal cues, in contrast, appear to match the dimension of warmth.

In the next subsections, we detail these ten elementary haptic features and show how previous studies stated their specific complementary contributions to haptic perception. For each of them, we identify the corresponding perceptual metric proposed by the literature when there is one, or suggest one according to the results and terms of previous research, as summarized in Table 3.1.

Percepts → Cue Types ↓	**Compliance**	**Geometry**	**Friction**	**Warmth**
Kinesthetic	Rate-hardness [96]	Local surface orientation [35]	Kinetic friction [124]	/
Cutaneous	Contact area spread rate [19]	Local indentation [161]	Static friction [143]	/
Vibratory	Dynamic stiffness [55]	Stroke spectral response [92]	Stick-slip [91]	/
Thermal	/	/	/	Thermal profile [182]

Table 3.1 – Representative quantities for the ten haptic percept/cue combinations.

3.1.1 Compliance features

Although compliance has been traditionally assimilated to stiffness (force/displacement ratio, independent of damping), the "spring force" approach has been found to have both realism and technical stability limitations [186]. A variety of approaches intended to replace it with better representative quantities.

Kinesthetic cues: Considering the gestual aspect of compliance that is felt through proprioception, the **"rate-hardness"** metric has been proposed to better match the psychophysical quantity that is actually perceived [96]. Rate-hardness is defined as the initial rate of change of force over the penetration velocity, and is used to simulate both stiffness and damping behaviors with better stability.

Cutaneous cues: Pressing an object does not only bend its surface, but also flattens the fingertip, producing a change in contact area that is very precisely detected by receptors in the skin. Somewhat counter-intuitively, these cutaneous cues have been found to be much more important than kinesthetic cues in the perception of compliance [181]. Rather than force or pressure distribution, the change in contact area seems to be the decisive element for softness judgments, leading to interesting illusion cases [122]. The **"contact area spread rate" (CASR)** has been proposed as a metric [19]. It is defined as the rate by which the contact area spreads over the finger surface as the finger presses a surface.

Vibratory cues: Examining the compliance of a specimen can also be achieved with a probe with similar performances [45]. The transient vibrations produced by tapping are known to be important hardness cues, improving rendering both realism [92] and manipulation performances [90]. Their capture and modeling has been extensively studied in the form of a single-frequency decaying sinusoid [63]. However this approach oversimplifies the richness of real tapping transients, as realism is improved when larger spectral characteristics are taken into account [55]. Moreover, the relationship between the fundamental frequency of the transient and the physical properties of the material are unclear [54]. Thus, Higashi et al.

proposed to use spectral impulse response profiles, which they called **“dynamic stiffness”**, to characterize compliant virtual objects [55]. It is typically modeled by an autoregressive filter with a few dozen of coefficients.

3.1.2 Surface geometry features

Surface geometry comprises relief patterns from large-scale curvature, or shape, to small-scale asperities, or texture. Texture is usually split into two categories: “fine” roughness refers to asperities below 0.1 mm and is felt through stroke vibrations, while “coarse” or “macro” roughness refers to reliefs at the millimeter scale that can be well perceived with static cutaneous contact [58]. On the other hand, the two devices “NormalTouch” and “TextureTouch” of Benko et al. of exemplify the difference between local and and global shape rendering [15].

Hollins and Risner demonstrated that fine and coarse asperities are mediated by two distinct perceptual mechanisms, the first one relying on contact vibrations and the second one involving pressure spatial distribution [58]. It is noticeable that these two features are spontaneously explored with two distinct strategies, namely lateral motion and static contact. Another exploratory movement named “contour following” [103], aims at inspecting the global shape or volume of an object with large movements. In this case the kinesthesia (or proprioception) is likely to be predominant in the perceptual process. Therefore, there should be a perceptual shift from macro roughness to shape similar to the one from fine to macro roughness. The location of this shift is obviously in the vicinity of a finger width, although it is reasonable to expect some overlap, similarly to fine and macro roughness.

Vibratory cues: The perception of fine roughness have been extensively studied with respect to various geometrical parameters (see [178] for a review), but was also shown to correlate with different physical measurements, depending on the subject [180]. To circumvent this issue, more recent approaches focus on the quality of the spectral restitution of vibrations measurements from real materials thanks to autoregressive filter modeling [33, 119]. By doing so, the wide **spectral response to stroke** is modeled and stored in a compressed format, from which stroke vibrations can be reproduced with a high fidelity.

Cutaneous cues: Asperities at the millimeter scale indent the fingertip on simple contact. Haptic research has a rich history of pin array devices reproducing these **local indentations** at fingertip receptors resolution (see [15] for a review).

Kinesthetic cues: Relief patterns with a curvature higher than the one of the finger require an active exploration to be felt. Thus, they involve proprioceptive information in addition to fingertip contact sensations. Several studies demonstrated that **local surface orientation** (integrated with tangential trajectory) is the dominant source of information for shape, rather than vertical displacement for example [35, 197].

3.1.3 Friction features

Friction refers to the variety of contact interactions refraining the relative movement between two touching bodies. Friction modeling is a complicated topic (for a review, see [7]), and even the most sophisticated models remain based on simplistic empirical laws. They generally match the different regimes observed experimentally by conditionally switching between several different relationships [81]. Although some refined models involve additional parameters, we will only consider here the very few common fundamentals of most approaches. The most essential distinction is made between sliding and stiction, that is when the two objects are respectively resting or moving relative to each other. In both cases, friction is traditionally described through the ratio between the resistive tangential force and the normal force on contact, also called friction coefficient.

Cutaneous and Kinesthetic cues: When a finger starts stroking a sticky surface, if the tangential/normal force ratio is low, the finger pad deforms without sliding until a certain limit, defined by the **static friction coefficient**. Overcoming this threshold and actually stroking the surface leads to experience a dynamic resistance to movement, that is given by **kinetic friction coefficient** (assuming no lubricant) [81]. We believe it is reasonable to state that the friction cues are mainly cutaneous under stiction, and mainly kinesthetic under sliding.

Vibratory cues: The vibratory phenomenon that is eventually observed on the transition between stiction and sliding is called **stick-slip**. There is little consensus on the very description of the stick-slip phenomenon. If some approaches consider it as the implicit result of the stiction-sliding transition [36], it can be more explicitly treated with a dedicated vibrator [91]. We will consider here a vibratory modelling similar to the one of fine roughness, that is a spectral response to stroke, as it is both explicit and extensive.

3.1.4 Thermal features

Temperature is a crucial parameter for material discrimination, but humans are much more sensitive to temperature differences rather than absolute temperatures [75]. Psychophysical judgments of thermal features mainly rely on both **target temperature** and initial heat extraction rate, that is proportional to **thermal diffusivity** [182]. From these two parameters, a thermal display can elaborate realistic cooling or warming profiles simulating the behavior of real materials. We will thus consider here exponential decay profiles, defined using heat extraction rate as tangent at origin, and target temperature as end value.

3.1.5 Discussion

To sum up, we propose to characterize haptic surfaces with ten elementary features, given by the possible combinations of physical cues and psychophysical percepts. Taken together, experimental results indicate that the more features are rendered, the more realistic the virtual material is. However, this has to be put in balance with technical limitations, as most actuators are specialized in a given stimulus. For instance, several studies stated that cutaneous cues dominated kinesthetic cues for compliance discrimination [181], but one should note that CASR displays do not have the popularity and technical accessibility that force-feedback devices have. Table 3.2 provides a summary of the technical solutions that are typically used to provide these ten different types of stimuli.

Yet, very little is known about the relative importance of each cues for a given percept. For instance, in the case of compliance, the relative importance of vibratory cues is unknown. The systematic study of cues relative importance for compliance, surface geometry and friction perception is needed to determine an optimal combination of stimuli for a given haptic experience to be realistic.

	Compliance	**Geometry**	**Friction**	**Warmth**
Kinesthetic	Normal force feedback [96]	Parallel platform [35]	Variable friction display [13]	NA
Cutaneous	CASR display [19]	Micro-pin array [161]	Tangential force feedback [36]	NA
Vibratory	Vibrator (tapping transients) [55]	Vibrator (stroking response) [92]	Vibrator (stroking transients) [91]	NA
Thermal	NA	NA	NA	Peltier module [75]

Table 3.2 – Typical rendering devices used to render each of the ten percept/cue combinations.

It should be kept in mind that the proposed conceptual distinction between cues is not tight and comprises some overlap. The most clear case is certainly the one of surface geometry. The well-documented "duplex theory" states that vibratory cues are necessary to perceive reliefs below $0.1mm$, and that coarser asperities are correctly perceived with static contact only, however vibratory cues contribute to coarse roughness perception through dynamic contact [58]. Also, it can be argued that the cutaneous and kinesthetic perceptions are hardly separable, as both local indentation and surface orientation integrate finger pad deformation with trajectory to form a spatially distributed percept. Nevertheless, the display of haptic shape at different scale involve different stimuli [52], and it seems reasonable to consider three different orders of magnitude relatively to the size of a finger, insofar the finger is clearly affected in three different ways, namely vibrations, indentation and compression.

Finally, the vibrations conveying either roughness or friction information are hardly separable in practice, whether for acquisition or rendering, as they both arise from the rubbing of the surface. One can hypothesize that they match different spectral or temporal patterns: for instance the friction information being mainly characterize by abrupt changes and transient dynamics while the roughness information would be expressed by stable patterns for a given speed and force. However this hypothesis remains hard to evaluate experimentally.

3.2 Haptic Material: towards holistic haptic texture mapping

In this section, we present a new haptic material format suited for multi-cues haptic rendering without prior knowledge on display hardware.

From their early development, force-feedback devices pushed hapticians to make use of texture mapping approaches, notably because of their demanding requirements in terms of update rate [56, 120]. Many force rendering algorithms made use of normal maps or height maps to efficiently render small-scale geometry [112, 157, 176, 177]. Several authors extended the method to other haptic features. If texture mapping has been extensively used for haptic rendering of small-scale geometry (see [177] for a review), only a few authors extended the method to other haptic features. Kim et al. used a single "material map" containing both stiffness and friction values [82], while Wakita et al. stored them separately in two gray-scaled maps [190]. Kamuro et al. used three different gray-scaled maps for stiffness, friction and vibrotactile features [78]. In addition, each one of these three papers also described a "paint-like" interactive interface for local editing of haptic properties in an intuitive manner. Finally, Kim et al. proposed a method to embed diffuse, depth, stiffness and damping maps in a single 24-bit image [85]. They also suggested an audio-vibrotactile rendering as an alternative to force-feedback, but did not mention other types of rendering. Although these different works had very similar approaches, each of them involved a custom format for haptic data that is not directly compatible with the other setups.

As an alternative to texture mapping, Lang and Andrews proposed to associate vertices of a 3D model with haptic features [95]. Although this approach is very flexible regarding the rendering devices, a strong limitation is that the haptic content is hardly transferable from one virtual object to another.

3.2.1 The haptic image format

Based on the ten complementary haptic features identified in the previous section, our format associate a texture (or image) with ten dedicated haptic maps. Our haptic material can be associated to the 3D mesh of a virtual object to provide all the necessary information for haptic rendering at any point of the surface, similarly to a virtual material for visual rendering.

Figure 3.1 – Example of a visual image and thermal map revealing a hidden piping system. **(a)** The visual image. **(b)** The thermal map and its two channels.

By extending texture mapping to a variety of features, our haptic image format benefits from its intuitive visualization and rapid editing possibilities. Once the haptic maps of an image are elaborated from real-world measurements, perceptual models or sketched by hand, it is fully characterized for any rendering setup to come: the rendered features will be selected depending on the available hardware and its ability to convey kinesthetic, cutaneous, vibratory or thermal stimuli. Furthermore, the spatial mapping of haptic properties enlarges the usual "material" rendering scope, where properties are uniform and homogeneous among a sample, to a more realistic context of "haptic surfaces" with localized haptic features.

In our illustrative example, a wooden texture image (see Fig. 3.1a), taken from a high quality scan-based texture package [189], is augmented with ten haptic maps. For sake of simplicity our haptic maps are all defined either as regular grayscale or RGB images. In addition, we will assume that vibratory features are defined in the form of regression models [33, 55], defined in specific files stored together with the haptic image. Therefore, the vibratory maps store only the references to vibration models, similarly to [78].

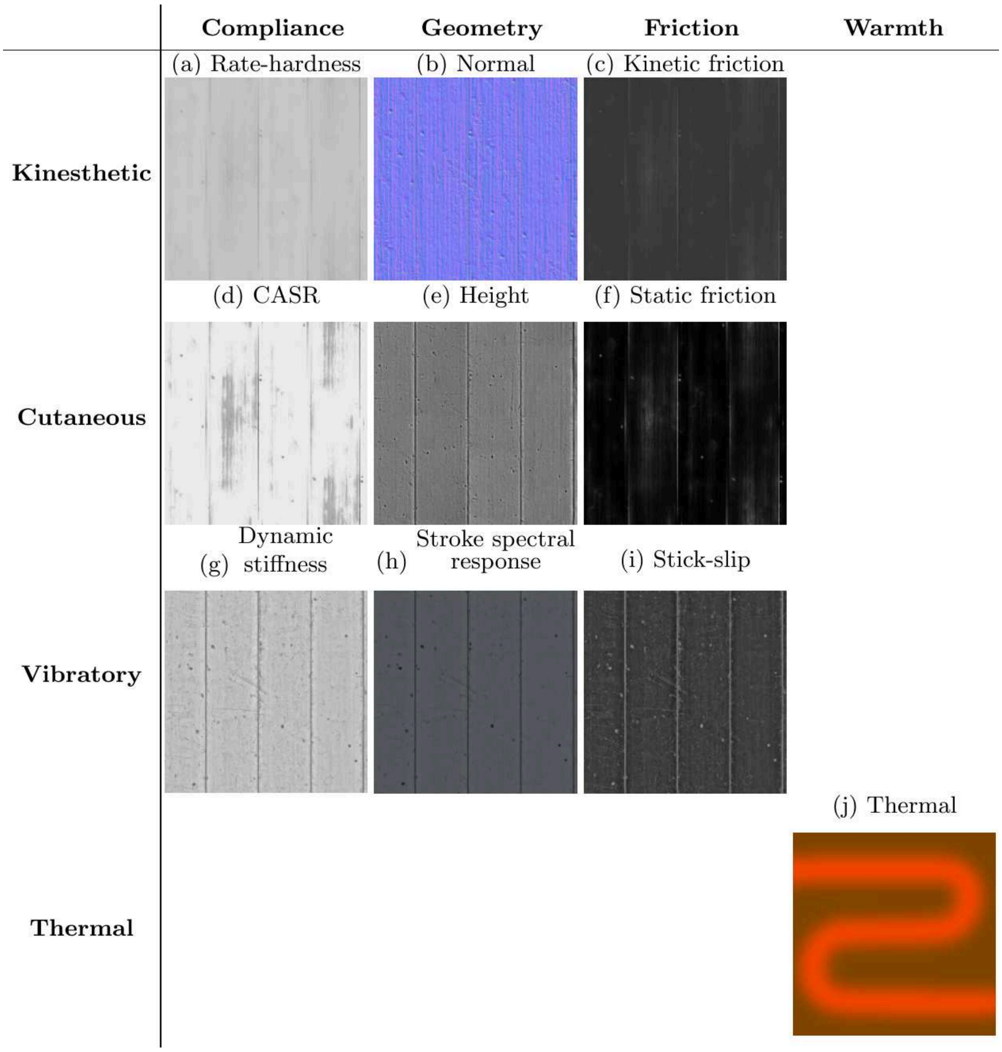


Figure 3.2 – Examples of the ten haptic maps of the haptic image format, organized along perceptual dimensions and haptic submodalities.

Fig. 3.2 presents an example of the ten haptics maps. The normal map (Figure 2b) stores the orientation of the surface for any point on the image. The height map (Figure 2e) contains the vertical coordinates of the surface with respect to the 3D mesh. Both are defined as it commonly is in computer graphics, and were provided within the texture package. In the absence of measurement from the real material, all other maps were visually sketched from the texture visuals. The rate-hardness, CASR, static friction and kinectic friction maps (respectively Figure 2a, 2d, 2c, and 2f) store eponymous values in 8-bit maps. Finally, the dynamic stiffness, stroke spectral response and stick-slip maps provide references to their respective models stored in separate files.

The thermal map (see Fig. 3.1b) is a 24-bit RGB image. The R and G channels are respectively used to store the local values for relative temperature and the thermal diffusivity (B channel is not used). The local temperature values are defined relatively to ambient temperature (which is defined assigned to the whole virtual object, like mass). As detailed on Fig. 3.1b, the color shades arise from a uniform dark green value expressing the uniform low thermal diffusivity of wood, and uneven local temperatures due to an potentially invisible heat source.

3.2.2 Specification table

Texture mapping techniques also addressed extensively the trade-off problem between resolution and performance, leading to various tricks like anti-aliasing and mipmapping. When applying this approach to haptics however, the question remains delicate as the different haptic maps address different physical quantities, matching different perceptual thresholds that might not have been directly address in previous literature. As an example, it is not trivial to decide which range and resolution should be required for a static friction coefficient.

Therefore, we propose a general-case specification table to define the format, range and resolution for haptic maps content. In specific contexts requiring other ranges or enhanced precision, custom specifications could be used to interpret the maps in the appropriate way. Table 3.3 summarizes the units, range and resolutions for each metric.

Haptic feature	**Format**	**Range**	**Resolution**
Rate-hardness	8-bit	0-10240 N.s^{-1}/m.s^{-1}	40 N.s^{-1}/m.s^{-1}
Contact area spread rate	8-bit	0-25.6 N/cm^2	0.1 N/cm^2
Local surface orientation	3x8-bit	2 x 0-180°	0.012°
Local indentation	8-bit	±5mm	0.039mm
Kinetic friction	8-bit	±5	0.04
Static friction	8-bit	±5	0.04
Relative temperature	8-bit	±25.4°	0.2°
Temperature slope	8-bit	0-5.0°/s	0.02°/s

Table 3.3 – General specification table for the features stored in the haptic maps. Vibratory maps are not considered as they store only references.

3.3 Conclusion

In this chapter, we proposed a new format for haptic texturing allowing to associate haptic data with a visual content. First, we argued that ten elementary haptic features could be extracted from previous studies as playing complementary roles in haptic perception of surfaces, both from a technical and a perceptual point of view. These elementary features arise from the combination of the four main perceptual dimensions of haptic perception with the four types of physical cues, or submodalities.

Then, we presented a new format which extends the texture mapping method to these ten elementary features. Our format provides a generic description of haptic materials without prior knowledge on display hardware. It is therefore especially suited for the constitution of haptic databases, which are meant to be shared between haptic researchers using various devices. The usage of images (maps) to store haptic information makes it easy to generate and manipulate haptic data, which can be artificially produced by hand or automatically, or encoded from measurements values.

Our format benefits from texture mapping's technical maturity: when using haptic materials, users can seamlessly make use of convenient methods such as tiling or unwrapping to adapt to many use cases. The possibility to edit haptic properties directly on volumetric objects through a haptic interface opens the way to fast-prototyping *haptic design*, providing means of quick experimental iterations to sensory designers in the production of multi-sensory experiences.

KinesTouch: 3D force-feedback rendering for tactile surfaces

4

Contents

In this chapter, we present the "KinesTouch" approach: the use of force feedback to provide normal and lateral motion and force abilities to a touchscreen (see Fig. 4.1). Our approach allows to address four different psychophysical dimensions, covering a wide range of co-located haptic sensations - with a single device and without requiring any additional prop worn by the user.

Most efforts in surface haptics have been concentrated on generating various types of vibrations that can alter the physics of the finger sliding on the screen, providing friction forces and even small relief sensations [84, 198]. However, such approaches do not allow to display other haptic properties such as stiffness or large-scale shapes.

A few solutions have designed touchscreens with kinesthetic feedback, i.e., able to move in space rather than vibrate, in order to involve spatial proprioception. Some approaches used parallel platforms for co-localized inclination rendering [83, 115], eventually combined with variable friction [51], but they kept a focus on rendering geometric features rather than material properties like stiffness, slipperiness or roughness. Sinclair et al. have proposed a remarkable solution combining 1-DoF kinesthetic and force feedback [164, 165], showcasing many interesting perceptual and interaction possibilities. Yet, besides its limitation to one axis, their device remains cumbersome and complex to spread out. The work of Takanaka et al. [174] is the only one, to our knowledge, to provide a touchscreen with lateral motion to evoke haptic properties. Interestingly, they chose to keep a non-slipping contact with the screen and simulated inertia and stiffness rather than sliding the screen against the finger to simulate friction or slipperiness. Although many innovative technologies have been developed to provide co-localized friction effects, the potential of the lateral motion of the screen under the finger has not been investigated yet.

4.1 The KinesTouch approach

The KinesTouch approach enriches touchscreen interactions with a set of tactile and kinesthetic effects in both normal and lateral directions. When the user touches an object or an image displayed on the touchscreen, the screen moves to simulate various haptic properties: it can resist more or less to pressure to render stiffness, move up and down according to object shape, vibrate during a stroke to evoke texture roughness, or slide laterally to change the slipperiness sensations.

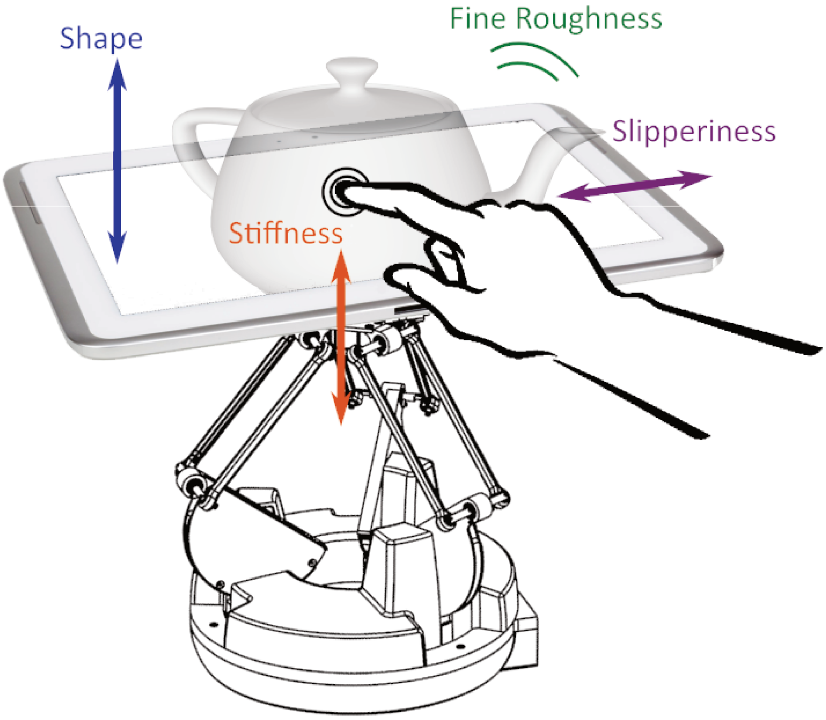


Figure 4.1 – Our KinesTouch prototype combines a standard tablet with a consumer-grade force-feedback device. It enables a free-hand direct interaction with 2D or 3D content augmented with a wide range of haptic effects: Stiffness, Shape, Sliding, and Roughness.

In the following sections, we present a set of four co-localized haptic effects. We will focus on the case of using a 3-DoF impedance device for the control law.

Notations

In the remainder of this paper, vectors and matrices will be expressed in the fixed reference frame with positive z upwards. The screen is considered to be horizontal, parallel to the xOy plane. Also: $\vec{X}_0$ will refer to the 3D center position of the workspace, $\vec{X}_t$ will refer to the 3D screen position with respect to $\vec{X}_0$, $\vec{f}$ will refer to the 2D finger position on the screen, $\mathbf{I}_3$ will refer to the identity matrix, $\vec{e}_z$ will refer to the vertical unit vector, $K_{\max}$ will refer to a high stiffness value, depending on hardware performance, used for position control[1] (1 N/mm in our setup).

4.1.1 Stiffness effect

The Stiffness effect allows the user to feel a resistance to deformation when they push an object on the screen. It simulates the elasticity of the virtual object, and address the compliance perceptual dimension. The effect consists in an opposing normal force which increases with penetration depth, as shown in Fig. 4.2. The two other directions of the touchscreen are locked in position.

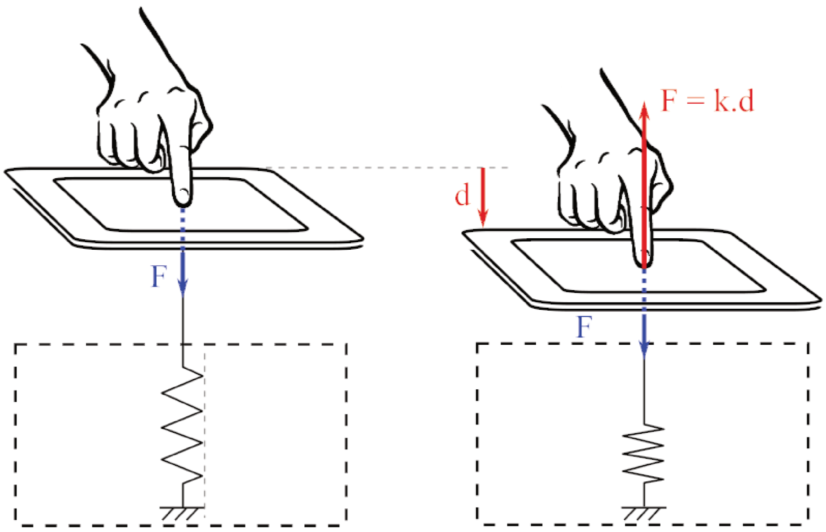


Figure 4.2 – Stiffness effect: the user feels an elastic force-feedback when pushing the screen.

Using an elastic deformation model, the control law of our Stiffness effect is:

$$\vec{F}_{stiffness} = \begin{bmatrix} K_{max} & 0 & 0 \\ 0 & K_{max} & 0 \\ 0 & 0 & k_{mat} \end{bmatrix} (\vec{X}_0 - \vec{X}_t) \tag{4.1}$$

[1]Impedance force-feedback devices provide forces to their end-effector, while measuring its position. Although they can't act directly on position, they can still be used for pseudo position control with a high stiffness force linking the measured position to the desired one.

with k_{mat} the simulated stiffness.

4.1.2 Shape effect

The Shape effect allows the user to feel the 3D shape of an object. It reproduces reliefs that are larger than the tip of a finger and need active exploration to be perceived. The effect consists in a normal displacement corresponding to the change in vertical projection of the 2D finger position on the object 3D shape, as shown in Fig. 4.3. The two other directions of the touchscreen are locked in position (i.e., there is no lateral motion).

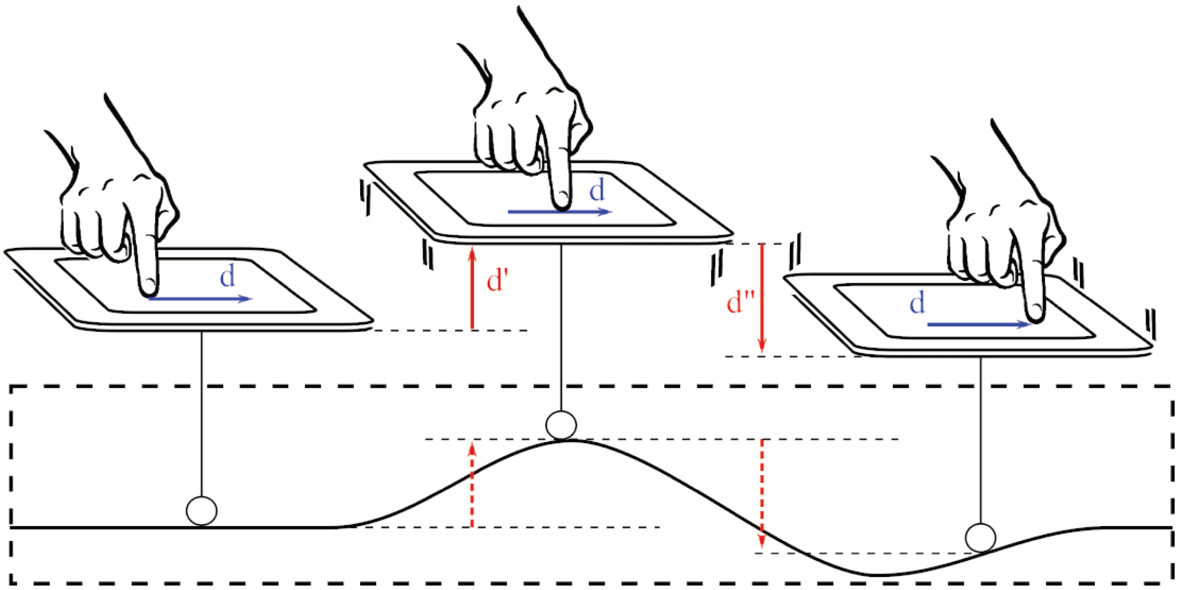


Figure 4.3 – Shape effect: when the user strokes over a relief, the screen moves up and down.

The control law of our Shape effect is:

$$\vec{F}_{shape} = K_{max}\ \mathbf{I}_3\ (\vec{X}_0 + h(\vec{f})\ \vec{e}_z - \vec{X}_t) \tag{4.2}$$

with $h(\vec{f})$ the vertical projection of the finger position onto the 3D shape.

The shape is accessed "from the top": only its visible upper part (relatively to the horizontal plane) can be explored. However, a simple rotation of the shape in the virtual space allows to access its bottom part.

4.1.3 Roughness effect

The Roughness effect allows the user to feel vibrations evoking a periodic grating when they stroke an object on the screen. It renders the fine roughness property, modeled by a small spatial period. The effect consists in an oscillating force taking into account both the simulated spatial period and the finger exploration velocity, as shown in Fig. 4.4. The touchscreen is otherwise locked in position.

$$\vec{F}_{roughness} = \delta \sin(2\pi\lambda||\vec{\dot{f}}||)\ \vec{e}_z + K_{max}\ \mathbf{I}_3\ (\vec{X}_0 - \vec{X}_t) \tag{4.3}$$

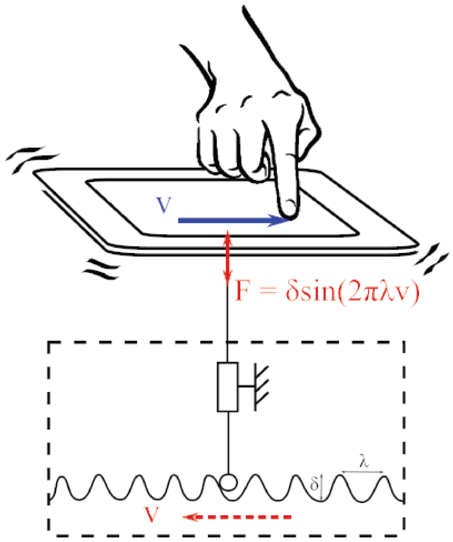


Figure 4.4 – Roughness effect: the screen vibrates as the user strokes over a texture so to create a fine roughness sensation.

with δ the grating depth, λ the grating spatial period.

4.1.4 Sliding effect

The Sliding effect provides various sliding sensations to the user when they stroke an object on the screen. As it modifies the sliding phenomenon between the screen and the finger, it addresses the friction perceptual dimension. It consists in a tangential movement of the screen meant to increase or diminish the relative sliding, that is the velocity difference, with the finger.

We expect two different sensations corresponding to the two possible sliding directions: a "Follow effect" and a "Reverse effect" which are described hereafter. The touchscreen motion is locked here in position in the normal direction.

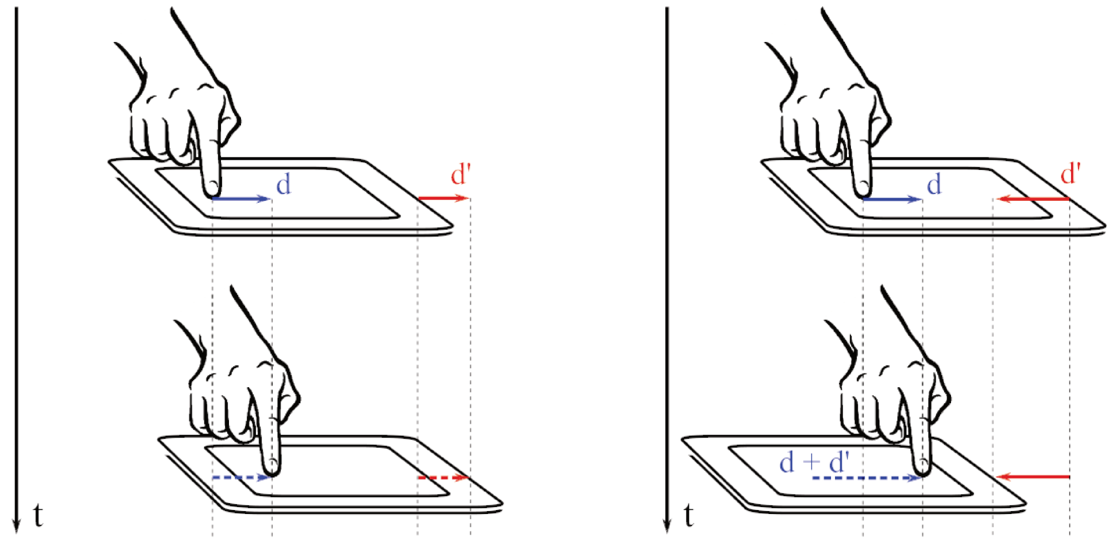
The "Follow effect", illustrated in Fig. 4.5a, consists in moving the screen the same way the finger moves on the screen, so that relative sliding is decreased or even kept close to zero. In this case, while the finger moves in the reference frame, its position on the screen remains almost static.

The "Reverse effect", illustrated in Fig. 4.5b, consists in moving the screen in the opposite direction to the finger's movement, so that relative sliding is increased.

The Sliding effect is achieved with the combination of two forces: a "moving force" proportional to the finger's tangential velocity, and a damping force in the binormal direction:

$$\vec{F}_{slipperiness} = \alpha\ \vec{\dot{f}} - \nu\ \vec{\dot{f}} \wedge \vec{e}_z + K_{max}\ (\vec{X}_0 \cdot \vec{e}_z - \vec{X}_t \cdot \vec{e}_z) \quad (4.4)$$

with $\alpha \in [-1, 1]$ the slipperiness coefficient and ν the damping coefficient.



(a) (b)

Figure 4.5 – Sliding effect: the screen moves laterally to increase or diminish relative sliding. **(a)** Follow effect: the screen follows the finger so to keep relative sliding close to zero. **(b)** Reverse effect: the screen moves in the opposite direction to the finger so to increase relative sliding.

4.1.5 Idle behavior

When the screen is not touched, it should stay still or move back to the center of the workspace, so that the force-feedback device remains close to its neutral position. This is done by applying a simple centering force instead of one of the previous effects:

$$\vec{F}_{idle} = K_{max}\,\mathbf{I}_3\,(\vec{X}_0 - \vec{X}_t) \tag{4.5}$$

4.2 The KinesTouch prototype

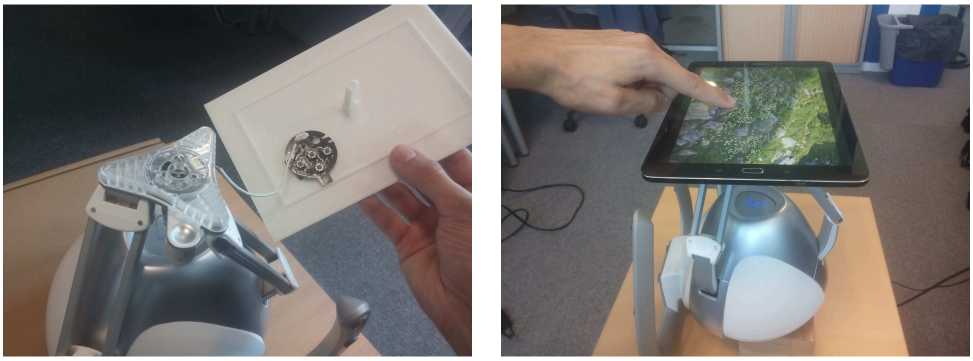
In this section, we describe the design and implementation of our prototype using a standard tablet and a Falcon haptic device. We designed a custom end-effector in order to be able to attach the tablet on the haptic device handle, and a prediction-correction algorithm to compensate the touch tracking latency. We also present the synchronization between visual and haptic loops, and the control law for the haptic rendering.

4.2.1 Hardware

The Falcon is a standard 3-DoF impedance haptic device, initially designed for the gaming industry. We combined it with a Galaxy Tab SM-T810, which exhibits rather high resolution (2048x1536), comfortable size (9.7”) and an acceptable weight (389g).

4.2.1.1 Assembly of tablet and force-feedback device

The Falcon's grip has several buttons and is removable, but a security mechanism deactivates the device when the grip is removed, detecting the electrical contact with the grip. This problem was overcome by unmounting the default grip and keeping only the coupling part and the electronic circuit. A tablet adapter, shown in Fig. 4.6a, that reproduced the interlock while offering a flat shape to affix the tablet, was 3D-printed. As the precise relative positioning of the tablet was not of importance for the haptic effects presented in this paper, it was affixed to the adapter with a simple Velcro grip. The Falcon was then rotated by 90 degrees and positioned sideways so that its "pushing" direction was upwards, as shown in Fig. 4.6b.



(a) **(b)**

Figure 4.6 – KinesTouch prototype. **(a)** 3D printed adapter. **(b)** Global setup.

4.2.2 Software

4.2.2.1 Handling latency issues

Besides the visual display, the tablet application is also responsible for touch tracking and filtering. In practice, the built-in touch tracking of the Galaxy Tab SM-T810 has a latency of a few dozens of ms, and the Unity application has a refresh rate of 60Hz. This results in a delay in the position measurement up to 2cm in usual slide movements, which is problematic for real-time haptic rendering. Furthermore, despite the high resolution of the screen, instantaneous touch velocity estimation suffers from spikes due to pixel quantization. For these reasons, touch position and velocity were computed and filtered before being sent and used in the haptic rendering loop, according to the following prediction algorithm, inspired from [185].

First, the measured touch position $\vec{f}_{mes}$ is converted in real-world meter coordinates. Then, a simple linear prediction is applied:

$$\vec{f}_{pred} = \vec{f}_{mes} + k_{pred} * (\vec{f}_{mes} - \vec{f}^{prev}_{mes}) \tag{4.6}$$

where x^{prev}_{mes} is the previous measured touch position and k_{pred} the filter parameter.

Finally, an exponential smoothing filter is applied to get the corrected position:

$$\vec{f} = \alpha * \vec{f}_{pred} + (1 - \alpha) * \vec{f}_{pred}^{prev} \tag{4.7}$$

where $\vec{f}_{pred}^{prev}$ is the previous predicted position and α the filter parameter.

The parameters were set after testings to: $k_{pred} = 8$ and $\alpha = 0.15$. Instantaneous touch velocity is smoothed with an exponential smoothing filter with $\alpha = 0.45$.

4.2.2.2 Visual and haptic loop synchronization

The haptic rendering is computed by a dedicated application running on a laptop and using the CHAI3D framework. On the tablet, a Unity application is used for the visual rendering and the touch tracking. The two applications communicate with each other using the Open Sound Control (OSC) protocol [199]. As applications run at different rates, this communication is asynchronous. On both sides, incoming messages are treated in a specific thread and update global variable values which are then used in the main thread. A network connection is emulated through the USB cable connecting the tablet and the laptop, in order to keep OSC communication latency under 1ms.

The haptic rendering is mostly located in a haptic thread running at about 1000 Hz inside the CHAI3D application. An additional 60 Hz thread is meant to send the Falcon position to the tablet application. The synchronization of the two loops is illustrated in Fig. 4.7. In the Unity application, a main loop updates touch information, sends them to the CHAI3D application, and updates the visual display. This visual display compensates the Falcon movements so that when the tablet is moving, displayed objects remain immobile in the user's reference frame.

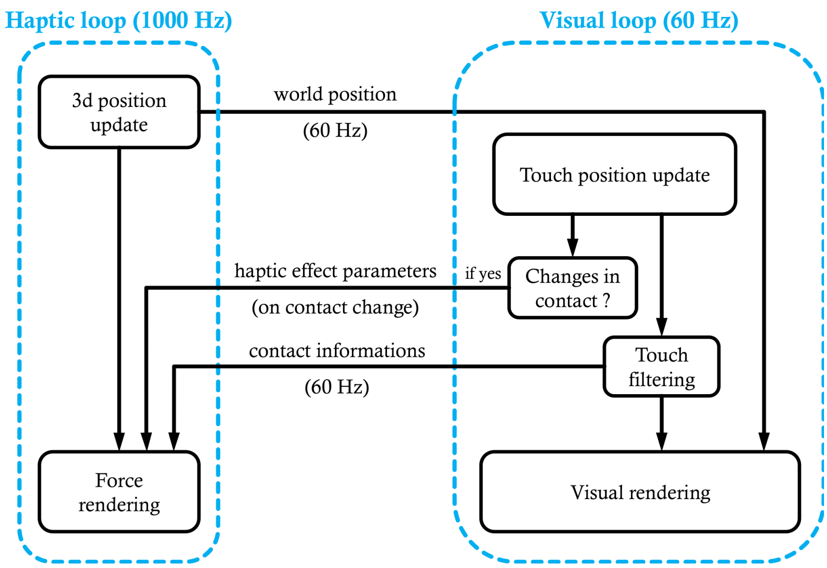


Figure 4.7 – Software architecture.

4.2.2.3 Transparency

In the previous descriptions of our haptic effects, the system is supposed to be perfectly transparent, with no inertia. However the weights of the touchscreen and effector are not negligible compared to the other involved forces, and have to be compensated. This is simply achieved by adding a constant opposite force in the control law.

4.2.3 Control law

The final haptic rendering was obtained using a single control law that merged all our haptic effects[2]:

$$\begin{aligned} \vec{F}_{total} = (mg + \delta \sin(2\pi\lambda||\vec{f}||))\vec{e}_z + \alpha\vec{f} - \nu\vec{f} \wedge \vec{e}_z \\ +\mathbf{K}\ (\vec{X}_0 + h\vec{e}_z - \vec{X}_t) \end{aligned} \tag{4.8}$$

with $\mathbf{K}$ the stabilization matrix, chosen with respect to the effect according to Table 4.1.

Effect	Idle, Shape, Roughness	Stiffness	Sliding
$\mathbf{K}$	$K_{\max}\ \mathbf{I}_3$	$\begin{bmatrix} K_{\max} & 0 & 0 \\ 0 & K_{\max} & 0 \\ 0 & 0 & k_{\text{mat}} \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & K_{\max} \end{bmatrix}$

Table 4.1 – Stabilization matrix values for the different effects.

4.3 User study

We conducted a user study to evaluate the sensations produced by the KinesTouch prototype. Due to the large variety of our haptic effects, we have focused on our most innovative effect: the Sliding effect. Our choice was motivated by the fact that equivalents of Stiffness, Shape and Roughness effects have already been largely studied in the haptic literature. In contrast, the Sliding effect had never been explored in the literature and there are no clear assumptions on what the user's perception will be. Thus, we conducted a user study to answer the following question: are users able to consistently and efficiently discriminate different Sliding effects?

We compared three sliding sensations: the Reverse effect (REVERSE, see Fig. 4.5b), the Follow effect (FOLLOW, see Fig. 4.5a), and a control stimulus in which the tablet remains static (STATIC). Three hypotheses were tested:

- **H1**: different stimuli would produce different sensations
- **H2**: seeing the moving screen contributes to distinguish between stimuli, i.e., visual cues increase the discrimination accuracy.

[2] The Falcon was found to produce forces proportional, but not equal, to the forces requested through the CHAI3D API. This problem was overcome by applying a gain factor that was empirically found to of about 4.5 on two different Falcon devices to get the right forces. This is consistent with another study, although they found the gain to be equal to 3 [188]. This difference of value might be explained by the difference of CHAI3D version.

- **H3**: the smoothness of the screen diminishes the sensations produced, i.e., tactile cues increase the discrimination accuracy.

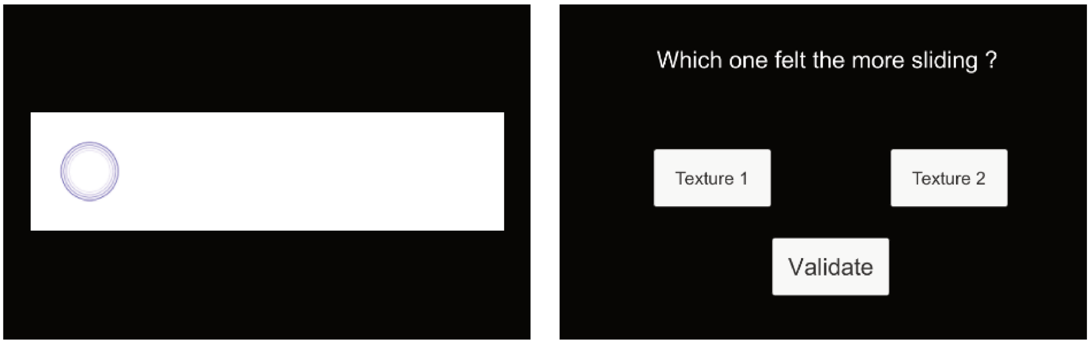
4.3.1 Procedure

18 volunteer unpaid subjects (16 male, age 31.2 ± 12.1) took part in the experiment which consisted in two sessions of about 45mn on different days. All of them were right-handed or ambidextrous.

After reading and signing a consent form, subjects were asked to seat with the right arm resting besides the tablet screen. For each trial, a narrow white area was displayed on the screen, and the subject was invited to slide their finger inside this area (see Fig. 4.8a).

Each trial was composed of the active exploration of two stimuli, followed by a forced-choice question to designate on which one the subject felt the more sliding (see Fig. 4.8b). Each stimulus lasted 3.5 seconds from the moment the screen was touched, then the screen turned to black and waited for the touch release to pass to the second stimulus or the question. The subject provided the answer to the question directly on the screen.

At the beginning of each session, two practice trials were first performed to ensure that the subject understood the procedure. During these introductory trials, a moving target was displayed to suggest a back and forth movement at 0.5 Hz. Subjects were informed that the stimuli would be optimally felt within this range of velocities but were left free in their inspection otherwise.



(a) (b)

Figure 4.8 – Screenshots of the experiment application. **(a)** The stimuli area with the trial moving target. **(b)** The forced choice presented after each stimuli pair.

4.3.2 Experimental Design

The experiment had three independent variables: the stimulus, the visual cues (i.e., seeing the tablet moving) and the tactile cues (i.e., screen roughness). Three pairwise comparisons were considered: REVERSE vs. FOLLOW, REVERSE vs. STATIC and FOLLOW vs. STATIC. To avoid order effects, the inverse comparisons were also considered.

In order to evaluate the importance of visual cues, half of the trials were performed with the whole mechanism being visible (V1, see Fig. 4.9a), and half with a black cover hiding the mechanism and its movements (V0, see Fig. 4.9b). In order to evaluate the importance of tactile cues, half of the trials were performed with a window privacy film applied on the screen (F1) and half without (F0). This transparent and electro-statically adhesive film had small but clearly perceptible reliefs that produced quite strong vibrations under the finger when being stroked. Affixed to the screen, there was no decrease in brightness but a tiny pixel diffraction on each relief. Trials were split in four condition blocks corresponding to the visual and tactile crossed conditions: V0F0, V0F1, V1F0, V1F1. In order to minimize order effects, the blocks' sequence followed a 4x4 Latin-square design. In each of the two sessions, two condition blocks of 60 trials (10 repetitions for each of the 6 pairwise combinations) were performed.

(a) **(b)**

Figure 4.9 – General setup without and with cover. **(a)** The V1F0 condition (without cover). **(b)** The V0F0 condition (with cover).

For each trial, the answer as well as the response time were recorded. In addition, a discrimination score for each subject was computed for each combination and factor (3 comparisons x 2 visual conditions x 2 tactile conditions). The discrimination score was computed as follows. First, each trial was counted as +1 or -1 according to stimulus chosen as the "more sliding" (the pair order being taken into account). For example, in a REVERSE vs. STATIC comparison, +1 will mean that REVERSE is considered to be more sliding that STATIC and vice-versa. Second, the data for each combination was normalized between [-1,1], showing the preference between the two stimuli. Finally, as we observed that subjects had different interpretations of the question, but were consistent in the stimulus they chose as "more sliding", we considered the absolute value of the discrimination score [0,1].

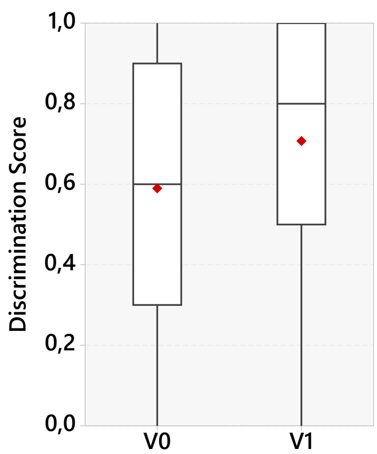
Thus, as indicated in Table 4.2, a discrimination score of 0 indicated that the subject had no preference between the two stimuli and answered randomly (with a 50% accuracy), whereas a discrimination score of 1 indicated that the subject consistently chose one stimulus over the other (with a 100% accuracy).

Preference rate	50%	60%	75%	80%	90%	95%	100%
Discrimination score	0	0.2	0.5	0.6	0.8	0.9	1

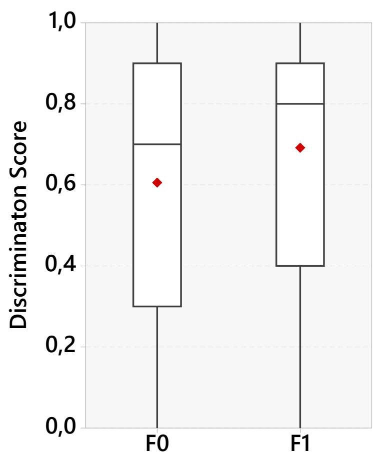
Table 4.2 – Correspondence between preference rate and discrimination score.

4.3.3 Results

Fig. 4.10 shows the distributions of the discrimination scores grouped according to the independent variables. On each figure, the red dot indicates the mean value, in addition to the median value and quartiles indicated by the box. An Anderson Darling normality test revealed that the data distribution were not normal, so we performed an aligned rank transform in order to enable a full factorial analysis using ANOVA. The three-way ANOVA comparison, visual and tactile cues vs. the discrimination score revealed a significant main effect on the visual condition ($F_{1,17} = 9.56$, $p < 0.01$). Post-hoc tests showed that this effect was significant ($p<0.05$), V1 had a higher discrimination score ($M = 0.71$; $SD = 0.3$) compared with V0 ($M = 0.59$; $SD = 0.33$). These results support **H2**. In contrast, no main effect was found on the tactile condition ($F_{1,17} = 3.64$, $p = 0.073$). Yet, the results seems to suggest that there is an impact of the screen roughness: F0 ($M = 0.61$; $SD = 0.34$) compared to F1 ($M = 0.69$; $SD = 0.30$). Nevertheless the results do not support **H3**. Regarding the different comparisons, the ANOVA did not show a significant effect ($F_{2,17} = 3.00$, $p = 0.063$). Again, the results are close to the significance threshold. Post-hoc tests seems to suggest that subjects were less accurate for the REVERSE vs. STATIC comparison ($p=0.053$). Finally, the ANOVA did not show any interaction effect.



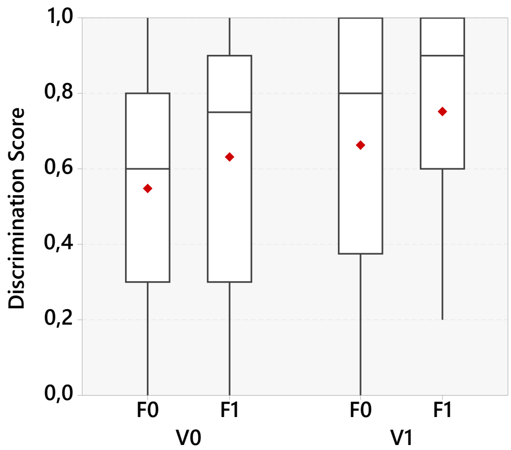
(a)



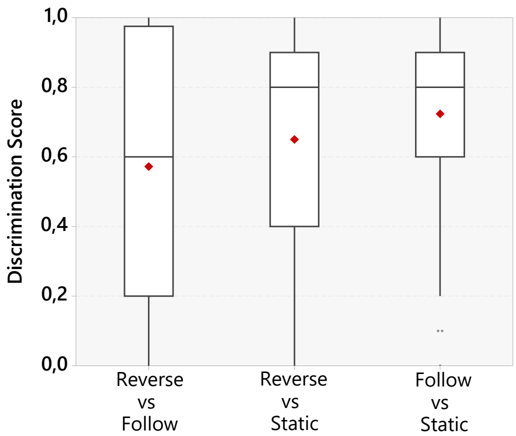
(b)

Figure 4.10 – Score distributions across **(a)** visual condition and **(b)** tactile condition.

Fig. 4.10a shows the score distributions according to the visual condition. Scores were significantly higher in the V1 condition, that is with the mechanism visible, than in the V0 condition, that is with a cover hiding it. As shown in Fig. 4.10b, scores were also higher, but not significantly, in the F1 condition than in the F0 condition, i.e. with the textured film on the tablet rather than without. The distributions of the crossed visuo-tactile conditions, shown in Fig. 4.11a, are consistent with the results of the non-crossed conditions (Fig. 4.10): scores were significantly higher with the mechanism visible, and not significantly higher with the textured film on the tablet rather than without. The highest average score is achieved, as expected, in the V1F1 condition, with half of the subjects having a score above 0.9.



(a)



(b)

Figure 4.11 – Score distributions across **(a)** crossed visuo-tactile conditions and **(b)** stimuli pairs.

Fig. 4.11b shows that the scores were different regarding which stimuli were compared. When the Reverse and the Follow effects were compared, the scores are distributed quite uniformly between 0 and 1. In contrast, for the comparison between the Follow effect and the control condition, half of the subjects have a discrimination score above 0.8 and a few have a score close to zero.

4.3.4 Discussion

Our results suggest that the two effects are well and consistently discriminated by a great majority of subjects. Indeed, even in the least favorable condition, V0F0, half of the subjects had a score above 0.6, which means they were consistent in at least 80% of their answers. In the most favorable condition, V1F1, half of the subjects had a score of 0.9 or higher, indicating 95% of their answers were consistent. It is noticeable that in most conditions, score distributions were very large, ranging from 0 to 1, meaning that some subjects answered randomly and some subjects answered with a perfect consistency. The mean values, however, are above 0.5 in all conditions, which means that in average, whatever the condition, the subjects were consistent in their classification on at least 75% of the trials. Moreover, in almost all conditions this mean value is slightly lower than the median value, which indicates that it is worn down by a few values close to 0.

These results demonstrate that the subjects' ability to discriminate between the three stimuli were generally well above the random threshold with or without visual and/or tactile cues. As expected, visual cues had significant positive impact on discrimination. More surprisingly, the rough textured film on the screen had only a minor effect. We were expecting it to make the difference between stimuli very clear, as the sensation on stroking is very different: in contrast with the very smooth screen, the textured film produces strong vibrations when stroked.

However, an unexpected side effect was that the textured film was much less sticky than the screen, so that although the tactile sensations were stronger, it was much easier to stroke it fast. We think that this could have biased the answer about the “sliding” sensation, and could explain why subjects had different strategies to rank the stimuli. During the experiment, we noticed that most users had a clear ranking for a given visuo-tactile condition, but it was not necessary the same when the visual or tactile condition changed.

While the subjects were clearly able to discriminate the three stimuli, their ranking in terms of sliding was different among subjects and conditions. This might simply reflect the polysemy of the “sliding” term, and the very blurred vocabulary we have when it comes to describe tactile experiences. Further studies could disambiguate the sensations produced by the lateral sliding of the screen during stroke. For instance, asking the subjects about both roughness and sliding sensation could help to identify the dependence or independence of these two parameters. Also, a comparison with real material samples rather than between haptic effects might help avoiding misinterpretations and keep a low inter-subject variability.

4.4 Use cases

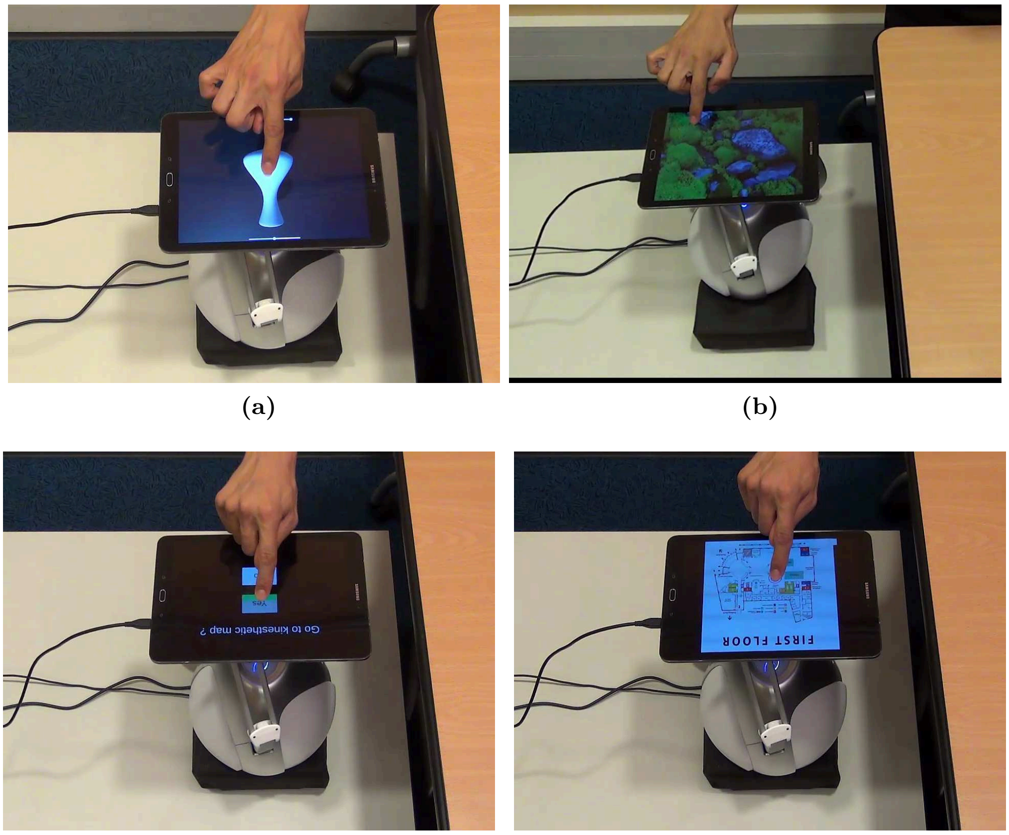
In this section, we showcase a few use cases that we implemented to demonstrate the application of the KinesTouch approach in a variety of contexts (see Fig. 4.12).

In our first use case, the user can explore and interact with virtual 3D objects. This use case relies mainly on the Shape effect. In our implementation, the user can feel the shape of several objects such as a vase or rocks.

In our second use case, KinesTouch is used to interact with a 2D image in order to feel its texture. This use case relies mainly on the Stiffness, Slipperiness, and Roughness effects. Thanks to these effects, the user can feel the changes in: local elasticity, friction, and relief in the picture. In our implementation, a picture of a plant landscape is used, associated with several “haptic maps”, similarly to the normal maps used for textures in 3D engines (here: “stiffness map”, “friction map” and “roughness map”).

In our third use case, KinesTouch is used to enhance interaction with a Graphical User Interface made of several buttons. This simple use case relies on the Stiffness effect. In our implementation, the buttons need to be pushed at a certain depth, but have different levels of stiffness, which makes them easier or harder to validate.

In our fourth use case, the user can explore the interactive map of a building. This use case relies on the Shape, Slipperiness, and Roughness effects. In our implementation, the 2D



(a) (b)

(c) (d)

Figure 4.12 – Use cases for the KinesTouch approach. **(a)** Interacting with 3D objects. **(b)** Perceiving 2d images tactually. **(c)** Haptic widgets. **(d)** Interactive maps.

map (in top-view) of a big mall with three floors is used. The user can explore the layout of the shops using the finger. When stroking over stairs the user can move up or down to a different floor. The user can be attracted or repulsed from specific points/areas of interest. A vibration can also be added in presence of a targeted item.

4.5 Conclusion

In this chapter we have presented KinesTouch: a novel approach to enhance touchscreen interactions using kinesthetic- and force-feedback. In contrast with previous solutions, KinesTouch allows, with a single device, to address four different dimensions of tactile sensations: stiffness, shape, fine roughness and slipperiness). Moreover, it provides for a novel way of dealing with sliding/friction rendering: lateral kinesthetic-feedback.

We designed a proof-of-concept prototype based on the hardware and software combination of a standard tablet and a consumer-grade impedance haptic device. We detailed our set of haptic effects and provided a general command law to deal with transparency and loop synchronization.

We conducted a user study on the Sliding effect to confirm that it could well induce different sliding sensations. Visual cues were confirmed to influence sliding judgments, but further studies would help clarifying the role of tactile cues.

Finally, we showcase several use cases illustrating the possibilities offered by the KinesTouch to enhance 2D and 3D interactions on tactile screens in various contexts.

Touchy: A visual approach for simulating haptic effects on touchscreens

5

Contents

A large variety of solutions have been proposed in the previous literature to instrument tactile screens with dedicated actuators providing various haptic feedbacks. They stimulate mechanical receptors in the hand to provide compelling haptic sensations like variable friction [111], relief patterns [84, 156] or shape rendering [165]. However, the **custom hardware** they involve make them **difficult to disseminate**. Haptic technologies tend to be complex, cumbersome and expensive; providing **simple and lightweight solutions** remains a persistent challenge for the field.

Pseudo-haptic feedback is an alternative approach based on the fact that **haptic perception can be distorted or even overcome by another modality like vision**, and thus not absolutely depending on a physical actuator [99]. Most contributions in this field rely on displaying a cursor with an alteration of one of its spatial property, that expresses the simulated haptic feature. For instance, stiffness, friction, mass, and surface curvature

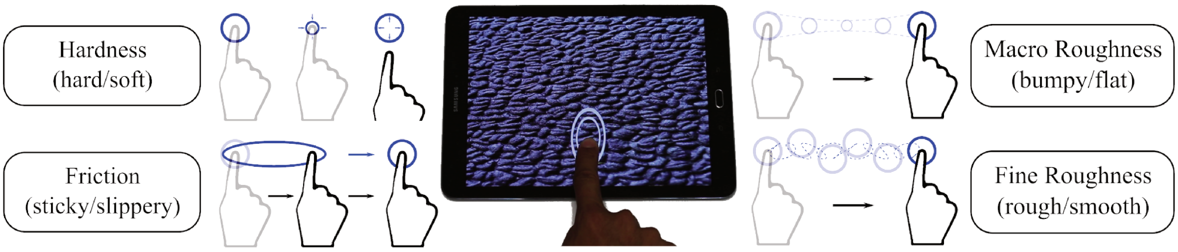


Figure 5.1 – Touchy is a co-localized cursor for tactile displays that deforms and/or moves to evoke a variety of haptic properties, covering four different perceptual dimensions: fine roughness, macro roughness, compliance, and friction.

features can be evoked respectively by changes in shape, speed and trajectory (see [97] for a review).

Only a few authors explored alternative to a computer mouse cursor to carry pseudo-haptic effects. Argelaguet et al. deformed the image locally to simulate a deformation [6], while Watanabe used the displacement of a background pattern [192]. Ujitoko et al. underlined **two challenges in applying pseudo-haptic principles to touch interactions: occlusion** (the finger touching the screen hides the cursor) and **decoupling** (altering cursor speed breaks at some point the co-localization, and thus the illusion) [184]. Interestingly, most authors who made use of a cursor controlled with a touch surface kept a mouse-like cursor, without really discussing its aspect.

In this chapter, we introduce **"Touchy"**, a novel interaction metaphor which expresses a variety of haptic features **through the alteration of the motion or the shape of a cursor** co-localized with the user's finger (see Fig. 5.1). As it is purely visual and software-based, **Touchy does not require any mechanical actuator**, which makes it trivial to integrate on any device with a tactile screen, and especially relevant for handheld devices. We present **seven pseudo-haptic effects** inspired from physical models which evoke haptic properties like roughness, stiffness or friction through the vibrations, stretches, dilatations and compressions of the cursor. Then, two psychophysical experiments evaluating the ability of our effects to induce specific sensations are presented and discussed. Finally, we extend our approach to 3D scenes, and discuss the differences between 2D and 3D content enhancement.

5.1 The Touchy metaphor

Touchy enhances touchscreen interactions without the need of any mechanical actuator, through a variety of pseudo-haptics effects. When the user touches the screen, a cursor appears under the finger and follows it as it strokes the screen, before disappearing on release. The cursor is a white circle about two times larger than a finger. When the finger hovers an area with haptic content, the cursor's motion and shape are altered in order to express the relevant haptic properties. For instance, the cursor might vibrate according to roughness, or deform according to stickiness (see Fig. 5.2c).

We showcase seven different pseudo-haptic effects which address five haptic properties:

stiffness, (fine) roughness, reliefs, slipperiness and stickiness. These five haptic properties can be organized along the corresponding perceptual dimensions (mentioned in Section 2.1.5): compliance, fine roughness, macro roughness, and friction. In the following sections, we describe the design of our effects according to their intended corresponding perceptual dimension.

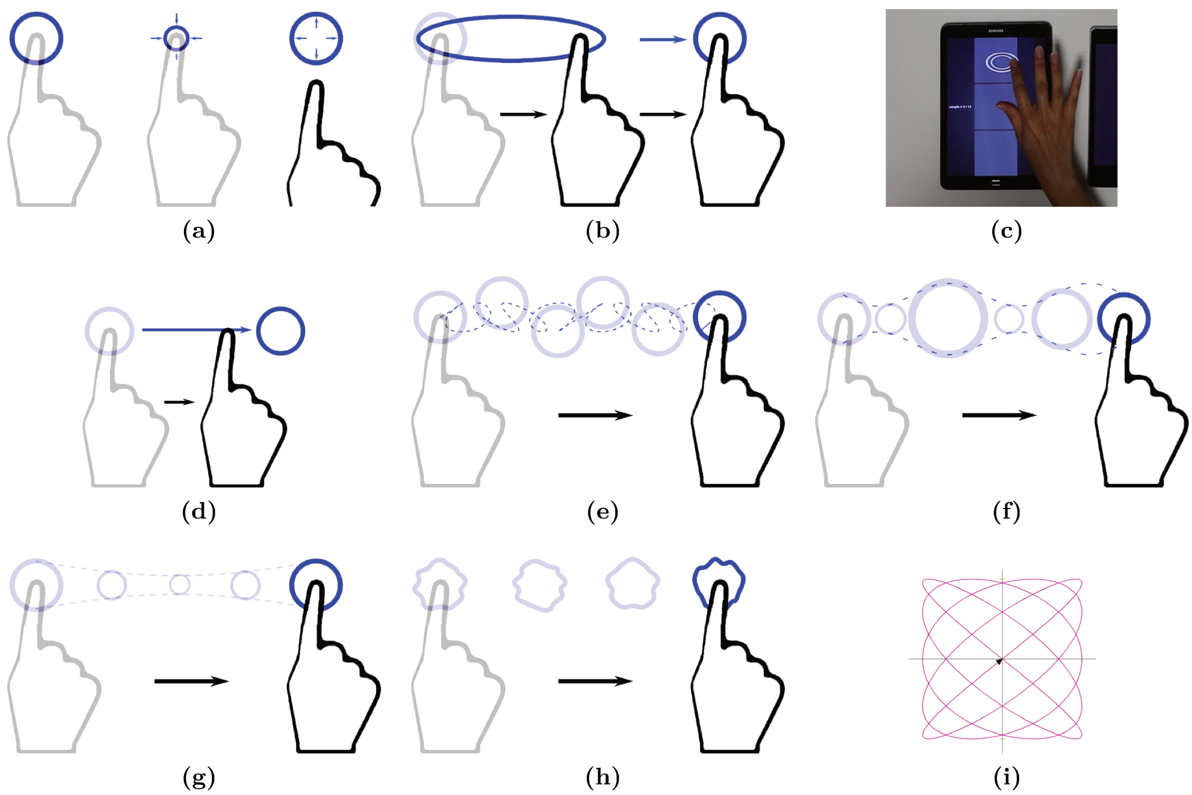


Figure 5.2 – **(a)** The Compress effect evokes softness by shrinking over time. **(b)** The Stick effect evokes stickiness by deforming on small movements. **(c)** A virtual sample with the Stick effect. **(d)** The Slide effect evokes slipperiness through velocity decoupling. **(e)** The Displace effect evokes fine roughness through motion vibrations. **(f)** The Dilate effect evokes fine roughness through size vibrations. **(g)** The Size effect evokes macro roughness through size changes. **(h)** The Encase effect evokes macro roughness through 3D shape changes. **(i)** The vibration pattern used for the Displace Effect.

5.1.1 Compliance dimension

This dimension relates to elasticity, stiffness, softness; that is, the relationship between pressure and deformation. Most touchscreens do not provide a pressure input, however Argelaguet et al. suggested to use a simple time-dependent profile as an acceptable approximation [6]. The simulated pressure grows with time until a limit value, and decrease in the same way on release.

The **Compress effect** (see Fig. 5.2a) relies on this substitution of pressure profile by a time profile. On touch, the cursor appears and immediately shrinks progressively to a target size. On release, the cursor comes back to its initial size before vanishing. The stiffness is represented by the ratio between target and initial cursor sizes.

5.1.2 Friction dimension

According to Okamoto et al. the friction dimension relates mainly to stickiness/slipperiness, and dryness/wetness, although being also correlated with fine roughness [132]. Understanding the physics of friction phenomena is still an active research topic, as their important number of parameters and non-linearities makes them tricky to model in an accurate way [81]. However, some simplistic models like the Coulomb's law have been useful in mechanical engineering for centuries.

The **Stick effect** (see Fig. 5.2b) simulates dry friction according the Coulomb's law. It reproduces the two regimes of the well-known stick-slip phenomenon. In the sticking regime, the cursor stretch as if one of its extremity was fixed to the initial position, while the other one follows the finger. When a given amount of deformation is reached, the effect enters into the sliding regime where the cursor follows the finger without any shape alteration. The effect switches back to the sticking regime if the finger velocity drops below a given threshold. The stickiness is represented by the deformation limit between the sticking regime and the sliding regime.

The **Slide effect** (see Fig. 5.2d) simulates fluid friction and induces a difference between the finger and the cursor speed. The cursor is accelerated proportionally to the finger's speed, as long as they are in contact. It is also decelerated by a viscosity force opposed and proportional to its speed. The slipperiness is represented by the C/D ratio between finger speed and cursor acceleration.

In order to handle decoupling issues, the cursor is accelerated by the finger only if they are in contact, which is not intended to last long. Once they are separated, the finger "does not act" on the cursor anymore. However, as soon as the user releases and touches the screen again, the cursor is back under their finger. Thus, the decoupling sensation remains limited.

5.1.3 Fine roughness dimension

Fine roughness is about high frequency geometrical features of a surface which are too small to be perceived through static contact. When stroking a surface, the vibrations occurring under the finger are the most salient and effective information to evaluate its fine roughness. These vibrations are known to be correlated to the user's finger pressure and speed, however only speed responsiveness was found to be necessary for perceptual realism [32]. If the stroked surface features a spatial period, it clearly dominates the vibratory spectrum, although the involved physics are still far from being understood in details [69].

These vibrations can thus be represented, as a first approximation, by a single-frequency vibration with a modulation of amplitude and/or frequency according to the finger speed. For sake of simplicity, we chose to use finger displacement as phase, multiplied by the wavenumber corresponding to the simulated roughness.

The **Dilate effect** (see Fig. 5.2f) applies this oscillation to the size of the cursor. When the user strokes the screen, the cursor oscillates in size.

The **Displace effect** (see Fig. 5.2e), in contrast, applies roughness vibrations to position. An 2D oscillatory offset is added to the cursor's position. The selected pattern (see Fig. 5.2i) induces an offset between the two axes in order to be hardly identifiable by the user. It was given by: $f : x \rightarrow [sin(\omega * x), sin(0.8 * \omega * x)]$ where x is finger displacement and ω is the wavenumber.

5.1.4 Macro roughness dimension

Macro roughness relates to relatively low frequency reliefs. Unlike the previous properties, which are considered as spatially homogeneous, macro roughness is a spatial variation in itself. We used relief maps to store the macro roughness information (see Fig. 5.3). A relief map is a monochrome image that gives, for any relative position on the haptic texture, the corresponding relief height.

The **Size effect** (see Fig. 5.2g) simulates a simple perspective effect by magnifying and diminishing cursor size proportionally to relief height on contact point.

The **Encase effect** (see Fig. 5.2h), in contrast, takes the area covered by the cursor, reads the values corresponding to this whole area in the relief map, and changes the 3D shape of the cursor in order to reproduce the reliefs *around* the finger position.

5.2 User Evaluation

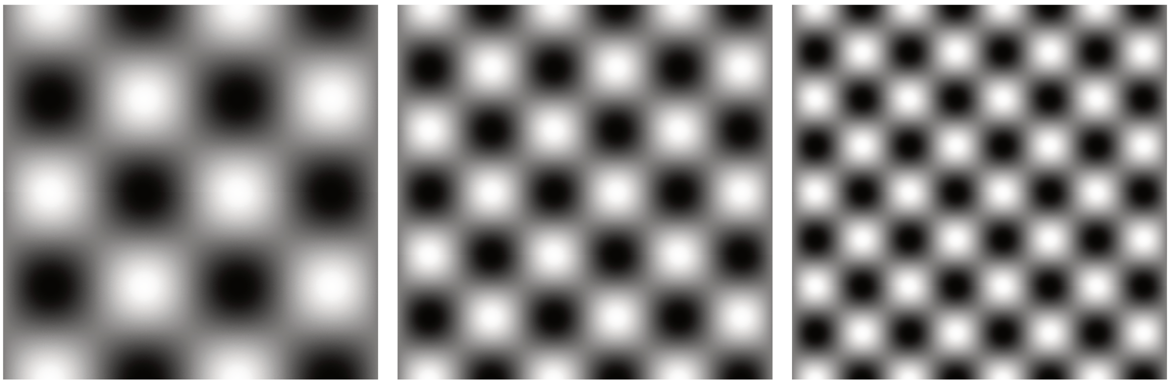
In order to evaluate the ability of our pseudo-haptic effects to induce clear and specific haptic sensations, we designed two user studies.

The first one was intended to validate that our effects were suited for psychophysical evaluation, that is, that for each effect, a variation of the given haptic property would be perceived as a comparable variation in terms of "overall intensity". The second one investigated in details the qualitative percepts induced by each effect, by comparison with real material samples organized in a reproducible tactile chart.

Apparatus and participants

Visual content has a significant impact on haptic evaluation. In order to study the ability of Touchy to convey haptic information independently of any visual content, we used a uniform gray image for our virtual samples.

The Touchy effects are inspired from physical models which take one specific haptic property as an input: stiffness, fine roughness, reliefs, stickiness, or slipperiness. Three "levels" (L1, L2, L3 conditions) were defined for each of the seven effects, featuring different values of the simulated property (L1 for low value, L3 for high value). These values were subjectively chosen so that the three levels would be easy to distinguish. The 21 virtual samples were displayed on a digital tablet at the same size as the real samples on the tactile chart (about



(a) (b) (c)

Figure 5.3 – Reliefs maps used for the Size and the Encase effects, featuring **(a)** 2, **(b)** 3, and **(c)** 4 spatial periods.

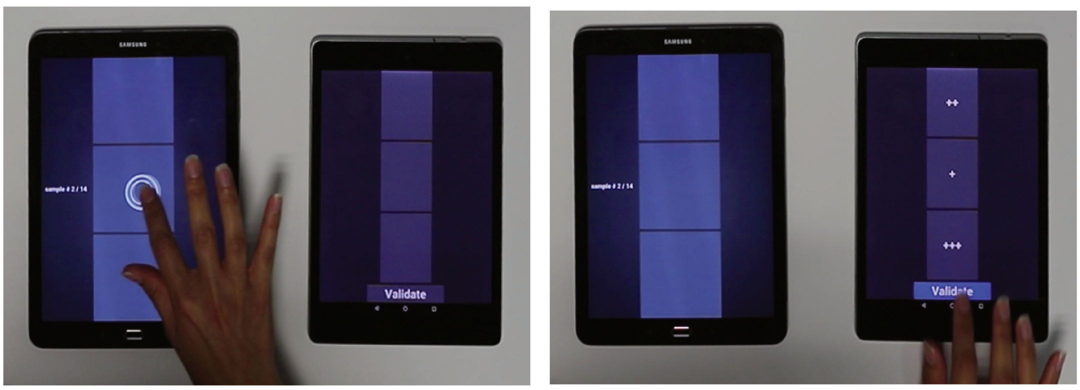
5cmx5cm). For the Size and Encase effects, three different relief maps with 2D sinusoidal profiles, shown in see Fig. 5.3. The L1, L2 and L3 conditions corresponded to the respective spatial periods of 2.5cm, 1.7cm, and 1.25cm.

14 unpaid volunteers (4 females, age 28-55, mean: 41) took part in the two studies that were performed in a single session of about 45min. All of them but one reported to be right-handed.

5.2.1 First study: sorting task

Hypotheses and objectives

This study aimed to ensure that the perceived intensity of each effect was positively correlated to the three levels we designed, by testing hypothesis **H1**: the perceived intensity of an effect is stronger for L2 than for L1 and stronger for L3 than for L2.



(a) (b)

Figure 5.4 – Sorting task between the three levels of each effect. **(a)** The three levels are explored. **(b)** The subject sorts them by intensity.

Procedure

We grouped our virtual samples by effect to constitute seven trials composed of the three levels of an effect arranged in a random order. During a trial, the three samples were presented simultaneously on a digital tablet. The subject was invited to explore them, then had to sort them according to their intensity (see Fig. 5.4). The subject was invited to perform a simple movement (touch, stroke and release over about 2 seconds) to explore the virtual samples, but was left free otherwise. They were not explicitly informed about the number of effects and display rationale.

We also expected a learning effect with degraded performances for the first encounters with the effects. In order to take this into account, the whole set of seven trials was performed two times in a row, the first time being considered as a blank test to get familiar with the effects. There was no other repetition.

Results

Table 5.1 shows the confusion percentage per effect for the sorting task. For all effects except Size, the order was correctly identified more than seven times over ten, which supports **H1**.

For all effects except Encase, there was little confusion between L1 and L3. Summing these conditions together, the correct answer rate were of 64% for Size, 79% for Encase, and above 85% for the five other effects.

Effect	**Compress**	**Stick**	**Slide**	**Displace**	**Dilate**	**Size**	**Encase**
No permutation	86%	79%	93%	71%	79%	50%	79%
L1-L3 permutation	7%	14%	7%	14%	7%	14%	0%
Other permutations	7%	7%	0%	14%	14%	35%	21%

Table 5.1 – Results for the sorting task.

Discussion

Our results support **H1** for all effects except Size, which means that the subjects were able to perceive the three levels as three psychophysical intensities, as they were designed to be. Although subjects were let free to decide which stimulus was the “strongest” and which one was “weakest”, they spontaneously chose the expected order in more than seven times over ten. The worse performances were the ones of the Size and the Encase effect, which might be related to the fact that in contrast with other effects, their haptic property was stored in a map. It is likely that the exploratory movement was too quick or not enough controlled for them, as they were less salient than the five other effects that did not relied on a map but on an homogeneous property.

5.2.2 Second study: multi-dimensional rating

Hypotheses and objectives

In this second experiment, we wanted to investigate which precise sensations were evoked by each effect. We hypothesized that each effect would elicit one specific kind of tactile sensations, and therefore that its variations would perceptually differ according to the corresponding dimension only.

The qualitative evaluation of a haptic effect can be tricky to design. Spontaneous vocabulary is often poor to describe tactile sensations, and the same word can be used to describe features that are perfectly distinguishable (for instance smooth). Moreover, the direct comparison between two pseudo-haptic effects is delicate: the ability to discriminate two visual cues might not be very informative about the actual sensations provided by the two effects. Therefore, we decided to evaluate our effect in comparison with real materials rather than any other virtual stimulus. By doing so, our study focus on the ability for Touchy to provide sensible information about a virtual texture that is comparable to real texture sensations.

The experiment aimed at testing, for each effect, **(H2)**: the haptic sensations induced by the three levels of the effect differ along one specific perceptual dimension.

Tactile chart

The 21 virtual samples described in the first evaluation were used, as well as a ”neutral” sample with no effect (L0 condition).

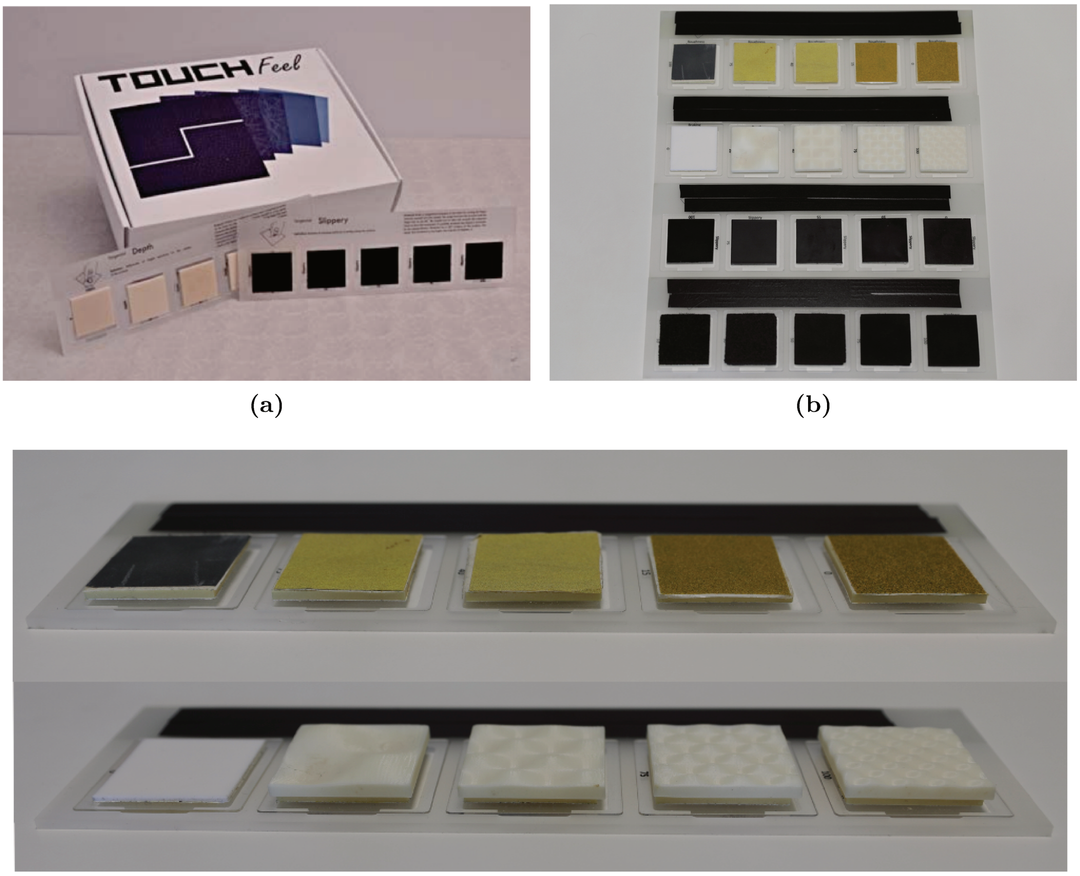
Besides, we conceived a tactile chart (see Fig. 5.5) adapted from the TouchFeel Box [1], that offers a variety of material samples organized by tactile descriptors. The chart was composed of four descriptors:

- Friction: from slippery (1) to sticky (5)
- Compliance: from soft (1) to hard (5)
- Fine roughness: from smooth (1) to rough (5)
- Macro roughness: from flat (1) to densely bumpy (5)

The friction and compliance descriptors were directly taken from the Box (Slippery and Hardness descriptors), as they matched pretty well the considered perceptual dimensions.

The fine and macro roughness descriptors, however, were customized as the closest descriptors in the Box (Roughness and Depth) were found to be non homogeneous and too far from the usual definitions in the literature. Our fine roughness descriptor was composed of five sandpaper pieces with variable grit (80, 180, 255, 360, 800). Our macro roughness descriptor was composed of four 3D-printed 2D-sinusoidal profiles with variable spatial period (5cm, 2.5cm, 1.7cm, 1.25cm) and an equal maximum slope (that is, the amplitude was

[1] http://www.zins-ziegler-instruments.com/en/portfolio-view/touchfeel-descriptors-touch-feeling/



(a) (b)

(c)

Figure 5.5 – Customized tactile chart used in the experiment. **(a)** The TouchFeel Box. **(b)** The custom tactile chart. **(c)** Customized samples: sandpaper pieces and 3D printed relief profiles.

inversely proportional to the spatial period). In addition, one flat sample was taken from another descriptor (Braking 0) of the Box in order to get five samples going from flat to densely bumped.

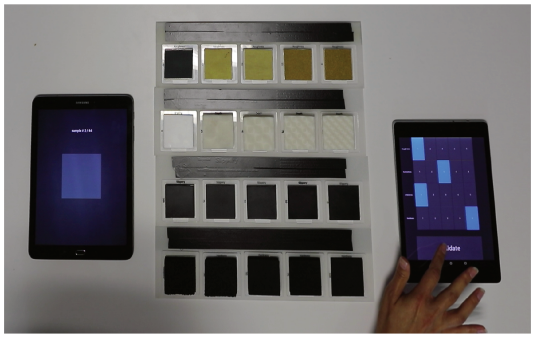
Procedure

The exploration of the virtual samples was similar to the first evaluation, except that only one virtual sample was presented at a time. The subject indicated, for each descriptor of the tactile chart, which descriptor sample was the closest to the effect. The answer was forced, so that the subject had to give the four answers (each one going from 1 to 5) before passing to the next trials (see Fig. 5.6).

Results

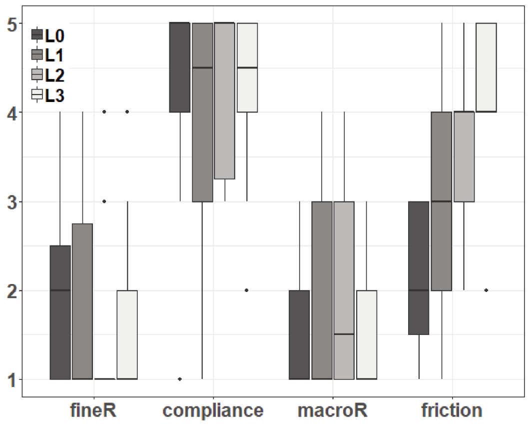
The answer distributions are shown on Fig. 5.7 and Fig. 5.8. For each condition, the evaluation of the neutral effect along the considered dimension was comparatively added, considered as the L0 condition. Non-parametric Friedman tests were performed to find significant

(a)

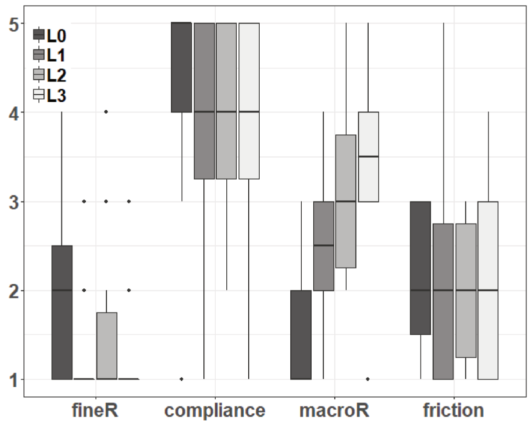


(b)

Figure 5.6 – Evaluation of a virtual sample with the tactile chart. **(a)** The virtual sample is explored. **(b)** Four answers from 1 to 5 situate the effect on the tactile chart.



(a)



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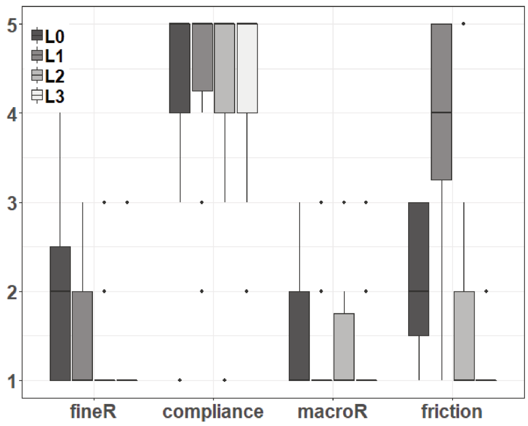
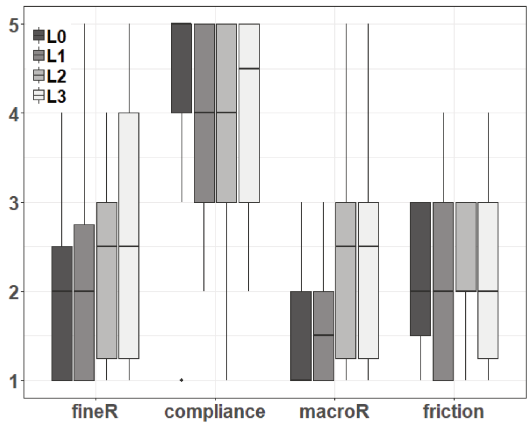


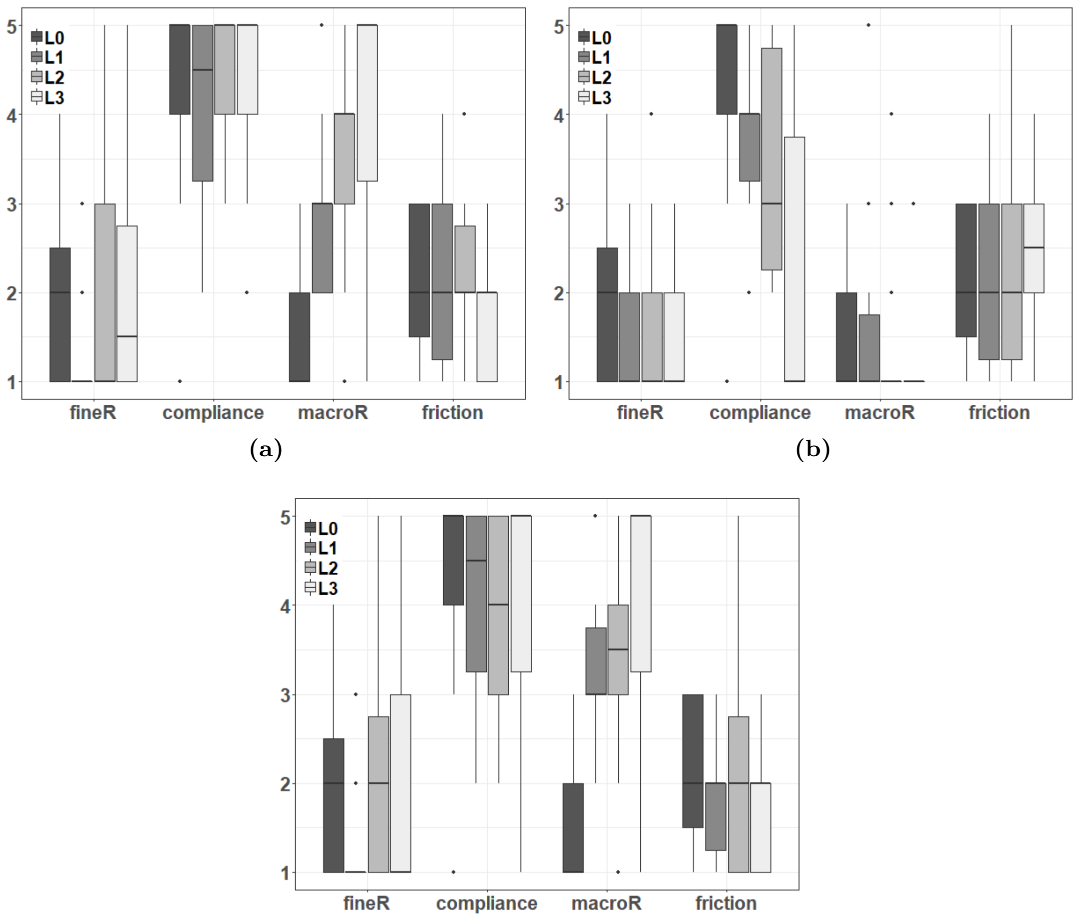
(c)



(d)

Figure 5.7 – Evaluation distributions according to intensity conditions for the Stick, Size, Slide and Encase effect. The frame indicates the perceptual dimension addressed by the effect. **(a)** The Stick effect. **(b)** The Size effect. **(c)** The Slide effect. **(d)** The Encase effect.

differences for each effect and dimension. When needed pairwise Wilcoxon tests with Holm-Bonferroni correction were performed between the L0, L1, L2 and L3 conditions. The results are summarized in Table 5.2.



(a) (b) (c)

Figure 5.8 – Evaluation distributions according to intensity conditions for the Displace, Compress and Dilate effect. The frame indicates the perceptual dimension addressed by the effect. **(a)** The Displace effect. **(b)** The Compress effect. **(c)** The Dilate effect.

For the Compress, Slide and Size effects, significant differences were found at least between L1 and L3, regarding the perceptual dimension they addressed only. These results support **H2**. For the Stick, Slide and Size effects, significant differences were found between the L0 condition and at least one other condition, regarding the perceptual dimension they addressed only. These results also support **H2**, as the effect elicit the right kind of sensations, but they reflect that the intensity range of the effect didn't match well the chart descriptor range.

The Displace and Dilate effects were found to present significant differences between L0 and at least two other conditions, but regarding the macro roughness dimension, instead of fine roughness. These results support **H2** and show that these two effects were indeed able to evoke relief sensations, but with a perceived frequency lower than expected, resulting in a swap in qualitative judgment.

Finally, the Encase effect did not show any significant difference between condition, although the p-values were very high in all conditions except L1-L3 for macro roughness, which was the expected most favorable comparison. These results do not support **H2** for the Encase effect.

Perceptual dimension	Conditions	Compress	Stick	Slide	Displace	Dilate	Size	Encase
Compliance	L0-L1	0.78	ns	ns	ns	ns	ns	ns
	L0-L2	0.56	ns	ns	ns	ns	ns	ns
	L0-L3	0.26	ns	ns	ns	ns	ns	ns
	L1-L2	0.152	ns	ns	ns	ns	ns	ns
	L2-L3	**0.037**	ns	ns	ns	ns	ns	ns
	L1-L3	**0.018**	ns	ns	ns	ns	ns	ns
Friction	L0-L1	ns	**0.035**	**0.043**	ns	ns	ns	ns
	L0-L2	ns	**0.035**	0.533	ns	ns	ns	ns
	L0-L3	ns	**0.032**	**0.083**	ns	ns	ns	ns
	L1-L2	ns	ns	**0.014**	ns	ns	ns	ns
	L2-L3	ns	ns	0.054	ns	ns	ns	ns
	L1-L3	ns	ns	**0.004**	ns	ns	ns	ns
Fine roughness	L0-L1	ns	ns	0.69	ns	ns	0.29	ns
	L0-L2	ns	ns	0.27	ns	ns	1	ns
	L0-L3	ns	ns	0.19	ns	ns	0.6	ns
	L1-L2	ns	ns	0.27	ns	0.11	ns	ns
	L2-L3	ns	ns	1	ns	0.67	ns	ns
	L1-L3	ns	ns	0.27	ns	0.12	ns	ns
Macro roughness	L0-L1	ns	ns	ns	**0.039**	**0.020**	**0.044**	1
	L0-L2	ns	ns	ns	0.056	**0.025**	**0.032**	0.32
	L0-L3	ns	ns	ns	**0.028**	**0.025**	**0.035**	0.32
	L1-L2	ns	ns	ns	0.17	0.33	0.229	0.116
	L2-L3	ns	ns	ns	0.17	0.33	0.229	0.572
	L1-L3	ns	ns	ns	0.17	0.33	**0.006**	0.071

Table 5.2 – Summary of the statistical analysis for the second experiment for each effect and perceptual dimension. Only p-values for pairwise Wilcoxon tests are presented. "ns" mean that the Friedman ANOVA did not show any significant differences ($p > 0.05$), while values in green indicate that $p < 0.05$.

Discussion

Our results suggest that Touchy, through its various effects, is able to efficiently elicit different haptic percepts. The Compress, Stick, Slide and Size effects were found to address their target perceptual dimension in a significant manner, while they had no effect along the other dimensions.

The Displace and Dilate effects were expected to produce fine roughness sensations, but they were perceived as macro roughness effects instead. This can be explained by the fact that for the low level of the effect, the oscillation frequency was very low for slow movements. Also, the oscillation frequency was directly proportional to stroking speed, which was not realistic for low speed. Instead of the frequency, the amplitude could have been modulated by finger speed to give better results while keeping the simplicity of the model. We believe that in this case, we would have obtained significant results on the fine roughness dimension for the Displace and Dilate effect.

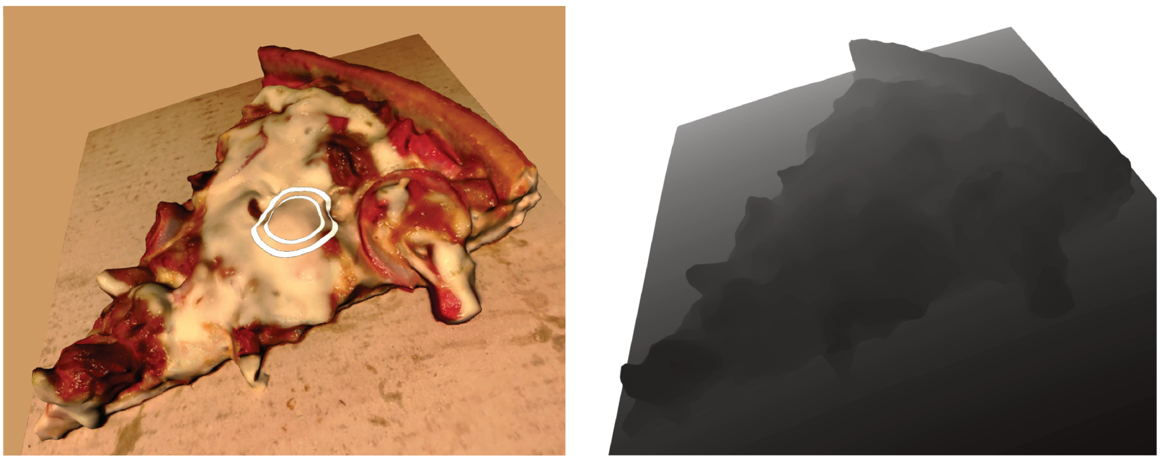
The Encase effect was not found to induce significant sensations. This might be explained by the reliefs maps used as stimuli, that do not represent realistic textures. Additional studies using more realistic maps (representing metallic meshes for instance) should be carried.

5.3 Extension of Touchy to 3D virtual environments

Our set of pseudo-haptic effects can be easily applied to an image, using maps to specify the values of each effect in any given area of the image. Yet, touchscreens do not only display pictures, but also views of 3D scenes. In order to extend our approach and take such content in account, we conducted an additional exploratory work to generalize Touchy to 3D content. In this section, we provide details on this development as well as illustrative examples of applications of Touchy with 3D content.

5.3.1 Extraction of depth information

The main change between 2D pictures and 3D scenes is the use of volumetric meshes. Not only haptic images are wrapped around object meshes, but the cursor itself is defined as a deformable mesh inside the virtual environment. In particular, the Encase effect does not rely only on the content of haptic material maps anymore, but also on the mesh shape. It is thus applied even in the absence of a haptic material in order to match the volumes of the scene (see Fig. 5.9a).



(a) (b)

Figure 5.9 – Adaptation of the Encase effect to 3D content. **(a)** The Encase effect in the Pizza scene [2]. **(b)** Depth map extracted from the virtual camera.

Another major change is the perspective dependence: the finger position on the screen is not sufficient to determine underlying haptic content. Additional computation is necessary to locate the contact point on the haptic image. Also, the size of the cursor has to be compensated with respect to its distance to the camera, so that it keeps the same size relatively to the user's finger.

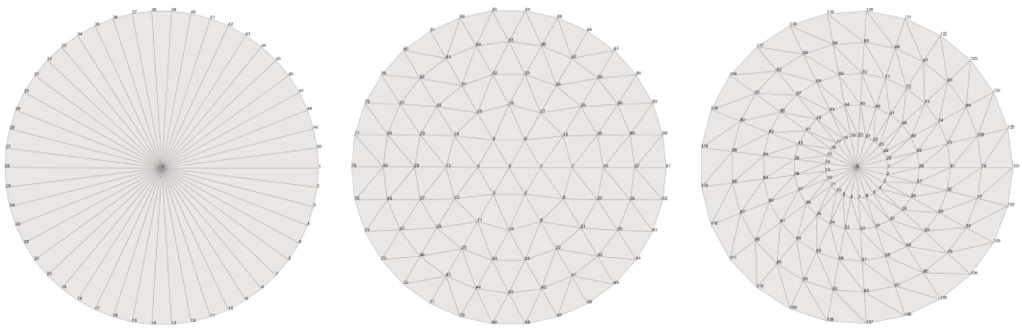
To sum up, extra calculations are required for the Encase effect to take in account the shape of the virtual object mesh. They are applied as follows. Each vertex of the cursor

[2] Pizza Slice by polarathene / CC BY 2.0.

mesh is displaced towards the cursor center along the radius, so that the drop along the path starting from the center is subtracted to the radius distance. If the surface is flat, then the vertex position is not modified, but if it is wavy, then the vertex gets closer to the center to preserve the arc length. The radial distance is computed iteratively from the center, by adding at each step the traveled radial distance with the drop from both the relief map and the perspective. Getting the drop from the relief map is trivial, by subtracting the height values at new and previous locations. Getting the perspective drop, however, requires depth information relative to camera position. Because this operation is performed dozens of time for each vertex of the cursor mesh, a raycast approach would be too heavy for real-time solving. In order to circumvent this issue, we took advantage of a high-resolution pre-generated depth map (see Fig. 5.9b), assuming no camera move.

5.3.2 3D cursor to support Touchy effects

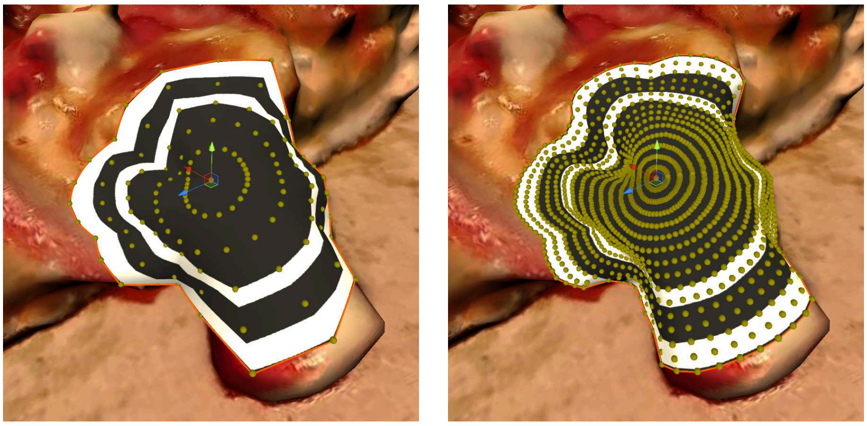
The pattern chose for the cursor mesh has a strong impact on both quality and performance. If a simple radial cursor (Fig. 5.10a) is computationally effective, it easily produces strong unrealistic deformations. An hexagonal alternative was considered (Fig. 5.10b), then optimized to an extended radial cursor (Fig. 5.10c). In this latter version, vertices are distributed along fixed-radius circles, and are easy to browse efficiently thanks to their polar coordinates.



(a) **(b)** **(c)**

Figure 5.10 – Alternatives for the cursor mesh structure. **(a)** Radial cursor (50 outer vertices). **(b)** Hexagonal cursor (5 rings). **(c)** Extended radial cursor (5 rings, 25 vertices per ring).

Provided a sufficient resolution, the cursor reproduces accurately the surface shape in good conditions (see Figures 5.11a and b). However on shape discontinuities, artifacts may occur. This is especially problematic with photogrammetric scans with sharp details which do not afford automatic smoothing. Another limitation of the use of photogrammetric scans is that their visual texture is usually a compact assembly of tiny pieces from several objects. In this case it can be complicated to generate haptic maps artificially without a specific mapping method.



(a) (b)

Figure 5.11 – Cursor resolution and discontinuities. **(a)** Low-resolution extended radial cursor. **(b)** High-resolution extended radial cursor.

5.3.3 Integration of the different effects

In our studies presented in Section 5.2, we considered each effect in an independent manner. In order to apply several effects concurrently, we observed a few rules to avoid interferences between them.

Firstly, we did not allow two simultaneous effects for the same perceptual dimension. The Displace and Dilate effects, because of their redundancy, were considered as two variations of the same fine roughness effect. The Stick effect and the Slide effect were combined into a single Friction effect (the Slide effect being the “sliding regime” of the Stick effect). Finally, the Size effect had no point in a 3D environment, and was discarded.

Secondly, we carefully chose the order of the effects. For instance, the Friction effect has a substantial effect on trajectory and should be applied first, so that underlying haptic data is updated to the corrected position for other effects. In contrast, high-frequency changes induced by the Fine roughness effect should be applied last, not to scramble other effects.

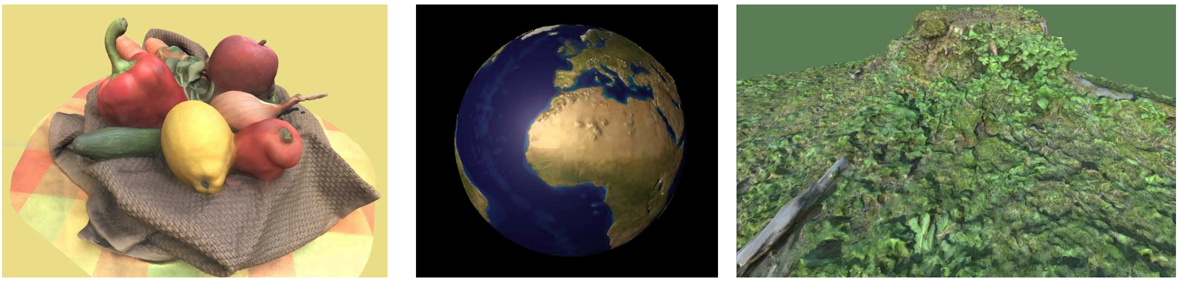
The general algorithm is as follows:

1. get touch location (with touch lag compensation)
2. perform raycast hit
3. apply Friction effect on trajectory
4. apply Compliance effect on size
5. apply Macro roughness effect on shape
6. apply Fine roughness effect on size or position
7. render the scene and display the cursor

5.3.4 Testings

We implemented several virtual scenes to showcase the potential of Touchy for 3D scenes enhancement.

In the "Pizza scene" (Fig. 5.9a), the cheese is soft and sticky (Compress and Stick effect), and the box is rough (Displace effect). In the "Edible scene" (Fig. 5.12a), the cloth and the lemon are rough (Displace effect), while the paprika and the apple are slippery (Slide effect), and each fruit or vegetable features a specific softness (Compress effect). In the "Globe scene" (Fig. 5.12b), the desert areas are rough (Displace effect) and the water is slippery (Slide effect). In the "Stump scene" (Fig. 5.12c), the vegetation is soft (Compress effect) and rough (Dilate effect), and the wood is hard (Compress effect).



(a) (b) (c)

Figure 5.12 – Illustrative virtual scenes. **(a)** Edible scene[3]. **(b)** Globe scene[4]. **(c)** Stump scene[5].

5.4 Conclusion

In this chapter, we adapted the principles of pseudo-haptic feedback to touchscreen interactions with a novel approach called Touchy. Touchy is able to simulate five different haptic properties of a virtual object (compliance, stickiness, slipperiness, fine roughness and reliefs) through seven visual effects which modify the shape and/or motion of the cursor in response to user actions.

Our approach addresses the challenges previously identified in the literature. Occlusion from the finger is avoided by the ring shape of the cursor, the visual aspect of which remain always visible during touch interaction. The "illusion break" caused by the decoupling between the cursor position and the finger position does not affect most of our effects which deal with the shape or small amplitude oscillations. Because it does not require any mechanical actuator, Touchy is particularly easy to disseminate.

We conducted two user studies to investigate the ability of our effects to evoke specific haptic features. The first one was intended to validate that for each of our effect, a variation

[5] Vegetable Basket by Moshe Caine / CC BY 4.0.
[5] Low-Poly Earth by Alan Zimmerman / CC BY 4.0.
[5] Tree Stump Nr.2 by 3DandVR / CC BY 4.0.

of the given haptic property would be perceived as a comparable variation in terms of “overall intensity”. The second one investigated in details the qualitative percepts induced by each effect, by comparison with real material samples organized in a reproducible tactile chart. Our effects were globally found to elicit several perceptual dimensions: compliance, friction or macro roughness.

Finally, we extended the Touchy approach to 3D scenes, and explored different methods to tackle performance issues. We showcased several 3D scenes to demonstrate the use of Touchy in a variety of virtual environment contexts.

6 Conclusion

In this thesis, we addressed the rendering of image-related haptic feedback on touchscreens. This type of feedback is typically enabled with additional actuation technology, either placed between the finger and screen or acting on the screen itself. Such solutions are often limited in their range of haptics effects, or require considerable technical complexity. In addition to these **two challenges of providing diversified sensations and take advantage of lightweight technologies**, the **accordance of haptic data with visual data** requires to characterize precisely the relevant haptic properties. We tackled those issues by following three axes of research: **1) data format and hardware independence**, **2) lightweight rendering solutions**, and **3) leveraging visuo-haptic interactions** to enhance user experience without additional actuation.

In **Chapter 2** we presented an overview of previous literature on three major aspects of haptic enhancement of touchscreens. First, we presented the perceptual mechanisms involved in the haptic perception of surfaces, and we discussed the question of which haptic features are actually perceived. Haptic perception is deeply structured by the distribution and sensitivity of different types of skin receptors, but also integrates higher cognitive factors and many interactions between sensory data. Haptic percepts can nonetheless be classified along four general perceptual dimensions, namely compliance, roughness, friction and warmth. Then, we addressed the topic of haptic acquisition, and the relationships between concepts such as haptic data, haptic modeling and haptic rendering. Finally, we reviewed the main technological approaches for haptic rendering on touchscreens, namely vibrotactile feedback, variable friction displays, shape changing screens, moveable screens, actuated proxies and pseudo-haptic feedback.

In **Chapter 3**, we proposed a format to address the question of associating haptic data with an image. We extended the texture mapping approach to a set of elementary haptic features, storing them in dedicated maps which make their visualization and manipulation intuitive. Our format is meant to be seamlessly integrated in audiovisual content creation workflows, and be easily manipulated by non-experts in multidisciplinary contexts. The elementary haptic features were extracted from a synthesis of previous literature on haptic surface perception. This decomposition of features along the different types of cues and different types of percepts, offers a higher level of description of haptic properties, while being more explicit and more understandable for non-experts. Besides, this set of features is not biased towards a particular hardware.

In **Chapter 4**, we presented the KinesTouch, a novel approach in tactile surface enhancement, which makes use of both force and kinesthetic feedback. With a single force-feedback device, it is able to simulate four different types of haptic properties. In particular, friction is addressed in a novel way, based on large lateral motion that increases or diminishes the sliding velocity between the finger and the screen. The design and realization of a consumer-grade prototype was presented. Furthermore, a user study was conducted on the sliding effect, in order to assess its ability to provide different sensations. Visual cues were confirmed to influence sliding judgments, although the role of tactile cues remains less clear.

Finally, in **Chapter 5** we introduced Touchy, a novel pseudo-haptic feedback method, where a symbolic cursor is introduced under the user's finger to evoke various haptic properties through changes in its shape and motion. Because it is purely visual and software-based, Touchy does not require any mechanical actuator, which makes it trivial to integrate on any device with a tactile screen, and especially relevant for handheld devices. It can be applied both on 2D images or 3D scenes. We provided a set of seven visual effects that we compared with real texture samples within a user study. Taken together our results show that Touchy is able to elicit clear and distinct haptic properties: stiffness, roughness, reliefs, stickiness and slipperiness.

Future Work and perspectives

In this section, we address the current limitations of the approaches that we proposed in this thesis, as well as the conceptual and technical improvements that could be investigated as future work.

Haptic Material

Multi-elementary-cues haptic rendering

In order to define our "haptic material", we identified ten elementary haptic features which are likely to play a complementary but distinct role in the haptic perception of surfaces. They can be distinguished among each other by both the type of percept (compliance, geometry, friction or warmth) and the nature of the generated stimuli (motion, contact, vibration, or temperature). We also identified examples of rendering devices able to elicit one specific elementary feature, but multi-cues rendering systems are uncommon. An interesting follow-up of this work would be to make use of a "holistic" rendering system, able to generate different types of cues independently [36, 77], to implement the rendering of each elementary haptic features, independently, on a single display. Many experimentations would provide interesting subjective results. For instance, simulating a single percept successively through different cues would be informative for general haptic rendering design.

Comparative psychophysical studies between elementary features

On the ten elementary haptic features we identified, only a few were studied comparatively in the literature. For example, the relative importance of cutaneous and kinesthetic cues for stiffness perception has been studied, but vibrational cues have never been put in comparison. For each percept, the psychophysical thresholds and relative importance of each type of cues could be investigated, which represents a consequent body of work for future research. This would provide informative knowledge on the optimal complementarity between haptic features and help the design of effective and parsimonious haptic rendering systems.

KinesTouch

Effect combination

Along with the KinesTouch approach, we presented four different effects based on force feedback. However we did not consider the combination of these effects, because it raises complicated issues about blocking of the DoF, at least with a Falcon device which is limited in terms of dynamics and workspace. Combination of effects could be experimented, in order to clarify both what are the interactions between the effects, and what are the hardware requirements for such a rendering.

Using an admittance force-feedback device

The Falcon Novint is a simple, low-cost 3-DoF force-feedback, that consequently has considerable drawbacks in terms of haptic precision. It is not isotropic and has highly non-linear damping [118, 188]. As an impedance device, it does not allow directly for position control, and has a limited stiffness capability to lock displacement in certain directions for instance. Applying KinesTouch approach to an admittance device would allow for a high quality position control. Also, with higher force capacities, alternative deformation models [139] could be used for the Stiffness effect instead of elastic linear one.

Handling the touch tracking latency

Most nowadays touchscreens have a touch tracking latency of about 50 to 200ms. This can be a serious limitation for precise co-located visuo-haptic effects. One can attenuate this issue using a corrective algorithm like the one we proposed for the KinesTouch. The best approach however, would be to use a low-latency touchscreen, which currently exists but not in a portable format of a tablet [129].

Vibration enhancement

In the KinesTouch approach, the fine roughness dimension is rendered by means of vibrations. Using the vibrator embedded in the tablet is possible but limited to a single frequency.

Another way of producing these vibrations is to apply an oscillating force through the force-feedback device. Using a single frequency proportional to sliding, sensations of a periodic grating can be created. In order to evoke richer roughness sensations, like non-periodic textures or tapping transients, a high-quality vibrator should be used, because force-feedback arms cannot accurately render rich spectral informations [93]. This could be achieved by affixing the vibrator behind the tablet, which would transmit the vibrations to the finger no matter its position on the screen.

Touchy

Improving models

The Displace and Dilate effects of Touchy were based on a simplified model of stroke vibrations, that is a mono-frequency oscillation. This model makes some sense when the stroked material features a predominant spatial frequency: the vibratory spectrum is then concentrated around an approximate fundamental frequency correlated both to the spatial predominant frequency and to the stroking speed. More sophisticated models could be investigated, stochastic ones in particular. However the display of such oscillations on a screen with a refresh rate of 60 Hz typically raises transduction fidelity issues.

Cursor shape, colocation offset and contextual parameters

Besides the physical models used for pseudo-haptic effects and their particular settings, many other aspects might play a role in the vividness of the pseudo-haptic effects, but can be tricky to study. For instance, if it is likely that the cursor aspect does play a role in the vividness of the effects, it is not trivial to determine alternative shapes to compare with. Another example is the importance of colocation for the approach. In exploratory testings, we noticed that a spatial offset between cursor position and finger position would not necessary "break" the effect, even when using two different surfaces for tracking and display. It seems that the limit at which the illusion breaks is not a geometrical distance, but rather relies on the ability for the user, with the help of the context, to establish a link between the input motion and the resulting feedback. Along with other parameters like temporal offset (delay) or artificial control inconsistencies (noise), there is room for studying the necessary conditions for pseudo-haptic effects to be robust and vivid.

Auditory pseudo-haptics

One of the most exciting follow-up of our pseudo-haptic approach would be to investigate the auditory modality, in the line of the work of Fleureau et al. [42], which we decided not to include in this manuscript as I had only a minor participation in it. In addition to a visual stiffness effect inspired from the Elastic Image [6], they proposed to generate audio cues by interpolating several audio recordings depending on stroke velocity.

An interesting extension of this work would be to make use of the dataset of Strese et al. [168], which associates images with force and audio recordings at various speed. Such an approach would allow to evaluate pseudo-haptic rendering with or without the corresponding visual sample, but also in the case of contradictory association (the texture rendering of one sample with the image of another sample).

Quantitative study of pseudo-haptic effects

In addition to the qualitative evaluation that was conducted on our set of pseudo-haptic effects, a more quantitative examination would be informative. The role of each parameter could be studied more in depth, in order to identify its specific role. In particular, threshold and just-noticeable-differences could be investigated for every parameter of each effect. Given that each effect is able to simulate one particular haptic property, what range does it cover? How many different values can be distinctly perceived?

Remaining challenges and open questions

Data-driven models

The topic of haptic material acquisition is still an open research question, as both real-world measurements and synthesis models have strengths and limitations. Several haptic databases have been made available [1, 26, 31, 168] with, among other things, vibration recordings of a large variety of textures. This data could be used for more sophisticated fine roughness effects, for instance. The visual provided in the databases could also be used to investigate the interactions between the visual and the haptic modalities. For instance, if a haptic texture model is rendered together with the visual of another sample, to what extent does the perceived haptic properties change?

Combination between visual and haptic modalities

In our KinesTouch approach, we followed an ”augmented reality logic” where the screen is considered as a window on a 1:1 scaled virtual world thats remains visually static when the screen moves. However, other ways to combine the visual and haptic modalities could be used, and further research is needed to evaluate the related impact. For instance, what perspective should be used for deformations? What if the visual cues are contradictory with the haptic cues?

Besides, we did not address the use of visual stimuli in our studies. One reason is that they can be challenging to define with respect to haptic stimuli. The study and development of visuo-haptic effects require to address the challenge of defining standard stimuli for both the haptic and the visual modality. In this regard, the ”Universal Haptic Library” of Abdudali et al. [1] offers interesting leads, notably on matching haptic perceptual space with automatically-extracted visual features.

Haptic 3D content on touchscreens

The haptic display of 3D content on a touchscreen remains a challenge. Provided that the screen remains rigid, or with limited deformations, there is a necessary contradiction between haptically navigating the depth of the virtual environment and keeping the finger on the screen. To some extent, this might be compared to motion seats which have a limited displacement range to simulate diverse acceleration effects: the issue depends not only on the hardware limitations, but also on the content to simulate, and the realism requirements laid down by the application context. Anyhow, clarifying the different solutions to minimize this side effect remains an open question for future research.

Haptic enhancement of videos

Whereas the work presented here focused on still images, its extension to video content is of course a major follow-up. Haptic enhancement of video has been addressed in previous literature, but was generally limited to the addition of a depth dimension, and did not really tackle the rendering of properties like compliance or friction. While in some contexts one can consider a real-time analysis of the video content to attribute specific haptic properties to different regions of each frame of the video, the predictability or unpredictability of the content is a necessary limitation.

On the other hand, if one includes 3D real-time rendering in the scope of video content, many possibilities open up. Because virtual environments contain much more information than a single video stream, they allow for many interactivity options, as well as offline analysis and precalculations. Besides, with the fast advancement of computer graphics, striking realistic real-time generated scenes are not a distant dream anymore. Virtual environments are therefore an adequate option for multimodal experiences, and especially for the haptic enhancement of a time-evolving visual content.

On another note, hybrid approaches can be considered: by matching precisely the physics and space of a virtual environment with a panoramic video content, one can benefit from advanced immersive interactions with a high quality visual content which does not require heavy real-time computations. The recent "Realtime Embodiment" VR experiences [34] developed by the Immersive Computing Lab of Technicolor are a perfect illustration of such a hybrid work. They expand the experience of 360 videos with embodiment (thanks to a virtual body which follows the movements of the user) and interactions (through virtual objects which behave accordingly to the video content).

Towards haptic cinematography

What would it mean to be able to touch a movie? What kind of experience would it be for the user, and what kind of art piece would it be? It is likely that interactivity will not be an option for advanced haptic art, because passive touch seems very limited compared to active manipulation. From the perspective of the "haptic artist", or content creator, this has strong implications. This might be compared, to some extent, to the fundamental difference between cinematography and VR “movies”: despite they are both audiovisual narratives, the choice of the point of view (which is either imposed by the moviemaker or controlled by the user) makes their creative process radically different.

We can hope that the industrial development of such technologies will not be too prescriptive, but rather open a period of radical novelty leaving room to crazy creators, as Georges Méliès was in his time. Georges Méliès was a professional prestidigitator when he discovered the Lumière brothers’ cinematograph, and he immediately decided to become something that did not existed at the time: a filmmaker. His genius and prolific pioneer experimentations laid down many technical and narrative basements for the what became cinematography.

Provided that we get new striking haptic technologies in the future, it is thrilling to imagine how artists would leverage such a medium: to achieve realism is one thing, but what would make it an art? One can hypothesize that the artistic value would come from elegant use of trickeries and shortcuts that would take advantage of the raw power of technology, rather than depend on it. In other words, haptic artists will have much to share with illusionists.

Author's publications

A

Peer-reviewed international conference papers

- **A. Costes**, F. Argelaguet, F. Danieau, P. Guillotel and A. Lécuyer.
  "Touchy : A visual approach for simulating haptic effects on touchscreens".
  In Frontiers in ICT, volume 6, page 1, 2019.

- **A. Costes**, F. Danieau, F. Argelaguet, A. Lécuyer and P. Guillotel.
  "Kinestouch: 3d force-feedback rendering for tactile surfaces". In *Proc. of European Association for Virtual Reality and Augmented Reality Conference (EuroVR)*, 2018.

- **A. Costes**, F. Danieau, F. Argelaguet, A. Lécuyer and P. Guillotel.
  "Haptic Material: a holistic approach for haptic texture mapping". In *Proc. of International Conference on Human Haptic Sensing and Touch Enabled Computer Applications (EuroHaptics)*, pages 37–45, 2018.

- E. Callens, F. Danieau, **A. Costes**, and P. Guillotel.
  • "A tangible surface for digital sculpting in virtual environments". In *Proc. of International Conference on Human Haptic Sensing and Touch Enabled Computer Applications (EuroHaptics)*, pages 157–168, 2018.

- J. Fleureau, Y. Lefevre, F. Danieau, P. Guillotel and **A. Costes**.
  "Texture rendering on a tactile surface using extended elastic images and example-based audio cues". In *Proc. of International Conference on Human Haptic Sensing and Touch Enabled Computer Applications (EuroHaptics)*, pages 350–359, 2016.

Hands-on demonstrations

- **A. Costes**, F. Danieau, F. Argelaguet, P. Guillotel and A. Lécuyer.
  "Touchy: tactile sensations on touchscreens using a cursor and visual effect".
  Hands-on demonstration presented at *IEEE Haptics Symposium (HAPTICS)*, 2018.

Patents

Two patents are currently in the process of being granted.

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Résumé long en français

Au cours de la dernière décennie, les écrans tactiles sont devenus un standard des interfaces homme-machine. Cependant, malgré leurs nombreux atouts, ils manquent encore de sensations tactiles : quel que soit le contenu visuel, ils restent plats, lisses, rigides et immobiles sous le doigt. Dans cet ouvrage, intitulé “**Contribution à l’étude de l’augmentation haptique d’images sur écran tactile**”, nous examinons les moyens permettant aux écrans tactiles de nous toucher en retour, et de produire des sensations tactiles variées associées à des images.

Contexte industriel

Bien qu’elles soient généralement très bien accueillies par le grand public, les **technologies haptiques pénètrent difficilement le marché de la consommation**. Les dispositifs à retour de force et les gants d’exosquelette ont été développés et étudiés de manière intensive depuis le milieu des années 90, mais ils sont restés limités à une poignée d’applications industrielles.

Une limitation évidente est leur coût élevé, leur encombrement et leur consommation d’énergie. Cependant, l’histoire du Falcon de Novint démontre qu’il ne suffit pas d’abaisser ces trois barrières. Ce dispositif de retour d’effort, qui ciblait le marché du jeu vidéo, a relevé le défi consistant à réduire le prix d’achat de deux ordres de grandeur, pour un encombrement très limité. Cependant, dix ans après sa sortie en 2007, l’appareil est encore largement méconnu du grand public et Novint Technologies a arrêté sa production, alors même que le terme ”haptique” ne cesse de gagner en popularité. Chaque année, des dizaines de projets de crowdfunding tentent de proposer de nouveaux contrôleurs haptiques : malgré l’intérêt constant du public pour la rétroaction haptique, les nouveaux produits autonomes ne font pas leur percée sur le marché de masse.

En revanche, les vibreurs intégrés dans les manettes de jeu et les téléphones portables sont devenus si courants que leur absence est généralement perçue comme un manque grave. Bien que leurs signaux soient relativement grossiers, ils se sont avérés cruciaux pour de nombreux cas d’utilisation, de la dactylographie de clavier virtuel aux notifications discrètes en passant par l’amélioration des jeux vidéo. Ils constituent en fait la seule technologie haptique répandue à l’heure actuelle.

En résumé, l’histoire technologique récente suggère que pour trouver leur marché, les technologies haptiques doivent être intégrées dans les produits existants, plutôt qu’être conçus comme des périphériques supplémentaires.

L'avènement des écrans tactiles

Les écrans tactiles se sont largement répandus au cours de la dernière décennie et sont devenus l'une des interfaces homme-machine les plus ordinaires. En plus du succès commercial des tablettes tactiles, les téléphones cellulaires et les ordinateurs portables ont également tendance à être équipés d'un écran tactile. Le nombre moyen d'écrans par foyer en France en 2017 dépasse cinq, de sorte que si l'écran de télévision reste le plus répandu, la consommation audiovisuelle diffuse vers d'autres supports, tactiles pour la plupart. Les écrans tactiles sont donc en passe de devenir la principale technologie d'affichage de contenu audiovisuel.

Les écrans tactiles offrent un large éventail de paradigmes d'interaction, sans les contraintes telles que le port d'un accessoire ou la limitation du champ de vision. Ils sont généralement bon marché et peuvent être autonomes, ce qui les rend très polyvalents. De plus, la co-location entre l'affichage visuel et le toucher rend de nombreuses métaphores d'interaction suffisamment intuitives pour que certains bébés puissent essayer de zoomer sur des cartes papier.

Cependant, malgré ces qualités, les écrans tactiles manquent encore de sensations tactiles: quel que soit le contenu visuel, ils sont plats, lisses, rigides et statiques sous le doigt. Les écrans tactiles nous invitent à mettre en oeuvre notre dextérité tactile, mais pas encore notre sensibilité tactile.

L'augmentation haptique des surfaces

Parallèlement à la diffusion des écrans tactiles, l'intérêt pour leur amélioration haptique s'est accru et est devenu un nouveau domaine de recherche appelé “surface haptics”. Le “surface haptics” fait référence à tout système actionnant une surface physique afin de produire des effets haptiques, de préférence sur le doigt nu [28].

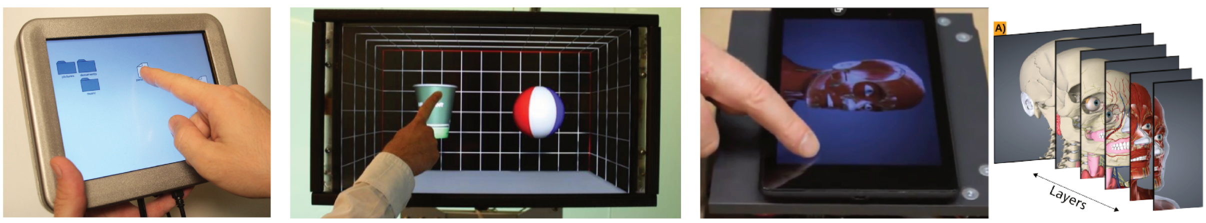
Dans le cadre de cette thèse, nous nous intéressons principalement au rendu haptique d'images sur écran tactile. Par conséquent, nous limiterons notre étude aux systèmes haptiques qui fournissent également une rétroaction visuo-haptique co-localisée. Les images que nous considérons peuvent être des images 2D, ou bien une vue d'objets virtuels dans une scène 3D.

Bien avant le développement des écrans tactiles, les prémisses du “surface haptics” étaient posées avec le concept des écrans à changement de forme. Des tentatives ambitieuses ont été menées pour actionner mécaniquement une surface afin de reproduire n'importe quelle forme d'une manière interactive. À l'aide de la projection vidéo, ces écrans peuvent fournir des formes et des informations visuelles co-localisées. Dans ces approches, la résolution du rendu est directement liée à la densité (élevée) des actionneurs, d'où un coût technique très élevé.

Les tablettes tactiles sont des dispositifs hautement intégrés : elles combinent la détection tactile et l'affichage visuel, tout en étant autonome en énergie et en exécution de logiciels. Actionner directement l'écran peut donc s'avérer très bénéfique. Par exemple, des systèmes à retour d'effort peuvent être utilisés pour actionner directement un écran tactile, et permettre de contrôler le contact par des forces ou du mouvement. Cependant, cette approche a été relativement peu explorée, malgré les possibilités offertes pour un coût technique raisonnable. Certaines approches alternatives utilisent un élément intermédiaire agissant sur le doigt avec un minimum d'obstruction visuelle. Enfin, un travail considérable a été réalisé sur la modulation de friction, qui utilise les vibrations ultrasoniques ou électriques pour modifier les phénomènes de contact physique entre le doigt et l'écran, et réduire ou augmenter les forces de frottement.

Applications

Comme les écrans tactiles ont un large champ d'application, leur augmentation haptique couvre une grande variété d'usages. L'ergonomie des interfaces utilisateur tactiles peut bénéficier d'un retour haptique, qui permet d'obtenir de meilleures performances et un meilleur confort pour les tâches de manipulation. En particulier, les technologies d'assistance sur les smartphones constituent un débouché avec un fort potentiel: notamment pour les technologies de lecture d'écran, qui sont actuellement principalement basées sur du retour audio. L'affichage physique des forme et des volumes permet d'enrichir la manipulation d'objets 3D, dans des contextes de design industriel ou de modélisation 3D. Par ailleurs, l'exploration et l'exploitation de données riches et complexes, comme les résultats de scanners médicaux par exemple, peuvent être largement facilitées par l'usage du mouvement et d'évènement haptiques mettant en valeur des point d'intérêts. Enfin, en raison de sa forte contribution à l'immersion et la présence, l'haptique est un sujet phare pour les industries du divertissement, des jeux vidéo à la consommation multimédia.



(a) (b) (c)

Figure 1 – Exemples d'applications du "surface haptics": bureautique courante, manipulation d'objets 3D et exploration de données médicales multidimensionnelles.

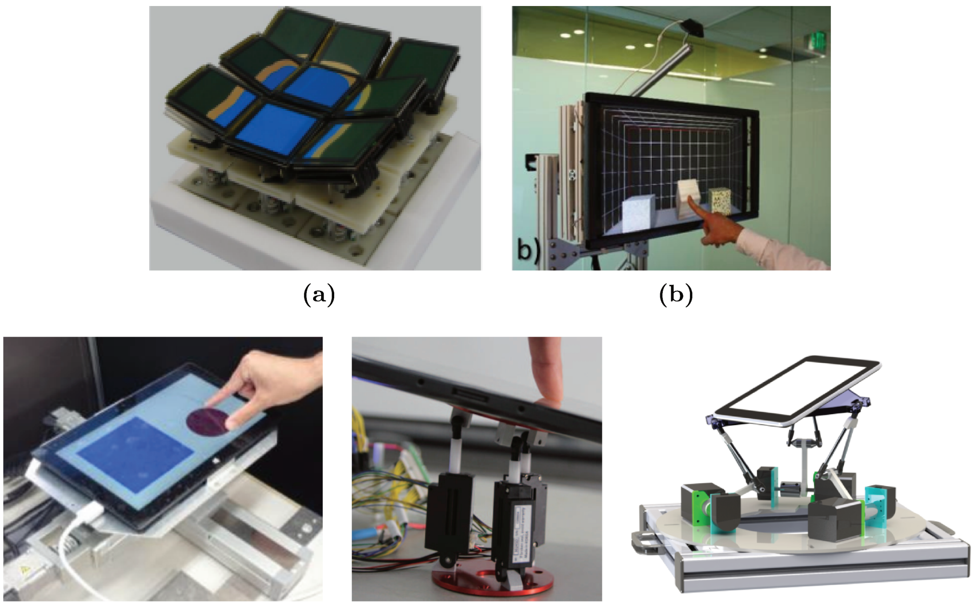
Approche

Nous avons élaboré une approche qui peut être résumée par le concept d'image haptique. La production et la conception d'une expérience visuo-haptique peuvent être envisagées sous trois aspects complémentaires : le stimulus haptique, le stimulus visuel et les conditions nécessaires pour qu'ils fusionnent en un percept unique et cohérent.

L'image haptique repose sur une méthode technique appelée ”texture mapping”, qui consiste à envelopper sur un maillage 3D différentes images contenant les informations nécessaires au rendu des détails fins. Dans le contexte des images haptiques, le mapping de texture définit une relation directe entre les données visuelles et haptiques. La méthode est donc particulièrement adaptée aux données haptiques hétérogènes, puisqu'elle les stocke spatialement dans des “cartes” dédiés. L'image haptique est adaptée à la décomposition des données haptiques en de nombreux éléments simples, et privilégie donc les méthodes et les dispositifs de rendu haptique offrant une diversité d'effets simples par rapport aux modèles uniques complexes. Enfin, l'image haptique est appropriée pour tirer parti des interactions crossmodales et des bénéfices de la multimodalité.

Contributions

Premièrement, nous présentons un état de l'art du domaine de l'augmentation haptique d'écrans tactiles. Nous présentons d'abord les mécanismes sous-jacents à la perception haptique des surfaces, depuis le déclenchement de signaux nerveux à la formation de percepts subjectifs. Ensuite, nous présentons comment la littérature précédente a abordé la question de l'acquisition de données haptiques, qui est nécessaire liée à des choix de modélisation. Nous discutons également quelques propositions récentes visant à partager les données haptiques sous la forme de bases de données accessibles au public. Enfin, nous passons en revue les solutions existantes pour actionner et fournir un retour haptique interactif sur écran tactile.



(a) (b)

(c) (d) (e)

Figure 2 – Exemples d'écrans tactiles actionnés.

Dans un deuxième temps, nous proposons un nouveau format pour le mapping de texture haptique indépendant du matériel de rendu haptique. Ce format est destiné à être intégré de manière transparente dans les processus de création de contenu audiovisuel et à être facilement manipulé par des non-experts dans des contextes multidisciplinaires. Nous montrons à partir des résultats expérimentaux issus de la littérature que dix caractéristiques haptiques élémentaires peuvent être utilisées de manière complémentaire pour le rendu des surfaces haptiques. Nous fournissons un exemple détaillé d'un matériau haptique et les dix cartes associées, ainsi qu'une liste de spécifications.

(a) **(b)**

Figure 3 – Exemple d'une image visuelle et d'une carte thermique révélant un système de tuyauterie caché.

Ensuite, nous présentons "KinesTouch", une nouvelle approche pour l'amélioration haptique d'écran tactile qui couvre quatre dimensions psychophysiques différentes avec un seul dispositif de retour de force : déformabilité, frottement, rugosité, et gémoétrie. Nous présentons la conception et la mise en œuvre d'un ensemble correspondant d'effets haptiques ainsi qu'une configuration de validation de concept. En ce qui concerne le frottement en particulier, nous proposons un nouvel effet basé sur de grands mouvements latéraux qui augmentent ou diminuent la vitesse de glissement entre le doigt et l'écran. Une étude utilisateur a été menée sur cet effet afin de confirmer sa capacité à produire des sensations de glissement distinctes. Enfin, nous présentons plusieurs cas d'utilisation illustrant les possibilités offertes par KinesTouch pour améliorer les interactions 2D et 3D sur tablette tactile, dans différents contextes.

(a) **(b)**

Figure 4 – Notre prototype de KinesTouch.

Enfin, nous proposons une approche pseudo-haptique appelée "Touchy", où un curseur circulaire est introduit sous le doigt de l'utilisateur, pour évoquer diverses perceptions haptiques à travers des changements dans sa forme et son mouvement. Nous présentons sept effets inspirés de modèles physiques simulant cinq propriétés haptiques différentes. Afin de valider notre approche, nous avons mené une étude utilisateurs où les effets ont été comparés à des échantillons de matériaux réels afin d'évaluer la façon dont ils sont perçus. Nous étendons également l'approche Touchy aux scènes 3D et présentons plusieurs implémentations pour démontrer la pertinence de Touchy dans des environnement virtuels variés.

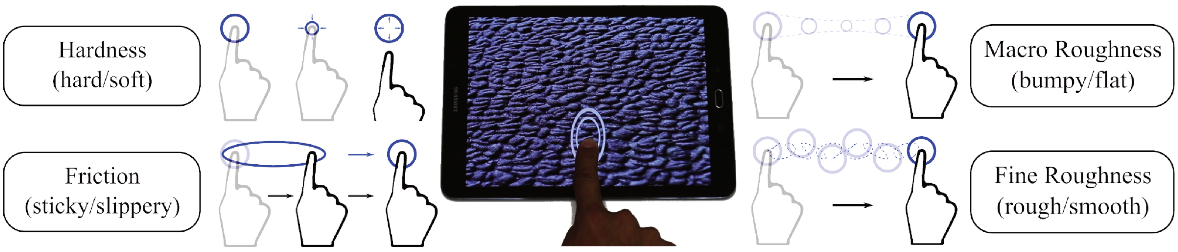


Figure 5 – Touchy est un curseur co-localisé pour les écrans tactiles qui se déforme et/ou se déplace pour évoquer une variété de propriétés haptiques, couvrant quatre dimensions perceptuelles différentes : rugosité fine, rugosité macro, dureté, et friction.

En conclusion, nous discutons des poursuites et améliorations possibles du travail présenté, ainsi que des perspectives à long terme et des questions restant ouvertes pour de futurs travaux.

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Contribution à l'étude de l'augmentation haptique d'images sur écran tactile

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Titre : Contribution à l’étude de l’augmentation haptique d’images sur écran tactile.......... ....

Mots clés : écran tactile, image haptique, surface tactile

Résumé : Au cours de la dernière décennie, les écrans tactiles sont devenus un standard des interfaces homme-machine. Cependant, malgré leurs nombreux atouts, ils manquent encore de sensations tactiles : quelque soit le contenu visuel, ils restent plats, lisses, rigides et immobiles sous le doigt.
Dans cet ouvrage, nous examinons les moyens permettant aux écrans tactiles de nous toucher en retour, et de produire des sensations tactiles variées associées à des images.
Premièrement, nous proposons un nouveau format de données haptiques qui fournit une description haptique générique d'un objet virtuel indépendamment de la technologie de rendu.
Ce format est destiné à s’intégrer aisément dans les processus de création de contenu audiovisuel, et à être facilement manipulé par des non-spécialistes dans des contextes multidisciplinaires.
Ensuite, nous abordons le challenge de produire des sensations haptiques variées avec une complexité technique limitée, grâce à notre nouvelle approche appelée "KinesTouch". Nous proposons en particulier un nouvel effet de frottement basé sur des déplacements latéraux augmentant ou diminuant la vitesse de glissement entre le doigt et l'écran.
Enfin, nous présentons "Touchy", une méthode appliquant les principes pseudo-haptiques aux interactions sur écran tactile. Nous proposons un ensemble d'effets pseudo-haptiques traduisant visuellement des propriétés telles que de la rugosité, de la rigidité ou du frottement par les vibrations, les déformations et la trajectoire d'un curseur circulaire affiché sous le doigt de l'utilisateur. Nous appliquons également ces effets à des scènes 3D et traitons des différences entre les méthodes de rendu de contenu 2D ou 3D.

Title : Contribution to the study of the haptic enhancement of images on touchscreens ... .

Keywords : touchscreen, haptic image, tactile surface

Abstract : Touchscreens have largely spread out over the last decade and have become one of the most ordinary human-machine interface. However, despite their many assets, touchscreens still lack of tactile sensations: they always feel flat, smooth, rigid and static under the finger, no matter the visual content.
In this work, we investigate how to provide touchscreens with the means to touch us and express a variety of image-related haptic features.
We first propose a new format for haptic data which provides a generic haptic description of a virtual object without prior knowledge on display hardware. This format is meant to be seamlessly integrated in audiovisual content creation workflows, and to be easily manipulated by non-experts in multidisciplinary contexts.
Then, we address the challenge of providing a diversity of haptic sensations with lightweight actuation, with the novel approach called “KinesTouch”. We propose in particular a novel friction effect based on large lateral motion that increases or diminishes the sliding velocity between the finger and the screen.
Finally, we introduce “Touchy”, a method to apply pseudo-haptic principles to touchscreen interactions. We present a set of pseudo-haptic effects which evoke haptic properties like roughness, stiffness or friction through the vibrations, stretches, dilatations and compressions of a ring-shaped cursor displayed under the user’s finger. We extend these effects to 3D scenes, and discuss the differences between 2D and 3D content enhancement.