"Haptic material": A Holistic Approach for Haptic Texture Mapping

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Abstract. In this paper, we propose a new format for haptic texture mapping which is not dependent on the haptic rendering setup hardware. Our "haptic material" format encodes ten elementary haptic features in dedicated maps, similarly to "materials" used in computer graphics. These ten different features enable the expression of compliance, surface geometry and friction attributes through vibratory, cutaneous and kinesthetic cues, as well as thermal rendering. The diversity of haptic data allows various hardware to share this single format, each of them selecting which features to render depending on its capabilities.

Keywords: texture, compliance, roughness, friction, temperature, haptic material

1 Introduction

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 [12][15][22], 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, simplify the processes, to facilitate setups' compatibility, and to spread haptic databases.

If the CHAI3D project[3] 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.

[3] www.chai3d.org

Haptic perception of surfaces is commonly divided in four main components: compliance, surface geometry, friction and warmth [28]. In order to express these properties, haptic devices produce four types of physical cues: kinesthetic, cutaneous, vibratory or thermal. Holistic haptic data should take into account all combinations between those percepts and cues, but most of them have been addressed separately, and they were never combined in a single format so far.

Texture mapping refers to a set of techniques to efficiently display fine the details of a 3D model in a realistic way without the need of a high-resolution mesh [1]. Originally developed in computer graphics, this approach has been advantageously applied to haptic rendering [13], 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 layers is appropriate to merge heterogeneous data.

In this paper, we propose 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. 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. We provide therefore two contributions:

- an analysis of the literature on haptic surface perception, according to both psychophysical quantities and rendering cues, leading to ten elementary haptic features
- 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 that 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-case specification table.

2 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 [28] and [35]):

- **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 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 1.

2.1 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 [37]. 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 [7]. 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.

Table 1: Representative quantities for the ten haptic percept/cue combinations.

Percepts → Cue Types ↓	**Compliance**	**Geometry**	**Friction**	**Warmth**
Kinesthetic	Rate-hardness [7]	Local surface orientation [14]	Kinetic friction [32]	/
Cutaneous	Contact area spread rate [6]	Local indentation [4]	Static friction [26]	/
Vibratory	Dynamic stiffness [40]	Stroke spectral response [17]	Stick-slip [19]	/
Thermal	/	/	/	Thermal profile [27]

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 [23]. 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 [36]. The **"contact area spread rate" (CASR)** has been proposed as a metric [6]. 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 [21]. The transient vibrations produced by tapping are known to be important hardness cues, improving rendering both realism [17] and manipulation performances [3]. Their capture and modeling has been extensively studied in the form of a single-frequency decaying sinusoid [10]. However this approach oversimplifies the richness of real tapping transients, as realism is improved when larger spectral characteristics are taken into account [40]. Moreover, the relationship between the fundamental frequency of the transient and the physical properties of the material are unclear [38]. Thus, Higashi et al. proposed to use spectral impulse response profiles, which they called **"dynamic stiffness"**, to characterize compliant virtual objects. It is typically modeled by an autoregressive filter with a few dozen of coefficients.

2.2 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 $0.1mm$ 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 [5] [35]. On the other hand, the two devices of [39] exemplify the difference between local and and global shape rendering.

Vibratory cues: The perception of fine roughness have been extensively studied with respect to various geometrical parameters (see [28] for a review), but was also shown to correlate with different physical measurements, depending on the subject [18]. 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 [29][33]. Doing so, the wide **spectral response to stroke** is saved 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 (see [39] for a review) reproducing these **local indentations** at fingertip receptors resolution.

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 [14] [25].

2.3 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 [2]), 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 [16]. 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 object 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) [16]. 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 [22], it can be more explicitly treated with a dedicated vibrator [19]. 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.

2.4 Thermal features

Temperature is a crucial parameter for material discrimination, but humans are much more sensitive to temperature differences rather than absolute temperatures [9]. Psychophysical judgments of thermal features mainly rely on both **target temperature** and initial heat extraction rate, that is proportional to **thermal diffusivity** [27]. 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.

2.5 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 [23], but one should note that CASR displays do not have the popularity and technical accessibility that force-feedback devices have. Table 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.

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 [5]. 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 [11], 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.

Table 2: Typical rendering devices used to render each of the ten percept/cue combinations.

	Compliance	**Geometry**	**Friction**	**Warmth**
Kinesthetic	Normal force feedback [7]	Parallel platform [14]	Variable friction display [30]	NA
Cutaneous	CASR display [6]	Micro-pin array [4]	Tangential force feedback [22]	NA
Vibratory	Vibrator (tapping transients) [40]	Vibrator (stroking response) [17]	Vibrator (stroking transients) [19]	NA
Thermal	NA	NA	NA	Peltier module [9]

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 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. 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.

3.1 Related work in haptic texture mapping

If texture mapping has been extensively used for haptic rendering of small-scale geometry (see [24] 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 [13], while Wakita et al. stored them sperately in two gray-scaled maps [20]. Kamuro et al. used three different gray-scaled maps for stiffness, friction and vibrotactile features [34]. 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 [31]. 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.

3.2 The holistic image format

By extending texture mapping to a variety of features, our holistic image format benefits from its intuitive visualization and rapid editing possibilities. The ten haptic maps can be elaborated either from real-world measurements and/or perceptual models, but can also be sketched manually.

In our illustrative example, a wooden texture image (see Fig 1a), taken from a high quality scan-based texture package [41], 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][40], defined in specific files stored together with the haptic image. Therefore, the vibratory maps store only the references to vibration models, similarly to [34].

Fig. 1: Example of a visual image and thermal map revealing a hidden piping system.

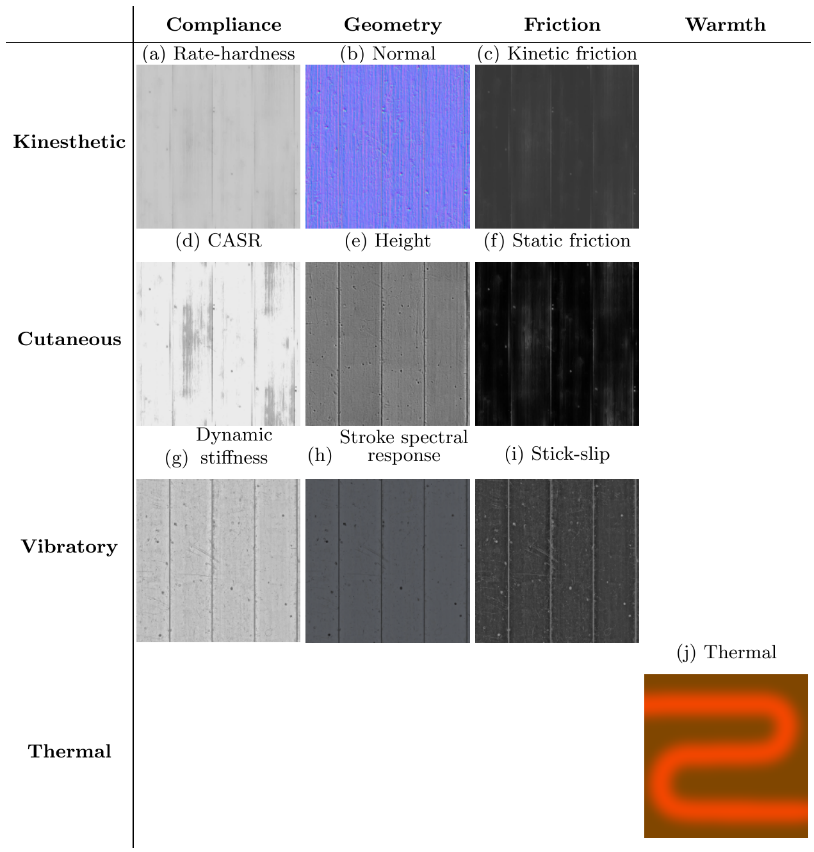
(a) The visual image.

(b) The thermal map and its two channels.

Figure 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 (Fig 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 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.

Fig. 2: Examples of the ten haptic maps of the holistic haptic image format, organized along perceptual dimensions and physical cues.



3.3 Format specification table

Our haptic format benefits from texture mapping's technical maturity: when using haptic materials, user can seamlessly make use of tiling or unwrapping.

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 summarizes the units, range and resolutions for each metric.

Table 3: General specification table for the features stored in the haptic maps. Vibratory maps are not considered as they store only references.

Haptic feature	Format	Range	Resolution
Rate-hardness	8-bit	0-10000 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°	0.002°
Local indentation	8-bit	±5mm	0.04mm
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

4 Conclusion and future work

In this paper, we presented a new format for haptic texturing taking into account ten different haptic features, which are complementary both from a technical and a perceptual point of view. This format provides a generic description of haptic materials without prior knowledge on display hardware. 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. Besides, this format especially suited for the constitution of haptic databases, which are meant to be shared between haptic researchers using various devices.

Yet, the optimal complementarity between the ten features remains to be ensured by the systematic study of pyschophysical thresholds and relative importance of each cues, which represents a consequent body for future research. An unified rendering software solution remains also a challenging following. Finally, the topic of haptic material acquisition is still an open research question, as both real-world measurements and synthesis models have strengths and limitations.

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