Chapter 2
Literature Review

Abstract This chapter presents a literature review of the previous work related to haptic textures. After an overview of the most relevant devices, control strategies, and algorithms used in haptics, the author presents the major findings on the perception of haptic textures and roughness. This review covers both the psychophysics experiments as well as the basic results of the physiology of tactile perception of textures and surfaces. The chapter is concluded with the discussion of the current understanding of the perception of virtual haptic textures generated with force feedback devices, thus setting the stage for the discussion of the research presented in the following chapters.

2.1 Introduction

The discussion of novel techniques and solutions regarding the rendering of haptic textures requires some background material on haptic devices, Sect. 2.2 at page 7; on algorithms used to generate virtual haptic sensation, Sect. 2.5 at page 29; on control theory applied to haptics, Sect. 2.3 at page 14; and on the psychophysics behind the haptic perception of textures, Sect. 2.4 at page 19. These four topics belong to the areas of engineering, psychophysics, and physiology, which are the core disciplines contributing to haptic technologies and that are intimately related. Without a precise characterization of the haptic device used, it is impossible to properly interpret any psychophysical experiment conducted on virtual haptic sensations, and it might be difficult to extend findings gained from one device to other devices. At the same time, facts related to the human somatosensory system (obtained with classical psychophysical studies on real tactile stimuli) offer valuable guidelines for improving the design of applications.

The centerpiece of any computer controlled haptic interaction is clearly the haptic device, which is the hardware used to stimulate the somatosensory system of the user.

2.2 Interfaces

In general, a haptic device, which is also called a haptic display, resembles a robotic system that applies computer generated tactile stimulation to the skin of a human.
user. These devices can be roughly categorized in four classes: vibrotactile, surface, tactile, and force-feedback interfaces.

Vibrotactile displays are designed to apply high frequency and low amplitude vibrations to the skin; stimulations can be applied to the hand as well as to other body parts, depending on the application. Vibrotactile stimulators are very common and can be found in controllers for video games and in cell phones; the key to their availability is the low cost of the actuators, usually a motor with an eccentric mass, but their capabilities are extremely limited.

Conversely, tactile displays produce a distributed deformation pattern to the fingerpad, either through indentation or stretching of the skin. Tactile interfaces can be used, for example, to provide blind users with access to digital media. Refreshable braille cells can be assembled to display a single line of characters from a text file. Recent advances in tactile simulators suggest the possibility of refreshable tactile graphics based on skin stretch [93].

Surface displays are based on the observation that the area of contact of the finger with an object changes during the exploration process. The actuators in the device move a flat plate against the finger of the user to change the size and location of the area of contact, producing the sensation of a shape. By changing the control of the device it is possible to produce convex, concave, and flat surfaces.

Finally, force-feedback devices can deliver a single, low frequency force signal to the user’s hand, usually through a pen-like interface, a knob, or a thimble. This class of devices has found a niche application in virtual reality, where they provide programmable haptic stimulation to the user. Among the most significant applications that benefit from force-feedback are: surgical simulation, virtual sculpture, CAD modeling, remote sensing, and video games. Although commercial devices offer solutions for each of these cases, it is difficult to use them in a research environment due to their inherent limitations. Most importantly, the study of virtual textures requires a degree of fidelity that is yet to be achieved in general purpose devices.

Only force-feedback devices relevant to the scope of this book are discussed. Before analyzing the different devices available and their characteristics, it is important to review some basic rendering algorithms for virtual environments.

### 2.2.1 Virtual Environments

Given the Cartesian position of a manipulandum \( \mathbf{x} = [x_1 \ x_2 \ x_3]^T \), a rendering algorithm computes a force field \( \mathbf{F}(\mathbf{x}, \mathbf{\dot{x}}) \) over the workspace. In general, virtual environments are defined as combinations of some fundamental elements, such as elasticity, viscosity, and friction.

For example, elastic unilateral constraints can simulate the boundary of objects; in 3D space it is possible to implement a so-called virtual wall in the half volume...
$x_3 < 0$ with the field:

$$
F_K(x, \dot{x}) = \begin{cases} 
[0, 0, -K_V x_3]^T & \text{if } x_3 < 0, \\
[0, 0, 0]^T & \text{otherwise},
\end{cases}
$$

(2.1)

where $K_V$ is the stiffness of the virtual wall. Viscous friction (also called damping) improves the quality of the rendering of virtual walls and can be synthesized according to:

$$
F_B(x, \dot{x}) = \begin{cases} 
[0, 0, -B_V \dot{x}_3]^T & \text{if } x_3 < 0, \\
[0, 0]^T & \text{otherwise},
\end{cases}
$$

(2.2)

where $B_V$ is the damping coefficient; the virtual wall response in the same half volume of Eq. (2.1) is computed as

$$
F_W(x, \dot{x}) = F_K(x, \dot{x}) + F_B(x, \dot{x}).
$$

(2.3)

The relevance of damping will be clear when discussing the passivity framework for haptic devices.

Virtual stiffness and damping are simple effects that can be summarized in a single equation; on the contrary, dry friction is a phenomenon that cannot be captured by a simple formula. Different rendering algorithms have been proposed for virtual friction, and a specific one will be discussed in relation to the new rendering approach introduced in this book. Informally, dry friction is a force arising at the contact of two surfaces and opposes their relative motion independently from the speed of the motion.

These elements of virtual environments are useful to analyze the performance of force feedback devices: it is possible to compare different devices based on the maximum stiffness and damping they can render.

### 2.2.2 Force Feedback Devices

Force feedback devices are robotics mechanisms (composed of a mechanical structure, actuators, sensors, and a control unit) which can exchange energy with the hand of a user through a handle (for example a stylus, a knob, or a thimble).

#### 2.2.2.1 Generalities

There are two classes of force feedback devices: admittance displays and impedance displays.

Admittance devices measure the force $F$ that the user is exerting on the handle and respond by moving the end effector according to a rendering law $[x(F) \dot{x}^T]$. Usually admittance devices must be strong because they need to impose a precise trajectory
to the end effector in response to user’s force. The frequency response and position accuracy of such devices are typically not suitable for haptic textures because they rely on gears and transmissions to provide large forces to the user, but they can mask small displacements due to friction.

Impedance devices are more attractive for haptic texture rendering because they are designed to have little inherent friction, damping, and mass. These characteristics contribute to the transparency of the interface and the user is less aware of the device and can focus more on the virtual environment. The rendering algorithms in Sect. 2.2.1 at page 8 are expressed for a impedance style interface: a force field $F$ is displayed as a function of the position of the device $x$ and velocity $\dot{x}$. In general, these devices can render forces much weaker than admittance devices, but the frequency characteristics of the rendering is much more suitable for haptic textures. Thus, only impedance style devices will be considered for the scope of this work.

### 2.2.2.2 Force/Torque Output Capabilities of the Device

During the rendering of a virtual environment a force feedback device acquires the position and/or orientation of the handle held by the user, which results in an $N$ dimensional vector; it then generates forces and/or torques which span an $M$ dimensional space in response to the user actions. The rendering algorithm computes the force $F_i$ and the torques $\tau_i$ at time step $i$ as a function of possibly all the previous position readings $x_j : 0 < j \leq i$; generally, the only the last measured position $x_i$ and the last estimate of the handle velocity $\hat{\dot{x}}_i$ are used to compute the forces.

It is possible to simplify the analysis by categorizing the devices according to dimension of the force/torque space $M$; in this book only force feedback devices relevant to haptic textures are presented. A notable omission are exoskeleton type devices, which can deliver multiple torques to different joints of the arm and wrist, with the goal of rendering very large objects. These devices are not used to generate force feedback textures because of their performance, for example a backlash of 1 cm is unacceptable for haptic texture rendering, but it is more than acceptable for exoskeleton type devices [41].

### 2.2.2.3 1D Torque or Force

The haptic knob is the simplest force feedback device available, see for example [69, 96]. It consists of a single rotary actuator, an angular sensor, and a small wheel through which the torques are transferred to the user. The actuator can be either a brake (which gives a resistive torque) or a motor (which provides active torques). In both cases, haptic textures are rendered by varying the torque output as a function of the rotational position and angular velocity of the device; this rendering can result in the user feeling a textured knob. In a more commercial application, a haptic knob can simulate detents typical of the controls of hi-fi systems, thus providing a programmable controller for a stereo. Devices in this class, however, cannot render
virtual constraints and textures at the same time, because of the single degree of force output; nevertheless, haptic knobs represent a valuable tools for basic haptic research. The same architecture can be used for implementing the force feedback steering wheels used in arcade driving games, [94].

A variation on the haptic knob is the haptic paddle that converts the torque of a single actuator in a force, displayed to the user through a handle, [124]. This device suffers from the same limitations of the knob but has been extensively involved in experiments aimed at validating the control theory results pertinent to haptic devices, e.g. [1].

### 2.2.2.4 2D Forces

Because they are able to render superficial properties, two dimensional haptic devices offer a good trade off between simplicity and capabilities. Usually based on parallel mechanical structures they can be divided in two main categories: joysticks, [67, 68, 103, 125], and planar devices, such as the Pantograph [11, 122]. The basic element is usually a five bar linkage, either spherical for joysticks or planar for Pantograph style devices. Due to the properties of five bar linkages, it is possible to have direct drive connection between the motors and the linkage while maintaining the stators grounded; this greatly reduces the apparent mass of the device without resorting to cable transmission.

Joystick-like devices have a stick that can rotate in 2 dimensions, pivoting through a fixed point; the actuators provide torques in the same two directions of rotation, those torques are felt as forces by the user holding the stick. Their rendering capabilities are limited to 2D force fields which depend on the orientation and angular velocity of the stick; as a result, the virtual boundaries that can be rendered are limited; for example, flat boundaries must contain the pivoting point. Nevertheless, joysticks are capable of generating the sensation of exploring 2D textured surfaces. Several researchers used the Immersion Impulse Engine 2000 joystick for haptic texture rendering, as discussed in Sect. 2.5 at page 29.

The Pantograph haptic display, on the other hand, renders a planar field of 2D forces that are felt through a small plate contacting a single finger. The plate stimulates both the kinesthetic and the tactile channel because the forces deform the fingerpad and move the finger at the same time. This device is used implement both 2D varying force fields as well as 1D planar constraints on which textures can be applied. It is then possible to use such devices for investigating almost all the rendering algorithms available for haptic textures. Since it is a device designed to render forces at the finger scale, the 2 N maximum force is sufficient for conveying realistic sensation. Stronger forces are necessary when dealing with arm-size devices. With regard to texture research, West and Cutkosky realized a custom-made 2D device to compare the detection of haptic textures when exploring real and virtual surfaces in the same conditions and through the same interface [147].
2.2.2.5 2D Forces, 1D Torques

An intermediate step between 2D and 3D devices was proposed by Sirouspour et al., who realized a modified Pantograph design for rendering 2D planar forces and 1D torques perpendicular to the same plane, [133]. In their design, the robot acquires the position of the handle on a plane as well as its rotation around the axis perpendicular to the workspace, from which the force/torque commands are generated. This extension allows the simulation of planar interactions between rigid bodies and has both a large workspace and allows infinite rotations around the vertical axis, but has not yet been used for rendering virtual textures. This device is currently being manufactured by Quanser [121].

2.2.2.6 3D Forces

3D impedance-style force feedback haptic devices have been subject of extensive research and design, because they can be applied to a broad range of scenarios while maintaining a relatively simple design. With 3D force feedback devices it is possible to render 2D virtual boundaries with a superimposed texture.

The most successful 3D haptic device is the Sensable PHANTOM™; developed by Massie and Salisbury [99]. The device has three motors, which provide the three torques necessary to produce a full 3D force display; two motors act on a 5-bar linkage which provides forces on a plane, which is then rotated by the third motor to generate an arbitrary 3D force. Due to a careful distribution of the masses and to a capstan transmission system, the PHANTOM™ is almost balanced statically (hence the user does not support most of the weight of the device) and provides a nicely damped, strong force feedback feeling. Multiple versions have been produced with different sizes, strength, and materials: the high quality models, Premium 1.0 and Premium 1.5, are very interesting for haptic research, while low cost plastic versions are more suitable for less precise applications [131]. In general, the users interact with the PHANTOM™ by holding a stylus, at the end of which forces are applied.

Two of the motors of the PHANTOM™ Haptic Device are not grounded, hence the user feels the inertia of their stators when moving the device; this artifact is minimized by the mechanical design and the small size of the actuators. A different approach is necessary when stronger forces (hence bigger motors) are required. Force Dimension developed a new design for 3D devices which can provide strong forces while keeping all the three motors stationary; the resulting devices, called Delta and Omega are simple and strong, with a contained increase in perceived inertia with respect to the PHANTOM™ [39, 40].

Finally, the Ministick is a statically balanced device that combines low inertia and high resolution; it is based on three five-bar mechanisms which allows for stationary motors and direct drive transmission between the motors and the links [3]. The most recent implementation of this design is being used to investigate the perceptual properties of virtual textures [25, 136]; it produces a maximum continuous force of 1.4 N (5 N peak), which is sufficient for finger scale haptics, and has a nominal resolution of 9.6 µm according to the design paper [136].
A study on the detection of the orientation of sinusoidal gratings showed similar thresholds when the task is performed virtually with the ministick and with the bare finger on real surfaces; the authors interpreted these results as a validation of the rendering capabilities of the ministick [139]; this conclusion is not completely supported by the results because of two reasons: the different mechanisms involved in direct and indirect touch should be discussed and quantified. Second, according to the force constancy theory [24], changing the stiffness of the virtual wall supporting the texture could affect the thresholds because of the specific algorithm used in the experiment to convert the geometrical profile in force field.

### 2.2.2.7 Multi DOF Force-Torques

Both the Sensable PHANTOM™ and the Force Dimension Delta are available in variants that provide 6 DOF force/torque feedback, by adding encoders and motors at the tooltip of the device. These extensions increase the perceived mass of the device and do not offer the same performance of specific multi-DOF designs.

An example of commercially available 6 DOF device is the MPB Freedom 6S, which combines a parallel design and cable driven transmissions to achieve low inertia, wide bandwidth, and high positional resolution. The main advantage of this device with respect to the other 6 DOF commercial interfaces is quality of the force delivered to the handle.

To avoid perceivable artifacts arising from friction and backlash in the mechanisms of the haptic device, a design based on magnetic levitation can be used: with a workspace of ±12 mm in translation and ±7 deg rotation, the magnetic levitation haptic device developed by Berkelman is very limited in its applications, but it was successfully used to display virtual textures [142]. The resolution of the device (5–10 µm) and the bandwidth of 120 Hz (−3 dB) offer a level of performance adequate for the texture rendering; nevertheless, guaranteeing the passivity of the device could be problematic, since position quantization is known to introduce non passive behaviors in low friction devices.

### 2.2.2.8 Frequency Response and Artifacts

The aforementioned commercial haptic devices have been extensively used for haptic research both for developing rendering algorithms and for studying the perceptual response of the somatosensory system. However, the engineering limits of such interfaces are not yet fully understood, and the manufacturer specifications often lack essential information such as the physical bandwidth of the device, whose effect on haptic texture perception was explored by Wall and Harwin [144].

A critical study on the engineering characteristics of the PHANTOM™ haptic device was conducted by Cavusoglu et al. [13]; the most interesting aspect of their study, with respect to the topics discussed here, was the confirmation of frequency
dependent amplification of the force signals, which can greatly distort the rendering of haptic textures. Further analysis of the frequency response of the PHANTOM™ was presented by Kuchenbecker et al. [81], where a high order invertible linear model of the device dynamics was proposed as a solution for shaping the open loop acceleration response of the device. This approach cannot be directly applied to closed loop haptic simulation, but represents an interesting development for time-based haptic synthesis of virtual textures, which is reviewed in Sect. 2.5.3 at page 33.

Contrary to the PHANTOM™, custom made devices are usually not investigated as extensively as it is required to guarantee artifact-free rendering. In particular, the ministick is an interesting device but little is known about its frequency related characteristics.

To ensure an artifact-free haptic signal, a haptic device is often analyzed in the context of control theory; this approach provides a theoretical framework which can be applied to different haptic algorithms.

2.3 Control Theory and Haptics

In general, two distinct notions are used to analyze the control properties of haptic systems: passivity and stability. Dynamic system, such as haptic devices, react to an input signal by changing their state and by providing an output signal. In the case of an impedance style force feedback device, the input is the motion of the handle by the user, and the output is the actuation (force/torque) applied to the handle.

A dynamic system is said to be stable if for every bounded input signal, it responds with a bounded output signal; simply put: if the user moves the handle with a finger, the device does not try to tear the limb apart from the owner. The same stable dynamic system exchanges energy with the environment, but no restriction is made on this exchange, as long as the output does not become unbounded.

The passivity of a system, on the contrary, is defined by constraining the energy flow between the system and the environment: a system is passive if when perturbed it responds by dissipating part of the input energy, thus returning less energy than it receives. More formally a one port system with effort $F$ and flow $\dot{v}$ is passive if:

$$\int_0^t F(\tau)\dot{x}(\tau) d\tau + E(0) \geq 0$$

for $t \geq 0$ and for every function pair $F, \dot{x}$, where $F$ the force generated by a haptic device at the handle, $\dot{x}(t)$ the velocity trajectory of the handle, and $E(0)$ the energy of the system at $t = 0$. In passivity literature, dissipated energy has positive sign, hence the flow is the velocity at the handle with negative sign. In other words, during a passive haptic interaction, the haptic device dissipates part of the energy of the user motion. While a passive system is clearly stable, stability does not imply passivity: for example a stable haptic device can generate bounded, periodic, self sustained oscillations around an operating point, which is a non passive behavior.
The use of passivity is widespread in the haptic community because it allows the decoupling between the analysis of the mechanical haptic system and the properties of the human user. Moreover, a passive system does not generate sustained vibrations at the tooltip, which is a typical artifact that spoils the haptic experience. The latest results in passivity analysis for haptic devices offer a set of constraints on the parameters of the virtual environments, which are based on the physical characteristics of the mechanical system (for example friction in the ball bearings and damping); most of the results refer to the simple case of the unidimensional damped linear virtual wall. The discussion of these results can be integrated with the limited attempts made for extending the passivity results to the non-linear and multidimensional case.

### 2.3.1 Passivity Results

The usual haptic device is controlled by a discrete sampled data controller, which in general reads the position of the handle, computes the force output, sends the appropriate signal to amplifiers which, in turn, deliver controlled power to the motors. This process is repeated as fast as possible, generating a periodic process. The frequency of this process is the sampling frequency, and during the interval between two iterations the forces are kept constant according to the zero-order-hold sampling scheme ($ZO\,H$). Typically, artifacts emerge when implementing a haptic virtual environment: the delay between the acquisition of the position and the actuation of the motors and the sampling period introduce an unwanted energy imbalance, resulting in a series of oscillations and vibrations.

#### 2.3.1.1 Physical Damping and Sampling Period

Colgate and colleagues studied the problem of rendering passive virtual walls of stiffness $K_V$ and damping coefficient $B_V$; they identified the relationship that ensure passivity in:

$$\frac{K_V}{2T} + |B_V| \leq B_P,$$

where $T$ is the sampling period and $B_P$ is the mechanical damping in the haptic device [27]. This classical equation has been extended by Colgate et al. in [26] to account for the effects of a first order filter used to smooth the velocity signal:

$$\frac{K_V}{2T} + \frac{B_V T}{2\tau + T} \leq B_P \quad (B_V \geq 0),$$

$$\frac{K_V}{2T} - B_V \leq B_P \quad (B_V \leq 0),$$

which includes the time constant $\tau$ of the filter. In a following paper [28] the authors explore the relationship between passivity and stability, showing that passivity
imposes more conservative constraints than stability on the virtual environment parameters; particularly, as the device damping $B_P$ decreases, the range of parameters that allow for stable rendering is bigger than the range of passive environments.

Among different extensions of those equations to multidimensional virtual environments, a very interesting formulation can be found in [97] where Mahvash and colleagues found two sufficient conditions for passivity for a delayed and sampled system: let $a(t)$ be the acceleration of the haptic device, if

$$|a(t)| \leq \frac{\sigma_0(S_P)}{T\sigma_0(B_P)},$$  \hspace{1cm} (2.8)

where $\sigma_0(S_P)$ is the minimum singular value of the physical friction matrix of the haptic device, and

$$|F(t_k) - F(t_{k-1})| \leq \frac{\sigma_0(B_P)}{2T} |x(t_k) - x(t_{k-1})|$$  \hspace{1cm} (2.9)

are verified, then the resulting haptic interaction is passive; due to the multidimensional nature of the system, the physical damping $B_P$ is replaced by the minimum singular value of the damping matrix $B_P$. For a linear virtual wall equations (2.5) and (2.9) are equivalent.

Another analysis of the passivity of non-linear virtual environment is provided in [102]; in this formulation, the non-linear environment is described in terms of the maximum differentials of the force with respect of position, velocity, and acceleration. Moreover, this paper also considers the influence of the virtual coupling, which is an approach to stability proposed by Adams and Hannaford [2].

### 2.3.1.2 Friction and Encoder Quantization

Two recent studies have shown that encoder quantization can be responsible for the non passive behavior of certain haptic simulations, particularly in devices with low inherent friction [1, 34]. In [1], Okamura and colleagues found a simple and elegant solution for the energy gains due to quantization when rendering a linear virtual wall:

$$K_V \leq \min \left( \frac{2B_P}{T}, \frac{2f_c}{\Delta} \right)$$  \hspace{1cm} (2.10)

is an extension of Eq. (2.5) that accounts for friction ($f_c$) and encoder quantization ($\Delta$). While this solution was found by analyzing the energy balance of the haptic simulation in the spatial domain, Diolaiti et al. [34] used the machinery of control theory to determine the behavior of a haptic device with friction and spatial quantization. This analysis confirmed that globally stable (passive) interaction is possible if Eq. (2.10) holds. Moreover, the authors identified three possible behaviors if the passivity equation is not met: limit cycles of very small amplitude (less than one encoder count) can happen if $K_V \leq \frac{2B_P}{T}$ and $K_V > \frac{2f_c}{\Delta}$; on the other hand, if the haptic device has enough friction but not enough damping, the simulation can be
either locally stable or unstable depending on the initial velocity, which can be too high for the friction to fully dissipate the energy of the system, resulting in unstable rendering.

### 2.3.1.3 Time Based Passivity

A simple real-time method to ensure passivity has been investigated by Hannaford and colleagues [53, 127]. The energy exchange between the virtual environment and the haptic device is monitored by the so-called Passivity Observer, and when the energy balance shows non-passive behaviors a programmable virtual damper (called Passivity Controller) is activated to remove energy coming from the virtual environment. The Passivity Controller approach does not model either the device dynamics nor the users behaviors, hence its wide applicability; in some cases the unmodeled dynamics of the haptic device could introduce artifacts, and some heuristic corrections based on the virtual environment might be needed [128]. Finally, this time-based approach can be used to control a flexible link, if a dynamic model is known [126].

### 2.3.1.4 Wave Haptics

Niemeyer and colleagues introduced the concept of wave variables in teleoperation [108, 109], and applied the same formalism to haptics [35]. This approach is based on a change of variables that converts the usual effort/flow pair into a so-called wave space, whose main property is the passivity under time delay. In practice, it is used to design an analog amplifier/controller which exploits the electric motor dynamics to improve the rendering of stiff passive virtual contacts. The results are encouraging in terms of high frequency response, but the difficulties of designing virtual environment in wave space as well as the requirements for analog controllers are limiting the adoption of this approach.

### 2.3.2 Stability of Haptic Systems

As already mentioned, stability is a less restrictive condition than passivity, but it requires a model of the human operator, which is reflected in a series of assumptions on the mechanical properties of the human hand or arm as well as on the behavior of the user. Sometimes, stability is studied in the worst case scenario, which happens when the user does not interact with the device [34].

Nevertheless, multiple stability conditions have been proposed based on different models used for describing the user/haptic device system. Under the hypothesis that both the human arm and the device can be modeled as second order systems, Minsky and colleagues found that, for a virtual wall to be stable, the inequality

$$\frac{K_T T^2}{2} \leq B_T$$  \hspace{1cm} (2.11)
must hold, where $T$ is the sampling period in seconds [105]. For purely damped virtual environments, equation

$$\frac{T}{2M_T} \leq B_T$$

(2.12)

must be verified, $K_T$ being the total stiffness, $B_T$ the total damping, and $M_T$ the total effective mass of the system haptic device—human arm.

Hayward and Bonneton extended the analysis to a system with a delay of a single time sample $T_s$ and found that

$$B_V \leq B_P + \frac{4M_P}{3T_s},$$

(2.13)

$$K_V \leq \frac{2B_P + B_V}{3T_s}$$

(2.14)

must hold for virtual wall to be passive, where $K_V$ and $B_V$ are the parameters of the virtual wall being rendered, and $M_P$ and $B_P$ are the physical parameters of the device [10].

Later, Gillespie and Cutkosky studied the problem of simulating a ball bouncing on a virtual surface: for this scenario they developed a new controller, based on dead-beat control, which solves the problem of the asynchrony between the digital sampling and the virtual contacts, because the ball crosses the threshold of the wall between two samples. This controller could then be used to render virtual walls, once a model of the user, and of the device, is provided [46].

The range of stable stiffnesses renderable by a device is limited; to improve the perception of hard contact and the stability of the system Salcudean and Vlaar proposed to add a pulse of braking force upon contact with the virtual wall [129]. The braking force is shown to partially compensate the deterioration of performance due to discretization.

The stability boundaries of a haptic device (modeled as a damped mass) rendering a damped virtual wall were explored in [66]; the authors found that the maximum stable virtual damping renderable depends on the physical damping in the device, and it is independent from sampling period and time delay. The authors also discuss the maximum stable stiffness and compare it with the passivity condition in Eq. (2.5): if there is delay in the rendering, Colgate’s equation is not valid, because the range of passive parameters ($K_V$ and $B_V$) derived from such equation contains values outside the stability boundary of the delayed system; this result implies that the passivity condition is a best case scenario for the virtual environments. Similarly, the influence of delay and damping on the stability boundaries has been studied and experimentally validated in a follow up work [45].

### 2.3.3 Virtual Coupling

The unification of the impedance and admittance approach to haptics is explored in a paper by Adams and Hannaford [2]. The authors propose that admittance style
displays could be used to display impedance type virtual environments and vice versa, for a total of four different combinations of devices (admittance/impedance) and virtual environments (admittance/impedance). The stability of those four kinds of systems is analyzed and passivity can be enforced by using a virtual coupling element, which acts as a converter of the force/velocity quantities between the virtual environment and the device. For impedance/impedance systems, the maximum stiffness of the elements in the virtual environment must be limited; the role of the virtual coupling in this case is to limit the stiffnesses that the device transfers to the user, so that if a virtual element is too stiff, the system does not generate oscillatory artifacts; however, when interacting with stiff environments the user would feel the compliance of the coupling and not the stiffness of the elements: this trade-off between stability/passivity and transparency must be taken into account when designing the virtual coupling. In conclusion, the virtual coupling simplifies the design of both the virtual environment and the device by decoupling their stability/passivity properties.

This brief review of the major results of control theory applied to haptics, shows the complexity of the problem of rendering stable or passive virtual environment. The general reliance of stability analysis on a model of the human user is definitely the major drawback; for this reason the passivity analysis is often preferred.

2.4 Texture Perception

The perceptual mechanisms underlying the tactile exploration of materials are still under investigation; it is still unclear which characteristics of the objects, and specifically of the textures, are perceptually more relevant. The link between physical measures of an object and their perceptual influence has been elusive so far; a recent work by Tiest et al. [141] tried to correlate the perceptual similarity of 124 samples of common objects with the physical roughness of their surface and the compressibility. By using multidimensional scaling (MDS), they established that subjects sorted the 124 objects according to four psychophysical dimensions, none of which coincided with either physical roughness or compressibility; moreover, these two properties are mapped in an horseshoe shaped curve in MDS space, which led to the conclusion that the perceptual space is not Euclidean. Previous studies conducted with MDS led to different conclusions: the perceptual spaced looked Euclidean and the dimensionality was between 3 and 4 [61, 63, 120]; these discrepancies can be explained by the limited sample size used in those early experiments, at most 25.

To label the dimensions, subjects are in general required to describe the stimuli according to a series of predetermined adjectives. There is consensus on the nature of the most important directions: stiffness/compliance (on the continuum soft-hard) and roughness (smooth-rough) are the most important characteristics, but their influence is often combined in the first MDS dimension, thus suggesting that they are not independently used to perceptually characterize surfaces.

Picard et al. [120] conducted a free-sorting experiment on 24 car seat cover samples; the most relevant conclusion regards the issue of semantic differences between
languages, because the most important dimension used by the subjects was labeled as soft/harsh, and roughness did not play an independent role. This results might be explained by the very specific set of stimuli as well as by the different nuances that the word roughness carries when applied to different materials.

Hollins et al. investigated the individual variations of this perceptual tactile space and found that while some subjects used mostly those two dimensions to group objects (rough/smooth and hard/soft), others discriminated also based on a third direction, labeled stickiness [63]. This result is very significant because it shows that, when a limited set of stimuli is presented, stickiness (hence friction) is not a third independent dimension for all subjects. In their previous study they found again a three dimensional space, where the first dimension was clearly aligned with roughness and the second with stiffness [61].

In conclusion, the space of tactile perception has not yet been fully understood, but it is clear from the literature that: at least four dimensions are involved, the space is probably not Euclidean, and that, although coupled with other properties, roughness has a strong representation in this space.

From the MDS analysis, it appears that roughness/softness is the dimension that is most related to texture perception; unsurprisingly then, roughness has been the topics of truly many studies, which approached the investigation of roughness perception from two different points of view: classical psychophysics experiments, based on subjects reporting on texture properties, explained which elements of the haptic interaction with surfaces influence the percept of roughness. Among those elements are: the mode of touch (active or passive, direct or mediated by a probe), the geometric properties of the surface (microstructure, macrostructure), the material properties of the texture (friction, compliance, temperature), and exploratory conditions (speed of exploration).

The second approach is based on the identification of the physiological events that determine the perception of roughness. Typical experiments consist of recordings of neural activity of monkeys in response to tactile stimulation. Under the assumption that neural mechanisms of monkey and humans are correlated it is possible to infer neural code for roughness by performing a psychophysical experiment on humans, and then record the neural response of monkeys exposed to the same stimuli. For example, human subjects could be asked to estimate the roughness of some gratings, then the same surfaces are applied to the fingerpad of monkey and the neural response is recorded (either centrally in the somatosensory cortex of the brain or peripherally in the median nerve that runs in the wrist); for an example see [138].

2.4.1 Early Work on Roughness of Textures

The first qualitative results regarding the perception of rough textures were collected by David Katz (1925), who tried to isolate the effect of a number of exploratory conditions [151]. With regard to this book, the most important result is that roughness
perception requires lateral motion between the skin (or the probe) and the surface under investigation. Moreover, rough textures can be reliably perceived through a probe: subjects can discriminate 14 different samples of paper (from smooth waxed paper to coarse cloth paper) by stroking them with a pencil. This ability is purely mediated by vibration, because once the pencil is covered in a vibration damping cloth, the discrimination performance is greatly impaired. These two observations confirm that roughness can be conveyed to a user through a haptic device. Among the conditions tested, Katz noticed that changes in exploration speeds have minimal influence on roughness when using a bare finger, but when speed exceeds 60 cm/s, roughness disappears altogether and a pain sensation arises. In similar experiments, Zigler noticed that roughness does not arise from stationary contact between the finger and a surface, but it requires a relative movement between them [100]; the author also reports that the experience of smoothness is mostly elicited when the interaction force is moderate or light.

More recently, Stevens and Harris showed that subjective estimates of roughness and smoothness are linear functions of the grit number of emery cloths when plotted in log-log space (the grit is a measure of inter element spacing of the particles on the surface of the cloths) [137]. Moreover, the authors proved that estimates of roughness and smoothness (across subjects) are perceptually reciprocal, both when the estimation is absolute or relative to a standard cloth. A similar study by Ekman and colleagues proved that roughness/smoothness are reciprocal also intra-subject, although the psychophysic functions differ substantially between subjects [38].

Finally, in contrast with the common assumption that active touch is generally better than passive touch [44], Lederman showed that roughness perception with a bare finger is not significantly affected by the mode of touch [87] an only marginally when mode of touch is combined with the exploration speed [88]. The kinesthetic perception and the proprioceptive sense, then, contribute marginally to roughness perception, and their role has been often overlooked in studies related to texture perception. Also, due to this marginal contribution of the proprioceptive sense, data obtained from experiments performed under active and passive conditions can be directly compared, when they deal with roughness.

### 2.4.2 Bare Finger—Macro-textures

Although this topic had been studied previously, Lederman’s PhD work is arguably the first systematic attempt to understand the psychophysics of roughness; by drawing inspiration on Stevens’ work [137], the author based most of her experiments on roughness estimation of different kinds of surfaces: linear metal gratings, raised dot patterns, and sandpaper among them. This research has been extended to virtual environments generated by a force feedback joystick [104], a haptic mouse [74], and a PHANTOM™ [92].

Lederman conducted a set of experiments with linear gratings, produced by cutting parallel linear groves of different width on the surface. This process results in a
series of raised ridges; these stimuli belong to the category of macro textures (with inter-element spacing >200 µm), and their estimated roughness was found to be significantly affected by a number of parameters, both when explored with a bare finger or through a probe.

When the surface is explored with a bare finger, the most important effect is usually the groove width both in metal [85, 88, 89] and plastic surfaces [83]. The psychometric function relating groove width and estimate of roughness has an inverted U shape in log-log space with a peak above 3.5 mm, confirming the results of Connor et al. who showed that roughness peaks for embossed dots spaced 3.2 mm [30]. A decrease in perceived roughness occurs as the ridge width increases, but this significant effect is not as large as the groove width influence [85, 89], similar effects of groove and ridge size were found by Sathian et al. [130]. An interesting comment on the metal gratings used by Lederman can be found in [85], where the authors reported that two different manufacturing processes created stimuli that exhibited a different finish due to the microstructure; the stimuli felt “somewhat different” although their macro structure was similar. This effect can be explained by the sensitivity of the finger to microtextures; the features left on the surface by the manufacturing process were smaller than 200 µm but contributed to the overall roughness perception.

The U shaped relationship between inter-element spacing and roughness is disputed by Chapman [101], Smith [134], and colleagues who used non dithered plastic raised cones (approx 1 mm in diameter) and found that roughness estimates were monotonic log-log functions of the inter-element spacing (from 1.5 to 8.5 mm). The most probable cause of the quadratic relationship found by Lederman, Connor, and others is the small elevation of the textural elements over the surface (grooves or dots), which causes the finger to touch the bottom of the groove, when the width exceeds 3 mm. This contact between the finger and the flat surface was less likely to happen in Chapman and Smith’s case because the patterns had taller textural features.

Focusing on the interaction forces between the finger and the surfaces, Lederman found that the normal force applied by the fingertip on the surface [89] has a large effect on roughness: more pressure equals rougher percept. Conversely, shear forces applied to the fingertip impair the estimates of roughness when subjects explore surfaces through layers of paper [86]; these experiments extend the findings of Gordon and Cooper, who found that asperities of surfaces are better detected when a piece of paper is interposed between the surface and the skin and moved together with the finger [51]. The explanation of this phenomenon can be found in the work of Smith and colleagues [134], who proved that roughness correlates with the rate of change in lateral force when subjects explore plastic surfaces with raised dots. As a consequence, constant shear forces could mask lateral force variations, and reduce the perception of roughness.

Furthermore, Smith showed that lubricating the surfaces (hence changing the friction coefficient) does affect the estimate of roughness because it reduces the lateral force variations. This conclusion is consistent with Ekman [38] who measured a log-log linear friction to roughness psychometric function. In contrast with those
results, Taylor and Lederman showed a negligible effect of friction when exploring metal gratings [140]. Since the friction coefficient was computed when the finger stroked along the ridges, they did not consider the effect of the variations due to geometry; this effect was instead included in the mean friction computed in the other two studies (Smith’s and Ekman’s).

2.4.2.1 Temporal Determinants

The effects of spatial features, and particularly the spacing between textural elements, have been confirmed; however, there is a debate over the influence of temporal determinants on the perception of textures. Lederman’s experiments showed that exploration speed does not influence the roughness perception of gratings [85, 88], even when the pitch of the surface is varied. From this observation it was concluded that the frequency of vibration of the skin does not affect roughness estimation. The same speed invariant behavior was observed by Chapman and colleagues for raised dots patterns, they also confirmed that frequency is not a determinant for macrotextures and mentioned that mode of touch was not significant [101]. To completely exclude the influence of frequency on roughness estimation, Lederman and colleagues used selective frequency adaptation to impair the perception of vibrations and asked the adapted subjects to estimate roughness. Two groups of adapted subjects, 20 and 250 Hz, was confronted with a control group and, although adaptation was measured, no significant effect on the estimates of roughness was found [90]. Hollins and colleagues confirmed, about 20 years later, that frequency adaptation does not affect the judgment of roughness for macrotextures, but greatly impairs the perception of fine textures [64]. Discordant results are presented by Cascio et al.; they found a significant influence of frequency on roughness perception when estimating and discriminating macro-gratings with various ridge widths, but no such effect could be found for stimuli of different groove width [12].

2.4.2.2 Spatial Intensive Model for Macrotexture Perception

The findings of the perceptual works on gratings can be explained “by the spatial—rather than temporal—aspects of their biophysical interaction with the hand [59]”. Taylor and Lederman [140] introduced a model to interpret the spatial determinants of roughness: they propose that roughness increases as a function of the mean volume of skin displaced by the mechanical interaction with the surface. A notable omission in Lederman work is the study of texture perception and discrimination in the case of no movement between the finger and the surface. According to Katz, there cannot be any roughness estimate without movement; Hollins and colleagues investigated this issue quantitatively and proved that movement increases the discrimination of fine sandpaper (particle size < 100 µm), but it has no effect for coarser samples. This finding is the basis for the so called duplex theory of texture perception: Katz already proposed that tactile perception is mediated by two different channels, one sensitive to pressure and the other related to vibrations. Hollins and colleagues confirmed that, at least for texture perception, the duality theory holds and has a neurophysiological explanation [60].
2.4.3 The Duplex Theory of Texture Perception

Building on Lederman’s spatial model, Hollins and colleagues proved that perception of fine textures is mediated by the perception of vibration, while macro textures are mostly perceived by sensing their spatial features. In experiments conducted with sandpaper, the transition between spatial and temporal perception happened for element sized of 100 µm [60], whose spatial period is around 200 µm. To further confirm this finding, experiments with sandpaper showed that textures with spatial period close to this limit feel rougher if an external vibration is applied to them [62]; because this increase in roughness is not dependent on the frequency, it is very likely that finer surfaces feel rougher due to the amplitude of the vibrotactile stimulation. Finally, as further confirmation, adaptation to frequency impairs the perception of finer surfaces but not coarse ones [64].

2.4.4 Neurophysiology of Texture Perception

Validation for the duplex theory is provided by the vast body of literature on the neurophysiology of touch in monkeys, whose somatosensory system closely resembles the human’s.

The tactile sensation arises in the skin, when mechanical deformation of the tissue is converted in neural impulses sent to the brain. This neuro-mechanical interfaces in the skin are called mechanoreceptors, and in the human glabrous skin there are four different kinds of mechanoreceptors, which can be identified both by the anatomy and by the characteristics of the neural response they generate. For the purpose of this book, only the most salient characteristics of the mechanoreceptors, their functions, and their link to virtual textures are reviewed. For in depth reviews on mechanoreceptors please consult [70, 72]. Of the four mechanoreceptors in the human skin, two are innervated by slow adapting fibers (SA1 and SA2) while the other two are rapidly adapting (RA1 and RA2).

2.4.4.1 SA1 Afferents and Receptors in Human Skin

At the interface with the dermis, the epidermis is structured in ridges, whose tips are innervated by branching myelinated neural fibers that terminate in the Merkel disks; in particular, Merkel endings cover 80% of the epidermal ridges area in monkeys fingerpad [117]. Two organizations of Merkel endings were found: branching afferents innervated either clusters (70 µm in diameter) or chains of Merkel endings with length greater than 200 µm. These fibers are called SA1, and are believed to respond to the mechanical strain energy density in the skin [72]. These receptors and afferents are found both in human and monkeys. When the skin is indented, SA1 fibers respond with a rate of impulses that increases with the indentation amplitude, but there is debate whether this relationship is linear (e.g., [8] on monkeys) or sublinear ([76] on humans). The SA1s have been shown to be the most reliable receptors that respond according to the spatial properties of the object being touched: curvature
2.4 Texture Perception

(human [50] and monkey [48]), edges (human [119], monkey [8]), orientation of curved surfaces [36], and, most importantly, roughness [29, 30, 71, 130].

The response of single SA1 afferents to textured surfaces could not be correlated to roughness estimates of humans, but, as a population, SA1 receptors do represent roughness, the code being the spatial variations of firing rate in the population of SA1 afferents: this neural code can be clearly predicted by filtering the textured surface with a spatial Gabor filter [29]. Moreover, the somatosensory cortex of monkeys, SI—area 3b where SA1 afferents are projected in the brain, contains neurons whose receptive field structure suggests the function of enhancing local features of a surface (like edges) [33], which could further explain the SA1 code for roughness. This theory about texture perception is disputed by Chapman and colleagues, who propose a simpler rate-based neural code which is then integrated with motion information in the somatosensory cortex [14].

Sathian and colleagues showed that SA1 response was unreliable indicator of roughness of gratings with small groove width [130], in accord with the large size of their receptive field [143]. Studies on gratings moving sinusoidally indicate that of the 2 spatial and 2 temporal determinants, only one spatial variable (groove width) and one temporal variable (peak temporal frequency of the grating spatial cycles) affect the neural response independently. The other two determinants (ridge width and peak speed of movement of the gratings) affect the neural response only in the measure that they change the groove width or the peak frequency [47]. Finally, the detection of gratings is improved when the features are presented parallel to the dermal ridges on the skin, with respect to orthogonal; recordings in monkey show that SA1 population responds more vigorously to gratings parallel to the ridges, matching the results on human performance [148]. This phenomenon could be explained by the ridge either acting like a lever, thus magnifying the strain at the location of the Merkel disks, or, by the same mechanical property, ridge movement could recruit more Merkel disks, for the same skin deformation.

Interestingly, SA1 receptors responds to forces aligned along preferred directions, thus encoding the directionality of the force stimulus [7]; this property is however shared with the SA2 and RA1 sensory systems.

This brief list of findings seems to indicate that SA1 afferents population is responsible for the detection of shape [49, 50] and mediate the sensation of roughness, for medium sized feature. The purely spatial hypothesis on texture perception, however, conflicts with findings from [12], as mentioned above; this discrepancy could be explained by the higher sensitivity of SA1 to dynamic stimuli [70]; however, the poor performance of SA1 on fine textures confirms the role of dynamic mechanoreceptors in the perception of textures (innervated by RA1 and RA2 fibers), thus validating the duality theory.

2.4.4.2 RA1 Afferents and the Meissner Corpuscle

About 150 RA1 afferents per cm² innervate the human skin and terminate in Meissner corpuscles, which are a fluid filled structure lodged between the adhesive ridges
in the skin (dermal papillae), closer to the skin surface than the Merkel disks. For a description of the Meissner corpuscle please refer to [116].

The proximity to the surface of contact is responsible for the low thresholds needed to stimulate the afferents; nevertheless, the RA1 afferents have very poor spatial discrimination because they respond with uniformity to stimulations over the entire receptive field (3–5 mm in diameter) [70]. A physiological study by Paré and colleagues established a density of approximately 45–60 Meissner corpuscles per mm² of monkey skin; moreover the innervation patterns are complex [117]: “Finally, a given MC may be innervated by one axon that supplies one combination of multiple MCs and another axon that innervates another, albeit partially overlapping combination. This anatomical arrangement suggests that the MCs are part of a partially shifted, overlapping continuum of afferents that include a mix of differing resolutions.” The dense innervation implies that each innervating fiber branches multiple times to reach different Meissner corpuscles.

The most important function ascribed to the RA1 system is the detection of slip during precision grip and manipulation of tools [135]; in particular, it is the only system that detects slip for surfaces with features height in the range 2–8 µm. For a review on the importance of cutaneous receptors on grip forces please consult [149].

The role of RA1 afferents on roughness perception is not yet clear [59]; the response of RA1 to textures moving on the fingerpad is greatly impaired by the limited spatial resolution, but due to their very low thresholds, RA1 afferents are responsible for the detection of very small features on smooth surfaces, for example RA1 can detect dots as small as 550 µm in radius and 2 µm in height; in comparison, the SA1 are four time less sensitive to dot height [82].

2.4.4.3 SA2 Afferents and Ruffini’s Corpuscle

The neurophysiological similarities between the hands of humans and monkeys are striking; however, the SA2 system is absent in monkeys [70]. Whereas the response of SA2 to lateral skin stretch is established, there is strong debate on the nature of the mechanoreceptor responsible for the sensation. Commonly thought to innervate the Ruffini corpuscle, the SA2 afferents account for 15% of the primary afferent fibers of the median nerve innervating the human hand; however, immunofluorescence of the mechanoreceptors and innervation of the monkey finger, failed to isolate a single Ruffini corpuscle [117]. Further studies on human tissue isolated only one candidate Ruffini mechanoreceptor in the finger and concluded that “…it seems unlikely that Ruffini corpuscles in human glabrous skin account for all but a small proportion of physiologically identified SAII afferents [118].”

Despite the uncertainty over the origin of the mechano-neural transduction, two functions of the SA2 system are known: the detection of pre-motion deformation of the skin against an object; and, most importantly, the perception of the hand position through the pattern of strain on the skin of the fingers (integrated with kinesthetic information from muscle spindles and joint afferents).

By its nature however, the SA2 system seems to be marginally involved in texture perception, and it has not been investigated in this context.
2.4.4.4 RA2 Afferents and the Pacinian Corpuscle

The RA2 system then presents very high sensitivity and responds to a relatively narrow range of frequencies (100–300 Hz). The mechanoreceptor responsible for the transduction of vibration into neural signal is the Pacinian corpuscle. Lodged deeply in the dermis, this ovoidal lamellar structure (varying in size between 1 and 4 mm in adult humans) is exquisitely sensitive to vibrations (in the order of 10 nm and more in amplitude, with a mean of 40 nm) and has a receptive field that is not as spatially defined as RA1 and SA1 [72]. There are approximately 350 Pacinians in each finger and 800 in the palm, each usually innervated by a single different fiber. In monkeys, approximately 2% of corpuscles are innervated by a branching axon [117].

The response of RA1 and RA2 afferents to vibrotactile stimulation is presented in a seminal paper by Mountcastle and colleagues, who studied the response of the skin to vibrations applied by probes with spherical tips (diameter 0.5 to 3 mm) [138]. The detection thresholds they measured are clearly bimodal, when plotted as a function of the stimulation frequency: further study on monkeys showed that RA1 fibers response peaks at about 30 Hz, while RA2 are extremely sensitive to stimulations at 250 Hz. The amplitude detection thresholds at 30 Hz are one order of magnitude bigger than at 250 Hz. This difference in sensitivity can partially be explained by the mechanical properties of the skin: mechanical wave conduction is very poor at 30 Hz, in fact vibratory stimulation must be within 5 mm from the center of the receptive field to excite the relative RA1 afferents. Notably, subjects can rely on RA1 to distinguish biharmonic signals differing only in phase (30 Hz + 10 Hz sinusoidal waves) while the Pacinian afferents cannot (100 Hz + 300 Hz sinusoidal waves) [5]. To explain this finding, an intensive model for pacinian representation of vibrations was proposed: the hypothesis was that vibrations could be distinguished according only to their pacinian weighted response. This model was partially rejected because the discriminability of multi-harmonic vibrations depended also on temporal properties [6].

It is established that roughness perception and texture detection of fine textures depends on the 250 Hz Pacinian vibrotactile channel: numerous studies by Hollins and colleagues established the role of the Pacinians by showing, among others, that adaptation to 250 Hz impairs the perception of fine textures, while coarser textures are not affected [64]. In following studies, by measuring the vibrations of the skin when scanning a surface, they concluded that “…the roughness of a fine surface (spatial period < 200 µm) is a function of the Pacinian weighted power of the vibrations it elicits.”

Pacinian adaptation has also been studied with MDS: a three dimensional space was found for the perception of raised-dot textures (14 conditions 1, 2…, 7 mm inter-element spacing, adapted and non adapted) [43]; adaptation to a 250 Hz vibration did not impair the perception of roughness of the surface, but made the individual dots feels smoother, which is consistent with the duality theory, since macro-textures are not perceived via the Pacinian system.
2.4.5 From Bare Finger to Probe

In a more recent study, the effect of adaptation to textures was studied in both direct and indirect touch. Exposure to a 416 µm texture proved to significantly reduce roughness estimates in indirect touch, as well as in direct touch for fine textures, but for coarse textures and direct touch no such effect was found [65]. This result is consistent with the intuition that, in indirect touch, only temporal determinants are available for texture perception.

The ability to distinguish surfaces and experience roughness through a probe was already described by Katz, and the MDS analysis of texture perception confirms that roughness is a perceptually relevant dimension both in direct and indirect touch [150]; this study also links roughness with the power of the vibrations in the probe during contact with a texture.

The estimated roughness of plates with dithered raised dots through a pen-like probe presents a log-log U shaped relationship with the inter-element spacing, similarly to what is observed for bare finger [73]. The inversion point of this function depends on the size of the tip of the probe: the smaller the probe the lower the inversion point, also the larger the probe the smoother the surface [84]. When a plastic sheath is used to remove the spatial component of stimulation to the fingerpad, the roughness discrimination is greatly impaired; on the contrary, the effect of latex glove (both on bare and sheathed fingers) is negligible, because the glove changes only the coefficient of friction at the contact site [73]. In both passive and active touch with a pen-like probe the largest effect on roughness is ascribed to inter-element spacing, but speed is indeed significant, showing a much larger effect in passive than in active condition [91], and the inversion point of the roughness function increases with speed; the most probable explanation for the speed effect is that when the subject (or the plate) moves faster, the probe sinks less in the texture, thus generating a smaller resistance; on the other hand when the spacings is sufficient for the probe to touch the bottom of the plate between dots, an inversion in the roughness estimate is expected. Interestingly, the larger the range of speeds used in the exploration the smaller the effect of speed on roughness estimation. Finally, as for direct touch, a higher normal force results in larger roughness estimates [84].

To account for these results Klatzky and colleagues proposed a preliminary probe/plate interaction model that predicts the drop point as a function of the probe size and plate geometry; the experiments, however, showed that the geometric drop point (of the probe in the texture) differs from the psychophysical inversion point, which then depends on dynamic parameters which are not captured by simply the drop point [75]. Finally in a summary paper, Lawrence and colleagues reiterated that roughness and groove width do not show a monotonic relationship, thus limiting the range of gratings that can be discriminated based on roughness only [83].

2.4.6 Texture Detection and Discrimination

Roughness is not the only perceptual quality that can be used for textures discrimination; in fact, it was found that the amplitude threshold of detection of a single
Gaussian bump of width $2 \times \sigma$ is linear in log-log space (exponent 1.3) with respect to $\sigma$. For this experiment, active touch with the bare finger was used, and the results are valid over a large range of bumps amplitudes ($0.15 \leq \sigma \leq 240 \text{ mm}$) [95]. The absolute threshold for $\sigma \leq 1 \text{ mm}$ is close to 1 $\mu$m, and the critical parameter for detection is thought to be the maximum slope of the bump. This last observation is consistent with [134]. This study provides a relationship between a single textural element width and the height necessary for its detection; extending these findings on sinusoidal gratings, Nefs and colleagues determined that subjects could discriminate between textures that differed as little as 2 $\mu$m in height or 30 $\mu$m in pitch [107]. Previously, Morley et al. found a discrimination threshold of 45 $\mu$m for textures with different pitch under active exploration, which increased to 102 $\mu$m when the finger was kept stationary [106]; taking into account the difference in stimuli, these two studies substantially agree on the performance of the tactual perception of gratings.

The amplitude discrimination threshold reported [107] is smaller than the resolution of most haptic devices used for texture rendering. In conclusion, haptics devices operate somehow above threshold, because they cannot generate texture profiles with amplitude differences of less than 2 $\mu$m. Moreover, force feedback devices constrain the user motion on the virtual textures by applying a penalty force as the user crosses the virtual boundary; for example, a penetration of 2 $\mu$m in a texture with stiffness 10 N/mm would generate a force of 20 mN, which is approximately 2 grams/weight, fairly hard to detect when the inertia of the devices is at least 10 times bigger.

To conclude, the discrimination capabilities of the somatosensory system are a challenge not yet matched by haptic devices; as a consequence, the properties of the haptic devices must be taken into great consideration when designing psychophysical experiments and when analyzing the results.

2.5 Virtual Textures

As previously mentioned, the perceptual investigation of haptic textures can be traced back at least to the beginning of the 20th century [151]; conversely, the literature about the rendering virtual texture is much more recent, staring around 1990.

2.5.1 Geometry Based Methods

Margaret Minsky supervised the development of Sandpaper, the first system capable of rendering haptic textures [103, 105]. Her setup was based on a 2D force feedback joystick, which could display different texture patches. The device rendered only lateral forces, which, in some experiments, were proportional to the spatial gradient of the virtual height field $h(u, v)$ at the location of the virtual probe $(x_1, x_2)$:

$$F(x_1, x_2) = K V \left[ \frac{\partial h}{\partial x_1} \frac{\partial h}{\partial x_2} \right],$$

(2.15)
where the height field is mapped according to \((u, v) = (x_1, x_2)\). The results confirmed that it is possible to convey the perception of a textured surface with a 2D joystick, hence 2D lateral force field can be effectively used to mimic surfaces with 3D micro structures. Furthermore, Minsky and Lederman demonstrated that the Sandpaper system was able to communicate to the user some form of roughness of the texture patches [104]. In this experiment, the perceived roughness could be almost entirely predicted by the maximum lateral force exerted on the hand exploring the texture.

The 3D extension of this method is explored by Hardwick et al. in [54]. Given a 3D coordinate frame \((x_1, x_2, x_3)\) a flat virtual surface at \(x_3 = 0\) and a 2D texture height field \(h(x, y)\) mapped according to \(x = x_1\) and \(y = x_2\) the force is computed as:

\[
F = \left[ -\left(\frac{\partial h}{\partial x}\right) R_z -\left(\frac{\partial h}{\partial y}\right) R_z R_z \right],
\]

where

\[
R_z = -K \min\left(x_3 - h(x_1, x_2), d_{\text{max}}\right).
\]

The value of \(d_{\text{max}}\) was set to approximately 0.1 mm to avoid instabilities. The device used in this investigation was a Immersion Impulse Engine 3000 with a maximum force of 9 N.

A different approach was proposed by Thomas Massie in his M.Sc. thesis [98], where he described some rendering techniques applied to the novel PHANTOM™ Haptic device. Massie’s algorithm generates textures by perturbing flat surfaces in 3D with sinusoidal waves; the force arising from the interaction of the user with such textures is always normal to the flat surface and depends on the penetration of the virtual probe into the textures. This process results in convincing textures, which feel frictionless, due to the absence of forces tangential to the textured surface. For this same reason, Massie’s approach remains very simple to implement and less prone to control instability. However, the virtual environment simulates a non physical interaction, which can introduce significant artifacts.

From these two pioneering works, it can be concluded that both normal forces and tangential forces can convey the feeling of textured surfaces. Basdogan et al. [4] combined the two stimuli by applying to haptics textures the bump mapping technique proposed by Blinn for computer graphics [9]. The feeling of roughness was generated by the perturbation of the normal to the flat surface with the gradient of the texture height field \(\nabla h(u, v)\), with respect to the surface parameterization \((u, v)\). The resulting force field has components both normal and tangential to the virtual untextured surface. This method was implemented on a PHANTOM™, and the users reported instability in the system; to solve this problem, Ho et al. [57] fine tuned the normal mapping model to limit the lateral force magnitude. Their solution is empirical but effective; however, in this book, a theoretical model of lateral force instability is proposed.

Since both 2D and 3D haptic displays could provide sufficient textural information, Janet Weisenberger et al. tried to determine which of the two modalities
conveyed the most effective texture perception, [146]; the devices under investigation were a PHANTOM™ and an Impulse Engine 2000. On these devices they implemented both Massie’s normal force algorithm and a viscosity based texture. The subjects were presented with virtual gratings aligned either along the X axis or the Y axis of the devices; their task was to discriminate the orientation of the virtual gratings. The strongest conclusion of this paper is the confirmation that both 2D and 3D devices can be used to render textures; although the Impulse Engine 2000 showed better thresholds than the PHANTOM™, no direct comparison between algorithms and devices was possible [145]. In a previous work they also showed that thimbles or pen like end effectors have no significant contribution on the discrimination of virtual texture orientation. Interestingly, Weisenberger mentions that renderings of sinusoidal surfaces with the PHANTOM™ exhibited instability when amplitude increased over a threshold; this phenomenon suggests that also Massie’s algorithm for normal force fields suffers from control instabilities.

Similar considerations need to be made when dealing with 3D interfaces because they can render both 2D textures, laterally varying force fields applied to a flat surface, and 3D textures, which also have a geometric displacement along the normal to the same surface. Ho et al. discussed the perceptual equivalence between 2D and 3D square waves on a custom made 3D display. They concluded that, for small amplitudes and spatial periods (< 1.5 mm), the two kind of textures are indistinguishable [58]. This result represents the first attempt to quantify the equivalence between two different texturing algorithms.

Another approach for texture synthesis is to draw inspiration from the roughness perception: the geometric model proposed by Lederman and colleagues [75] can be used to generate virtual textures. In the implementation by Unger and colleagues, the interaction between a spherical virtual probe an a surface with raised dots is simulated by constraining the sphere to be outside the surface; the roughness estimation of those virtual surfaces is different from the real ones, even when a velocity correction term is added [142]. No recordings of the user interaction are provided, making it difficult to assess if these results are due to the model, the device, or artifacts. Moreover, no assessment on the fidelity of the rendering can be made.

With a similar motivation, Otaduy and Lin extended the model by Minsky [104] and Hardwick [54] to account for the probe size [114]: in their algorithm, the normal penetration is “the vertical translation required to separate the probe from the textured surface”. The force field is then function of the gradient of this normal penetration. Simulation show a good qualitative matching between the roughness magnitudes estimated in [91] and the maximum acceleration of the hand that this new model would generate.

Finally, a new algorithm for rendering 2D haptic textures was proposed by Hayward et al. [56]; used to render 2D textures on 2D haptic devices, it is based on the idea of directional finite differentiation: it renders a force proportional to the directional change in the virtual height field of a texture, but the force direction is always along the user motion. In this way, the virtual environment generates only working forces that either resist or facilitate user motion. This method, inspired by Minsky’s and Costa’s gradient techniques, can render discontinuous and non differentiable
height fields without modifications, while gradient and normal based techniques require, at least, a differentiable height field.

### 2.5.2 Vibration and Reality Based Methods

Vibration is an important element of texture perception, its application to force feedback was investigated by Kontarinis et al. [78]; they showed that providing vibration feedback in a teleoperation setup definitely improved the user performance. Following this path, Okamura et al. proposed to augment the rendering of virtual object with data recorded during the exploration of real surfaces, which contained significant vibration components [110]. A stylus was stroked and tapped on real materials, and the vibration signal was collected by an accelerometer mounted on the probe. The resulting data was analyzed and correlated with factors such as velocity of exploration, normal force, and geometry of the surface, resulting in simplified deterministic models for generating virtual vibrations. For tapping, decaying exponential models were used. These open loop models, combined with standard force feedback techniques, were implemented on an Impulse Engine 2000 joystick, through which users were able to discriminate the properties of the original materials by feeling their virtual counterparts.

Okamura et al. extended this concept of reality based haptic rendering to a 3D device [111–113], and also developed a friction acquisition device that could be used to identify parameters for virtual friction models [123]. In addition, Costa et al., from the same research group, introduced the idea of using fractal texture profiles for rendering [31]; their virtual stylus model computed a lateral force proportional to the slope of the profile and rendered them on an Impulse Engine 2000; the RMS of the texture profile emerged as the most important factor for the perceived roughness of fractal textures.

Finally, Kuchenbecker improved reality based haptics by introducing the event based haptic method for virtual contacts [81], that is, the haptic device is programmed to replicate the acceleration profile that a user would experience when tapping an object. The open loop models of Kuchenbecker included also the inverse dynamics of the PHANTOM™. The same technique was successfully applied to extend the bandwidth of a teleoperation system [80]. While reality based haptics, as defined by Okamura, can be used over all the workspace of the device, the high quality results achieved by Kuchenbecker are probably confined to small parts of the workspace, because the closed form solution of inverse dynamic model changes with the position of the haptic device.

While the previous works dealt only with the implementation of new algorithms on available hardware, Wall and Harwin added a high fidelity probe to a standard PHANTOM™ haptic device [55]. The probe was a stylus shaped handle with a loudspeaker-type actuator that generated vibrations along the axis of the handle. This probe was meant to overcome the bandwidth limitations of the standard PHANTOM™ haptic device and was shown to improve the detectability of texture’s orientation, when compared with the original device [144]. The large bandwidth of
this probe (up to 1.5 kHz) allowed a precise representation of frequency based signals, but could not provide enough stiffness to create virtual boundaries as strong as the original PHANTOM™. Moreover, the probe could render vibrations only in 1D, which would be felt along the stylus axis. Nevertheless, Wall and Harwin used the probe to test a new algorithm for texture synthesis based on recorded data. First the geometrical profiles of different textures (mouse mat, sandpaper, and cardboard) were acquired, then the amplitude spectrum of such profiles was computed with the Fourier transform and was used to render virtual textures. To account for inter samples variations of the same materials, the coefficients for the Fourier reconstructions were chosen from a Gaussian distribution. The experiment, carried out with the high frequency probe, showed that, although the subject reported that the virtual surface felt different from the real material, they were able to distinguish between the three materials, confirming the validity of Fourier based stochastic methods.

### 2.5.3 Stochastic Models

Wall and Harwin were inspired by previous works on stochastic modeling of virtual haptic textures.

Initially, Siira and Pai proposed the idea of modeling textures with stochastic models in the time domain [132]; their system is based on the observation that finished surfaces have normally distributed geometrical features. Since the Gaussian distribution is invariant with respect to resampling, the temporal sequence of surface asperities encountered by the haptic device has the same mean and standard deviation of the spatial distribution of the features; moreover, this result is independent from the user velocity. Pai’s algorithm exploited this feature and generated the texture profile as a stochastic sequence in the time domain. The resulting geometric profile is not spatially consistent because different heights can be attributed to the same point on the surface at different times; this algorithm was tested on a Pantograph haptic device and was used to render both a 2D lateral texture as well as a 1D texture over a virtual constraint. In this last case, the lateral force was made proportional to the normal force generated by the virtual constraint.

This assumption of Gaussian distributed features was further investigated by Green and Salisbury in the context of remote sensing of soil properties [52]. A PHANTOM™ based system for acquisition and rendering of virtual textures was used to measure the varying friction coefficient of different sandpaper surfaces; the histogram analysis of the friction showed a Gaussian distribution, whose standard deviation decreased as the grit number grew. A rendering algorithm was also proposed to exploit this statistical property, and it generated a non deterministic, Gaussian, spatially varying friction field, whose mean and standard deviations were computed from the data.

A more complete framework for stochastic textures was proposed by Fritz and Barner [42]; rather than focusing on realism, this method was aimed at generating haptic textures perceptually different from each other. The proposed models were
a combination of three different components: deterministic profiles based on either multivariate Gaussians or sums of sine functions, random processes that perturbed such profiles, and banks of bandpass filters that shaped white noise. The perceptual roughness of Gaussian texture was consistent with previous results, where the bigger the variance the rougher the texture. Users reported that Gaussian textures felt like granite. Fritz and Barner also implemented a volumetric version of their texture algorithm, and its exploration felt like moving through gravel in a container.

Afterward, Pai et al. realized a robotic facility aimed at acquiring a complete virtual model of real objects [115]; their system acquires visual, haptic, and auditory measurements and produces physically based representation of the object properties. In particular, their representation of haptic textures was based on a directional varying friction field, which was computed with autoregressive models identified from the data. This method assumes that roughness perception is not dependent on the waveform of the force signal but only on its statistical features.

Finally, granular synthesis of haptic textures explicitly uses stochastic models to generate haptic textures from a discrete set of spatially localized samples (called grains) [32]. Similarly to other stochastic processes: “...the same area of surface will not have exactly the same texture at different points in time although the perceived qualities will be similar.” This limitation applies to all methods that use stochastic models to generate time varying textural forces, while it does not concern methods that generate random texture profiles and then use deterministic procedures to compute the forces.

### 2.5.3.1 Perceived Instability and Artifacts

Since most haptic research has been developed on the PHANTOM™ haptic device, the limitations of the hardware has greatly affected the quality of the results. Apart from the limited mechanical bandwidth of the device, which was already discussed, artifacts can also be introduced by the synthesis method implemented in the virtual environment and by the controller of the device.

The most comprehensive study on perceptual artifacts related to haptic textures with a PHANTOM™ was conducted by Choi and Tan [20, 22, 23]. These studies discussed the perceptual instabilities of two texture rendering algorithms, based on Massie’s algorithm [98], and on Ho’s [57]. First, the effects of the different algorithms and exploration strategies were studied [15, 17, 19, 20], and three types of instability were described: buzzing, aliveness, and ridge instability. The first term indicates the onset of fast limit cycles due to a non passive control of the device. Ridge instability refers to the feeling of being “sucked” into the textures; this phenomenon is solely related to the texture rendering algorithm, which generates a field independent from the user-exerted force. Lastly aliveness describes a low frequency artifact, different from buzzing, which is caused by large force variations in response of small stylus movements; this last artifact is elusive and could not be pinpointed either in a spectral nor in a temporal analysis of the user interaction with the virtual texture. Ho’s algorithm exhibited both buzzing and ridge instability, while Massie’s
was characterized by buzzing and aliveness. In the same experiments, texture exploration strategies showed a clear effect on the perceived instability. In particular, the action of stroking a texture was less prone to artifacts than free exploration.

In this first round of experiments, Choi and Tan used a variant of Massie’s algorithm which generates discontinuous force fields. As a result, low stiffness virtual environment induced non passive behaviors, thus generating the so-called buzzing. Moreover, no mention to Ho’s corrective measures was made, when discussing his bump mapping technique.

The discontinuity of the force fields is discussed in [16, 22], where both continuous versions of the algorithms are reported. The continuous version allowed stiffer virtual textures, hence partially resolving the buzzing problem, which is not surprising if examined from the control system point of view. On the other hand, aliveness was proved to be independent from the passivity of the haptic rendering, but a precise physical characterization was not found.

In the last experiments the effect of the update rate of the virtual environment was characterized [18, 21, 23]. Control theory had already found a mathematical relationship between update rate and stiffness of the virtual environment, but this framework is not discussed in Choi and Tan’s papers. Moreover, their results are somehow in contrast with control theory, a topic that is not mentioned in their conclusions. Nevertheless, the experiments confirmed the beneficial effects of higher update rates on buzzing; the paper concluded with the observation that higher update rates did not affect the perception of virtual textures, as long as no buzzing was present. According to the authors, the advantages of fast update rates are related only to stability and passivity concerns.

In general, Choi and Tan employed, at most, five subjects in their experiments and sometimes as few as two. The evaluation of their results must take into account the limited data available, as well as the fact that only some of the subjects participated in all the studies. Despite these limitations, this research offers a first important insight on the problem of rendering force feedback haptic textures; however, the strong focus on perceptual qualities and the limited analysis of the engineering aspects of the rendering system does not allow for a quick generalization of these results, because the influence of the haptic device is not sufficiently discussed and the algorithms are not linked to control theory.

Tan’s group continued the research on haptic textures with the ministick, Sect. 2.2.2.6 at page 12; their research provided a frequency analysis of perception of virtual haptic textures [25] and on the discriminability of real and virtual textures with such device [77]. In the first of these papers, users were able to discriminate sinusoidal textures from square waves based on the harmonic components of the signal. The second paper discusses the difference in detection thresholds between real and virtual textures: because the thresholds of these two cases is similar they conclude that the ministick is adequate for texture perception studies. While no argument can be made against this claim, few engineering characteristics are provided for the ministick, for example its bandwidth; even the resolution of the device is not clearly indicated (authors claim an astonishing 1 µm resolution in contrast with the 10 µm cited in the design paper). As long as these aspects are not clarified the research carried out with the ministick cannot be readily extended to other devices; in
addition, the investigation of the somatosensory system carried out with such device cannot be quickly accepted, due to the unavailability of the device’s properties.

2.5.4 Perceived Roughness of Virtual Textures

In a two paper series Lederman and Klatzky assessed the perception of virtual vis-
cous textures. In the first study with a Wingman Haptic mouse (a 2D pantograph style haptic device designed for the video games enthusiast), they found that by varying the resistive force it is possible to elicit the sensation of roughness. The space was partitioned in resistive strips (called ridges) separated by non resistive strips (called grooves), in a pattern mimicking the square gratings used in previous studies. The roughness estimated were completely different from the bare finger and probe case: users probably relied on the total resistance of the surface to rate roughness, but the authors were still able to detect significant effects of the microgeometry. In the second series of experiments, carried out with a PHANTOM™, they confirmed that users rated as rougher surfaces that offered more resistance: the coefficient of viscous friction, in fact, was the single most important effect; but roughness arises in function of the variations in viscosity and not of the mean resistive force. Finally, with the PHANTOM™ the spatial determinants had either not significant or very small effects. Due to the difference in fidelity of the two devices, a direct comparison of the results is difficult.

When exploring the visuo-tactile multimodal perception of virtual roughness, Drewing and colleagues found that the geometric model proposed by Lederman is also valid for virtual textures: when a PHANTOM™ haptic device is used to simulate a point contact on a surface with raised dots, the virtual probe has zero radius hence, according to the model, roughness perception should decrease as inter-element spacing increases, and this is the case [37]. A similar trend was found for virtual sinusoidal gratings both in blind and non-blind subjects [79].

2.6 Conclusions

This literature review shows that textures are a fundamental element for the experience of haptic virtual environments. Although many studies deal with the perceptual properties of real textures, currently available haptic devices are a major obstacle to the investigation of the perception of virtual haptic textures. Because of their specifications, haptic devices can generate stimuli far stronger than the perceptual thresholds identified by research in the psychophysics of touch.

This problem is compounded by the lack of a framework that would express the rendering capabilities of the haptic devices; also, the algorithms used to convert geometric profiles (or measurements) in force fields have not been discussed in the context of passivity/stability, leaving uncertainty on their performance: a notable
example are the artifacts reported by Hong Tan and colleagues that, without a clear characterization of the device and the algorithm, cannot be easily interpreted [17].

Most of the passivity/stability results in literature regard the simple example of a linear unidimensional virtual wall; haptic textures are multidimensional, non-linear, and possibly non-conservative force fields, a combination that was never investigated by haptic researchers. As a result, the passivity properties of virtual textures are not known.

If these challenges were solved, it would be finally possible to compare the perceptual properties of different algorithms in relationship with the properties of the device used; for example, once passivity is ensured and the correct rendering of the textures is guaranteed, perceptual artifacts could be reliably classified and linked to either the characteristics of the device or to the parameters governing the haptic algorithm, thus simplifying the design process of the virtual environment.

References

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2 Literature Review


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