A vibrotactile approach to tactile rendering

Abstract  While moving our fingertip over a fine surface we experience a sensation that gives us an idea of its properties. A satisfactory simulation of this feeling is still an unsolved problem. In this paper, we describe a rendering strategy based on vibrations that play an important role in the tactile exploration of fine surfaces. To produce appropriate excitation patterns we use an array of vibrating contacor pins. Similar to the colour model in computer graphics, we simulate arbitrary vibrations as a superposition of only two sinewaves. Each sinewave is intended for the excitation of a specific population of mechanoreceptors. We carried out first tests of our rendering strategy on Brownian surfaces of different fractal dimensions.

Keywords  Tactile rendering · Vibrotactile perception · Bistimulus theory · Brownian surfaces

1 Introduction

It is little known that the haptic sensory organ is the first one among the senses to be developed in a human embryo. However, it is well-known that in the virtual reality field systems supporting human tactile and haptic perception were the last ones to be investigated with some success and the whole field is far away from having reached some maturity. Our haptic and tactile sensory system has receptors in every part of the human skin and covers our body completely. As opposed to the visual and the hearing senses, the tactile sense cannot be shut down by blocking incoming signals as we can do it with the visual or acoustic senses by closing or covering the eyes and by using ear plugs. In any case, our haptic perception system is always active in all parts of our skin and this global sensory system communicates to us all the time comprehensively the mechanically felt sense of our very physical existence. All our senses work together in order to communicate to us relevant information that helps us to construct and update our internal model and our local habitat. Clearly, that internal model together with the permanent update enables us to be actively operational, including motion planning and performing very basic actions like grasping and touching and actively exploring any object we encounter.

Probably we are still at the very beginning of understanding and modelling appropriately all the relevant complex cognitive systems involved to accomplish the aforementioned basic orientation tasks. Here the problem to understand the basic cognitive systems may be split into several subtasks. One of them may concern the function and meaning of the local receptors of the outside world, the other subtask, which is perhaps even more difficult, may concern models explaining the global system functions that integrate the perception of the incoming signals to a global impression or global image. This paper focuses on tactile perception and employs and summarises
some partly recently established knowledge on functions of the tactile receptors in the human skin in Sect. 2. For the experiments described in this paper some insights concerning those receptors are especially important.

Tactile perception is usually considered crucial to complement the visual perception by confirming the feeling of what we see. Based on the understanding that this interaction between visual and tactile perception is extremely important, this paper reports on experiments where visual information contained in surface textures has been transformed into expected tactile signals conveying equivalent or at least compatible tactile perceptions occurring when touching those surface textures. Hence part of this paper deals with the generation of tactile signals creating the perceptions that are appropriate in the context of surface textures. To achieve the latter, some simplifying assumptions are made. The visual appearance of the texture of the surface (e.g., a textile) may have so-called symmetric well-ordered components created by repetitive structures. To classify the latter we consider here an important subclass of periodic 2-D geometric structures. Namely, we assume that the repetitive structure is created by a periodic parallel transformation of an elementary parallelogram that will be detected automatically. To this end, Sect. 5.1 describes strategies employing a combination of geometrical and stochastic methods to discover the elementary shape parallelogram. The latter basic geometric structure may then be used in repetition to create a simplified periodic structure. This may, e.g., happen by creating a dent texture using, e.g., a shape from a shading method to describe, e.g., a basic ovoid cap whose repetition creates the periodic structure.

A generally accepted taxonomy of textures (cf. [16]) assumes that apart from ordered components we can also recognize disordered unstructured components in surface textures. Considering the grey value image representing a surface texture, according to our model: In our human visual perception the unstructured parts of the latter grey value image are associated with different degrees of roughness that one would expect to feel if one were to touch the physical surface creating the particular surface texture. Those different degrees of expected roughness are classified by a parameter defined by a fractal dimension of the grey value image representing the surface texture. Employing the stochastic concept of Brownian motion it is possible to create height functions describing Brownian surfaces whose specific fractal dimensions can be prescribed by some stochastic parameters. The Brownian surface representing a surface with a specified roughness (fractal dimension) is finally used to create a tactile signal experienced by a person probing the Brownian surface with a stylus. More precisely, the person moves with a stylus over a virtual surface created by a phantom, i.e., a force feedback system that makes the user feel some resistance in case the probing stylus touches the virtual surface located in 3-D space. It is quite interesting that some preliminary experimental studies indicate that the perceived roughness intensity appears to increase strongly monotonously with the increase of the fractal dimension of the generated Brownian surface.

The tactile receptors in the human skin include the so-called pacinian and non-pacinian receptors. It is well-established that those two different receptors can be stimulated by vibrations. Moreover, it is well-known that the excitation intensity of that stimulation depends on the vibration frequency. According to our model in Sect. 5.4 there exist two different curves for the pacinian and non-pacinian receptors, respectively, describing for each vibration frequency the corresponding excitation intensity of the specific receptor type. The latter phenomenon has a counterpart in visual perception. In the tristimulus model (cf. [6]) the eye, or more specifically the retina, has three different receptors responding with different intensity to light with a given frequency. For each of the three visual receptors there exists a function obtained from measured data describing the stimulus intensity depending on the respective power associated with a specific frequency of the light. Practically valid models describing the type of colour perceived as stemming from the light reaching the human eye assume that the perceived colour is determined by the sum of the stimulation intensities experienced by all three receptors (cf. [4]). This implies the validity of the well-known RGB model. In the latter model, the total stimulation intensity is created by using light signals built up with three different colours corresponding to three basis frequencies only, where each of the three frequencies must be chosen with an appropriately adjusted energy. The model assumptions here lead to a three-dimensional model space describing all possibly perceivable colours. All those colours can be generated by “equivalent combinations” of any three different light sources, each of them radiating a different type of light with an appropriately chosen power depending on the power associated with the frequency distribution of the given three light sources. In this context it is only relevant that the three generated power/frequency distributions correspond to three linearly independent vectors (basis colours) representing equivalence classes of basis vectors in a 3-D vector space defined by vectors representing power/frequency distributions. This means that scaling each of the latter basis colour (light source) vectors with one appropriate positive real number will create any given total stimulation intensity perceived by the three receptors. This additive vector space concept useful for describing colour models is in Sect. 5.4 applied for modeling tactile sensations using two generating frequencies only. Analogue to the RGB model, we assume here that a “tactile colour” impression created by any vibration frequency distribution can be generated equivalently by the appropriately scaled intensities of two generating vibration frequencies (40 and 360 Hz) only. This is our current hypothesis in this paper, which still needs further experimental validation.