Tactile rendering of virtual objects

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Abstract

Using the hands for active exploration of an object can provide information about the object's surface texture and about surface features such as edges and corners. In a virtual scenario, such information can be delivered by an array of contactors on the skin. Tactile rendering is a software description of surface properties which specifies appropriate drive signals for the array during active exploration of a virtual object. The design of such an array is discussed, together with a possible strategy for tactile rendering

1. Introduction

The tactile aspects of a virtual object may be represented as a spatial distribution of synthetic touch sensations over the fingertips. These sensations can provide information about the surface texture of the virtual object and about the contact between object and skin (contact area and position of edges/ corners).

To excite the skin mechanoreceptors, an array of contactors on the skin may be used to provide spatiotemporal patterns of mechanical input to the skin surface. Encounters with virtual objects, during active exploration of the workspace by the user, produce appropriate patterns of tactile stimulation on the fingertips.

When presenting the tactile aspects of a virtual object, the intention is not to reproduce the significant features of the small-scale surface topology of the object in terms of a virtual surface. Instead, the intention is to reproduce the perceptual consequences of small-scale features of the surface topology, i.e., appropriate excitation patterns over the various populations of touch receptors in the skin.

2. Design of a stimulator array

The optimal spacing of contactors in a stimulator array is determined by the spatial acuity of the sense of touch – around 1 mm on the fingertip [1]. However, a contactor spacing of 1 mm equates to around 100 contactors over the fingertip, each of which requires independent control. This is realistic for a passive (non-moving) device [2, 3] but is difficult to implement in an active device, for which a spacing of around 2 mm (i.e., around 25 contactors on the fingertip) may be a better choice. (There is some evidence [4] that perceptions available from an array with 2 mm spacing are not very different than those from an array with 1 mm spacing.)

In order to produce "realistic" touch sensations, a working bandwidth of around 10 to 500 Hz is required for the drive mechanism of each contactor, corresponding to the frequency range over which the various mechanoreceptors are sensitive [5]. Pacinian receptors are expected to respond most strongly to frequencies in the upper part of this frequency range (100 to 500 Hz, say); stimulation at lower frequencies is expected to stimulate mainly non-pacinian receptors. "Comfortable" sensation levels are produced by amplitudes of a few microns at frequencies around 300 Hz and a few tens of microns at frequencies around 50 Hz.

Design requirements for contactor spacing, working bandwidth and output amplitude may be satisfied by a variety of electromechanical drive mechanisms. Hafez and colleagues [6, 7] have developed arrays of drivers, based on shape-memory alloy or moving-coil technology, which apply normal forces to the skin. Hayward and colleagues [8, 9] have used piezoelectric-bimorph actuators to apply tangential forces. Summers et al. [10] have used similar actuators to apply normal forces, as have Kyung et al. [11].

The stimulator array developed in the ENACTIVE network and the HAPTEX project is shown in Figure 1. Piezoelectric bimorphs are used to drive 24 contactors in a 6 × 4 array on the fingertip, with a spacing of 2 mm between contactor centres. It can be seen that the drive mechanism is placed to the side of the finger and ahead of the finger, rather than below the contactor surface (which, at first sight, appears to

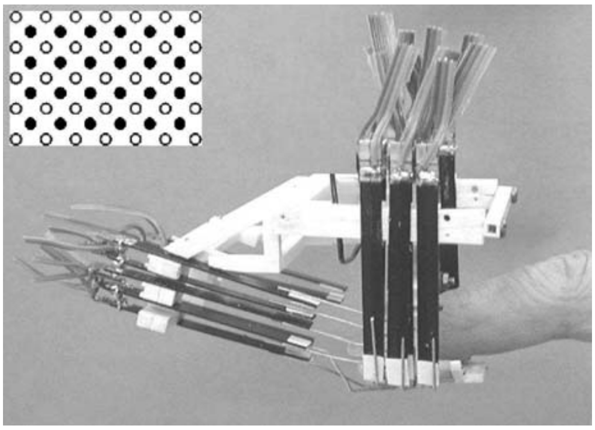

Figure 1. Stimulator array developed in the ENACTIVE network and the HAPTEX project. The contactor surface lies under the finger – contactors are driven by piezoelectric bimorphs (appearing as black rectangles). The inset shows the arrangement of 24 moving contactors, interspersed between the fixed contactors which transmit global forces to the fingertip.

be the most convenient location). With one such array on the index finger and another on the thumb, this positioning of the drive mechanism allows the finger to move close to the thumb so that a small virtual object can be manipulated between the tips of finger and thumb.

The contactor surface delivers to the fingertip the small forces associated with touch stimuli, but it must also deliver the larger forces associated with the overall mechanical properties of the virtual object, represented by the output of a force-feedback system. However, the moving contactors which provide touch stimuli are driven by delicate piezoelectric mechanisms and so they are unsuitable for delivering the force-feedback output, which may involve forces of considerable magnitude. Consequently, the contactor surface includes an additional set of contactors ("fixed" contactors – see inset to Figure 1) which deliver the force-feedback output, in parallel with the tactile stimulation from the moving contactors.

3. Drive signals for a stimulator array

During active exploration of a virtual tactile environment it is necessary to generate in real time a drive waveform for each contactor of the stimulator array(s) which are in contact with the user's fingertip(s). The amount of data which must be generated "on the fly" is thus considerable. For example, the ENACTIVE/HAPTEX system has 24-contactor arrays on finger and thumb, requiring 48 analogue drive signals, in principle each with a bandwidth of around 500 Hz. However, because of the limited temporal resolution, frequency resolution and phase sensitivity of human touch perception [12, 13, 14, 15, 16], there are possibilities for a significant reduction in the data flow. For example, each drive signal may be reduced to the sum of a limited number of sinusoidal components, distributed across the working bandwidth (10 to 500 Hz – see above). The drive signal may then be simply specified in terms of the amplitudes of these components, which require an update every 20 ms or so.

In the ENACTIVE network and the HAPTEX project, a cut-down version of this scheme has been developed, in which the drive signal to each contactor is the sum of components at only two frequencies: 40 Hz and 320 Hz. Following the suggestion of Bernstein [17], the higher frequency was selected (at 320 Hz) to target pacinian receptors and the lower frequency was selected (at 40 Hz) to target non-pacinian receptors. Each drive signal is specified by the sinewave amplitudes A_{40} and A_{320} of the two signal components. These are updated every 25 ms (once per cycle for 40 Hz, once per 8 cycles for 320 Hz). A virtual tactile surface is specified in terms of an amplitude map for each of the two frequency components that make up the stimulus.

4. Tactile rendering

During exploration of a virtual tactile environment a drive waveform is specified for each contactor of the stimulator array(s) – see above. A significant problem is the current lack of knowledge on the origin and nature of excitation patterns in real situations of tactile exploration of an object. The mechanical stimulation of a given receptor has a complicated relation to the mechanical properties and topology of the object's surface, to the mechanical properties of the skin and its local topology (especially skin ridges, i.e., fingerprints), and to the precise nature of the exploratory movement (speed, contact pressure and direction). Although it may be possible to produce an accurate software model of an object's surface, it is not at present possible to augment this with an accurate model of the skin/surface interaction. This situation may change in the near future: research is currently underway to develop an "artificial finger" with embedded transducers to mimic mechanoreceptors; improved finite-element models may also provide useful data.

For the particular case of the manipulation of textiles, the situation is more promising: Information on the nature of the mechanical input to the skin's mechanoreceptors is available from the Kawabata system for evaluation of textiles [18]. This provides a range of data on the textile sample under test, including surface roughness and surface friction profiles which are direct measures of the mechanical excitations produced when a probe is moved over the textile surface. The probe and associated instrumentation are designed so that the measured quantities correlate well with subjective assessment of the textile surface. Hence the Kawabata surface measurements provide an approximation to the "perceived surface", i.e., the surface after it has been "filtered" through the surface/skin interface. They thus provide a good basis for specifying drive signals for a stimulator array, in order to provide the tactile component for a virtual textile. Kawabata measurements have been used in this way by Govindaraj et al. [19]; they have also been used to provide source data for the tactile rendering developed within the HAPTEX project on virtual textiles. Preliminary work on tactile rendering within the HAPTEX project is described by Allerkamp et al. [20]. More recent ideas are presented below.

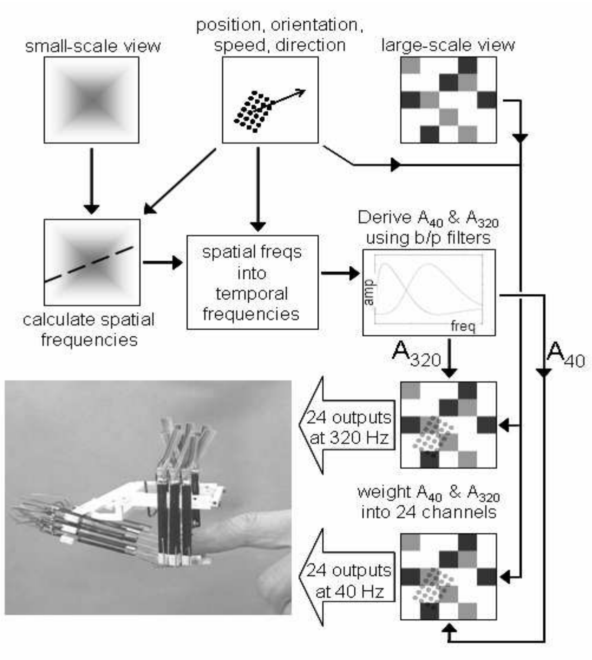

Figure 2. The scheme for tactile rendering which has been developed in the HAPTEX project

Figure 2 outlines the scheme for tactile rendering, by which the drive signal to each point in the stimulator array is specified in terms of amplitude A_{40} at 40 Hz and an amplitude A_{320} at 320 Hz (see above), and these amplitudes are in turn specified by the interaction between the virtual object and the exploratory movements of the user. For each digit, the tactile renderer generates 24 drive signals for the 24 contactors of the stimulator array. Input and output are specified in 25 ms timesteps. The input data are:

- a small-scale description of the object surface, represented as 2D *k*-space, derived from a pseudo-topology at around 0.01 mm resolution over an area of a few mm^2;
- a large-scale description of the object surface: a representation of the non-uniformity of the surface, specified as pseudo-amplitudes at 1 mm resolution over an area of several tens of cm^2;
- position and orientation of the finger pad on the virtual surface;
- speed and direction of the movement of the finger pad over the virtual surface.

The operation of the renderer is as follows: Taking account of the direction of movement, a spatial-frequency spectrum is calculated from the 2D *k*-space of the small-scale description of the virtual surface. Information about the speed of movement of the finger pad is used to convert spatial-frequency components into temporal-frequency components. The resulting temporal-frequency spectrum is reduced to only two amplitudes, A_{40} and A_{320}, by application of appropriate bandpass filter functions, corresponding to the 40-Hz and 320-Hz channels. (It should be noted that the signal-processing operations to this point may be performed only once per 25-ms timestep, i.e., they may be common to all 24 output channels.) Amplitudes for the 40-Hz component in the drive signals for each of the 24 channels are obtained from A_{40} by weighting according to data from the large-scale description of the virtual surface, for the 24 locations on the finger at which the contactors of the tactile stimulator are positioned. Similarly, amplitudes for the 320-Hz component in the drive signals for each of the 24 channels are obtained from A_{320} by weighting according to data from the large-scale description of the virtual surface. (Note that, in principle, different large-scale descriptions of the virtual surface may be used in the 40-Hz and 320-Hz channels, to allow for the observed difference in spatial resolution on the fingertip at the two frequencies.)

5. Discussion

When using stimulator arrays and rendering schemes as described above, the intention is to present time-varying spatial patterns of tactile stimuli which have two perceptual dimensions: one relating to intensity and one relating to spectral distribution. In order to establish the potential for such a system, it is necessary to determine whether a two-dimensional perceptual space can indeed be created in this way – it is very likely that the intensity dimension is available to the user, but less obvious that the spectral dimension is available. However, recent results from Kyung et al. [21] demonstrate that test subjects can detect changes of frequency when stimuli are presented via a stimulator array in an active task, so it seems that spectral information is indeed available in such a scenario.

Initial evaluations of the ENACTIVE/HAPTEX system (Figure 2) also suggest that a 2D perceptual space can be achieved. For uniform stimuli (i.e., stimuli with no spatial variation over the skin), the spectral dimension appears relatively weak – changes in spectral balance at constant subjective intensity tend to be less noticeable than changes in subjective intensity at constant spectral balance. (There are perhaps 4 to 5 discriminable steps of spectral balance along an equal-intensity contour.)

Perhaps the most interesting observation when using the ENACTIVE/HAPTEX system is a strong interaction between the perceived spatial aspects of the texture and the stimulation frequency. If the stimulation frequency is changed from 40 Hz to 320 Hz, the perceived sensation during active exploration changes much more if the texture is spatially non-uniform than if it is spatially uniform. It is clear that the spectral dimension provides a significant enhancement to the available range of tactile sensations. Experiments are currently under way to investigate the perceptual space in detail, and to further investigate the interaction between the spatial aspects of the texture and the nature of the perceptual space.

Using physical data from a selection of real fabrics (obtained with the Kawabata system), the ENACTIVE/HAPTEX system has been used to simulate the tactile aspects of those fabrics. Given the apparent mismatch between the real situation (fingertip touching a textile) and the virtual situation (fingertip touching the metallic contactors of a stimulator array), results are surprisingly good – in some cases test subjects are able to match real and virtual textiles in terms of their tactile qualities.

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