Multi-modal Interaction System to Tactile Perception

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Abstract. Haptic simulation of materials is one of the most important challenges in human-computer interaction. A fundamental step to achieve it regards the definition of how human beings can encode the information acquired by different sensorial channels' stimulation. In this context, this paper presents the study, implementation and evaluation of a multi-modal cutaneous feedback device (CFD) for the simulation of material textures. In addition to tactile stimulation, two further sensory components (e.g. eyesight and hearing) are integrated to support the user to better recognize and discriminate different classes of materials and then, overcome previous identified drawbacks. An experimental protocol is tuned to assess the relevance of each stimulated channel in material texture recognition. Tests are carried out with real and virtual materials. Result comparison is used to validate the proposed approach and verify the realism of simulation.

Keywords: Elettrocutaneous feedback, haptic, multi-modal stimulation.

1 Introduction

Haptic interaction still represents one of the most important issues in human-computer studies due to the effects that touch has on product experience. Systems are classified in two main areas: kinesthetic and cutaneous [3]. Studies aim to develop solutions to recreate tactile stimulation in order to improve the user experience of virtual prototypes. However, most of them do not deepen the correlation among all involved senses (sight and hearing) that equally contribute to user sensations. The importance of multisensory interaction is demonstrated by the numerous researches about virtual reality environments where the integration of haptic, visual and auditory feedbacks are looked for to increase user perception of the outside world.

In this context, this paper presents the study, implementation and evaluation of a cutaneous feedback device (CFD) for the simulation of material textures. In addition to tactile stimulation, two further sensory components (e.g. eyesight and hearing) are integrated to support the user to better recognize and discriminate different classes of materials and then, overcome previous identified drawbacks.

The current research is a step forward a previous one, focusing on the development of an electrotactile device for texture simulation [1]. The main novelties, descripted in this paper, regard:

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- Improvement of tactile stimulation through the addition of mechanical vibration to stimulate deep skin mechanoreceptors;
- Addition of audio components through the reproduction of the sound emitted by a finger rubbing on the material and the subsequent application of an auralization algorithm;
- Extension of the 3D visualization by the implementation of a virtual prototyping-based system to represent human interaction with the material.

The experiments were organized in two phases. In the first one, system performance is tested by assessing responsiveness and synchronization. In the second phase, an experimental protocol is applied to verify if users recognizes the class of material. For each user, tests are replicated by changing the number of involved sensory channels.

2 Background

Haptic systems are classified in two categories: kinesthetic one provides to reproduce force feedback, while in the tactile one cutaneous feedback was applied.

In the field of cutaneous feedback, most researches focus on the development of devices producing stimuli of a single nature [20-24]. Three classes of tactile stimulations can be recognized:

- mechanical stimulation through vibration of physical elements or through the use of ultrasonic waves [20-22],
- electrical stimulation through application of a current flow or an electric potential on the contact surface [23-24];
- thermal stimulation through heating of the contact surfaces.

About the mechanical stimulation, Fukuyama [20] proposes a Shape Memory Alloy (SMA) that accepts a pulse-signal to generate a vibration in accordance with the pulse frequency of the signal. He developed a vibration actuator to create the tactile stimuli. Ikei [21] presents a tactile display, which has fifty vibrating pins to convey the surface texture sensation of object surfaces to the user's fingertip. Finally, Takasaki [22] proposed a tactile display using surface acoustic wave (SAW): a glass substrate, which is non-piezoelectric material, is combined with a piezoelectric material. These approaches allow the system to recreate a cutaneous feedback, but its granular density is so low that it is not able to reproduce the physical properties of a material surface.

On the other hand there are many contributions in the implementation of electrical stimulation. Yamamoto [23] developed a tactile display with a thin conductive film slider with stator electrodes that excite electrostatic forces. Olivier et al. [24] developed TeslaTouch, a tactile platform based on principle of electro vibration, which allows the creation of a broad range of tactile sensations by controlling electrostatic friction between an instrumented touch surface and the user's fingers. In both cases, the electrical stimulation is based on the properties of friction and does not implement the other key characteristics of surface texture.

Some studies focus on the correlation between the physical properties of materials and cutaneous stimuli for texture simulation via cutaneous feedback devices. Kyung [14] e Altinsoy [9] studied the possible correlation between the roughness of the materials and the amplitude and frequency of the vibrotactile stimulus; Hughes [11] investigated how the gradient density affects decoding of the texture by the tactile perception. Some researches recognize the key role of friction in the reconstruction of an actual perception of a given material. Developed devices can reproduce a variable friction of the user interface through mechanical vibrations [5, 15] or through the variation of an electric voltage applied on the contact surface [12].

Other important studies have been conducted to determine the properties and functions of the Low-Threshold MechanoReceptors (LTMRs), indicators of the sensitivity threshold of the human being [8]. In summary, many studies aim to investigate how the human being encoded information from the tactile channel coming from the real world.

In sensorial stimulation, an important issue regards the influence of different sensory channels on the perception of the outside world by the human being.

Calwell [10] proposes a glove providing both a mechanical and a thermal stimulus: in this case the multimodality is achieved by combining two types of stimuli with the aim to improve haptic interaction. Otherwise, none additional sensory channel is involved. Vitense [19] developed a system with multiple feedbacks (auditory, haptic and visual). The three considered stimuli have not a physical correlation between each other, but are implemented in order to provide enhanced user experience in performing tasks through a graphical interface. In addition, the system, designed to be a support for the visually impaired, is focused on the creation of a GUI that provides additional sensory channels as a force feedback (haptic) and earcon (auditory) to give or an enhanced use experience or an alternative user interaction mode.

A great contribution to multimodal sensory integration is provided by the works of Spence [17] that studied the importance of synchrony of stimuli of different sensory channels in a multimodal system and Turchet [18] that explored the relevance of semantic congruence of a bimodal system (haptic and auditory).

About the implementation of multisensory stimulation, a further key element seems to be how to make the developed technology wearable. For instance, Burch, D. et. al. [4] use an active display in combination with the wearable thimbles implementing a tactile stimulation varying according to current finger position. Calwell [10] uses a glove to implement a multimodal system described above. Although most systems appear effective, the use of a wearing device makes them intrusive and not barrier free. Their insufficient usability often influences user perception of materials.

Most analyzed devices stimulate one-by-one sensorial channel and do not investigate the cross-sensory connections of touch, sight and hearing in material discrimination. Taking into consideration current research drawbacks, the present work proposes a multi-modal system, called Ipertouch, able to differently stimulate all sensorial channels to achieve a proper texture simulation. The implementation of the system passes through a series of experiments on real material samples involving differently blind users to verify the mutual influences of senses on material perception, determination and discrimination. The lack of sight and hearing allowed users only to determine the material class the sample belongs to, but not to identify texture properties.

3 System Development

Ipertouch is the evolution of a previous developed platform for the single cutaneous stimulation [1]. The previous platform was formed by a tactile display that reproduces the spatial profile of the surface texture of real materials. This platform was driven by a PC and is used in passive touch mode (finger is placed on the touchpad and the electrical signal is done flowing below it). Previous researches focused on the elaboration and processing of roughness profiles. Tactile signals derived from scanning of real materials and their subsequent processing and mapping current [2]. Therefore, signals used to implemented tactile stimulation are connected with real properties of materials.

In this work, we have completed the simulation system adding a mechanical vibration through a shaker, a signal generator and a control software developed by LabView, adding an audio feedback with a record of rubbing finger on the material processed with a spatialization algorithm and developing a visual feedback software to show the finger movement on the chosen material.

This platform is created as a tool to reproduce tactile stimuli reconstructing texture properties of real materials: it is composed of a hardware component that can provide the stimulation of the three sensory channels and a software component able to manage the information of each class of material that is selected and the synchronism of information about every three sensory channels. The following describes in detail the different elements of the system.

The hardware platform is composed of three basic elements representing the user interface through which the three sensory channels are stimulated.

The conception of tactile component is based on the principle of selection stimulation [25]: touch is stimulated through two different types of signals, an electric and mechanical one, to excite all types of mechanoreceptors located at different skin layers.

In detail, the platform is composed of a pad with 256 pin electrodes arranged as a 32x8 grid to spatially distribute the current flow. The electrodes are 1-mm diameter and they are 2.5 mm away. The processing unit is a multiprocessor platform consisting of one master and four slaves. Two force sensors (Honeywell FSS-SMT) are located under the tactile pad layer to change signal amplitude based on the pressure of the finger. The pad is mounted on a shaker (PCB K2004E01) driven by a signal generator (Hantek 1025G) linked on PC. The shaker provides to give the high frequency (HF) stimulation to the users.

A Head Mounted Display (HMD) WRAP920AR by Vuzix connected to the Computing Hardware is used to supply auditory and visual stimuli. Figure 1 shows the system architecture and main modules.

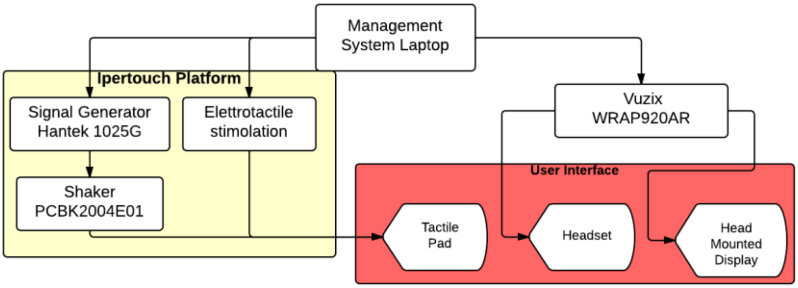

Fig. 1. Hardware Architecture of Ipertouch platform

The software components are shown in Figure 2. The human-machine software manages information and processes I/O data.

The system retrieves information to be processed from a database containing the initial roughness profiles, corresponding electrical and mechanical signals, pictures of material texture used as maps for graphic rendering and finally recorded sounds. Collected data are the outcomes of pre-processing operations carried out in Matlab R2013a to obtain proper signals for the different feedback devices. For instance, roughness profiles are split through low-pass and high-pass filtering operations to prepare the signals for both electrical and mechanical stimulation means. The cut-off frequency of filters is set to 250 Hz. An additional selective filter is applied on low frequency (LF) signals to eliminate the DC component. These actions were taken to ensure user safety in the electric signal.

The recording of sounds emitted by a finger rubbing on real material samples is carried out in semi-anechoic chamber with a 15dB background noise. The acoustic signal required a pre-processing due to the fact that the microphone was applied near the sample material during the registration. An auralization algorithm [7] is used first to process the audio records and then to add localization cues to the sound signal.

Finally, material visualization is achieved by representing a virtual hand sliding on a plane where the material texture is reproduced. The software has a computer graphic engine that renders the corresponding texture on the 3D object according to the class the configured material belongs to. The hand movement speed is the same of the sliding of the electro-mechanical signals and of the recorded audio. This setting guarantees the absolute semantic congruence between the different sensory channels.

The software is arranged into two parts. The first one ensures the synchronization of the signals reproducing the surface texture with the LF signals and HF signals. It is developed in CVI LabWindows to handle low-level commands and to assure the integration among the various hardware components (i.e. pad electrotactile, shaker and signal generator). The second one manages audio and video signals. It is implemented by adopting VB. NET programming language. The two software modules communicate with each other via a TCP-IP connection that is established automatically when the user starts with the application.

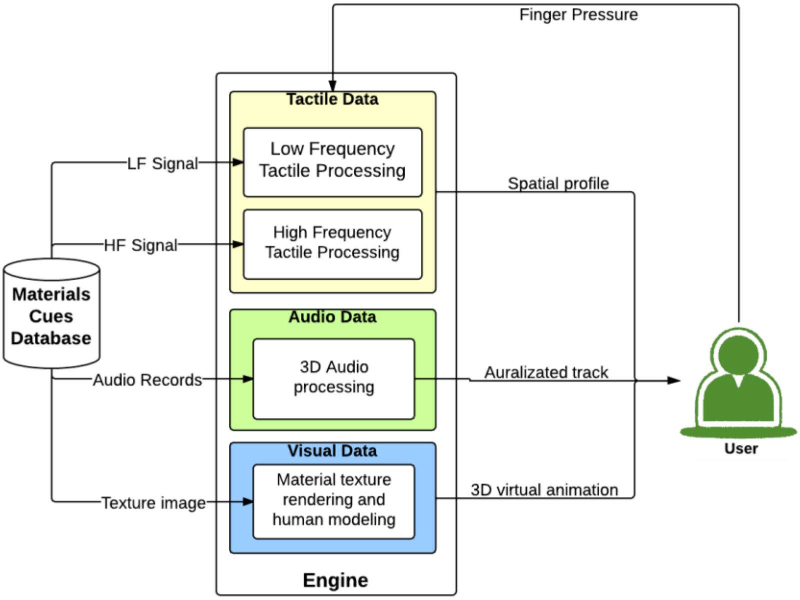

Fig. 2. Software architecture of Ipertouch Platform

4 Experiments and Results

In the experimental phase, two types of tests are conducted. The first regards the verification of system performance through the measurement of two parameters: responsiveness and synchronization. The second consists in evaluating the weight of three sensory channels through two experimental protocol.

In both experiments, testing sessions involved 20 participants (different persons for the two tests), 14 male (70%) and 6 female (30%). They were aged from 25 to 40 years old and the user sample has an average age of 32 years. Users were unaware of testing purposes and system functionalities. No user has finger sensibility problems.

System latency allows the analysis of responsiveness. It is achieved by measuring the time:

- from the moment when the user places his/her finger on the pad to the moment the system starts with the simulation and the user feels tactile sensations;
- from the moment the microcontroller varies the intensity of cutaneous stimulation according to finger pressure to the moment the user receives a feedback.

Times are measured from user input to completion of the system reconfiguration by a software routine in background. The management of the logic through the use of a microcontroller master and four slave controllers allows the system to perform operations in parallel, thus avoiding the congestion in the management of the operations. Average latency time results to be 5 ms in the start simulation, and 1 ms in the system reconfiguration.

Synchronization regards the simultaneous and coherent reproduction of three feedbacks. Software plug-in is developed to measure if the time of audio reproduction is coherent with the time of the texture visual representation and the signal speed. Tests shows an average time shift of 4.45 ms. Then a control routine is developed to realign the three signals in case of a time shift greater than 5 ms at the end of each cycle.

The efficiency of TCP-IP communication is critical to keep under control as tactile, visual and auditory components are not constantly synchronized, but with regular intervals. However, the TCP-IP connection results to be efficient because information is confined to a minimum of exchanged packages. The stability of connection is then ensured by an automatic routine that allows the reconnection and the automatic synchronism.

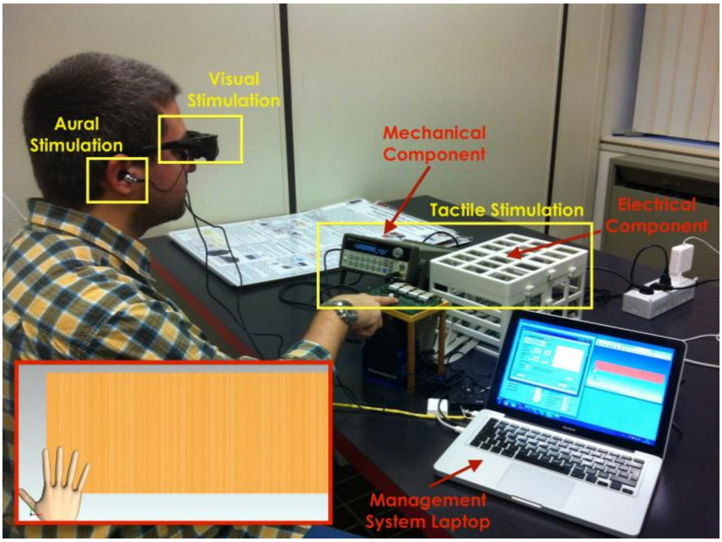

Fig. 3. View of setup test

In the second phase, user tests are carried out to verify material recognition. Experimentations are repeated on real and virtual materials in order to compare user sensations. The experimental protocol is the same adopted in [1].

First, a pre-testing procedure is necessary to set the system properly and calibrate the provided signals according to the user skin properties (electric impedance, humidity, saturation). Compared with the platform shown in [1], the calibration procedure has been automated, allowing the determination of the sensitivity threshold of the user through a simplified operation.

About material generation, ten sample materials were analysed for this study. Materials are classified in four classes: Paperboard, Wood, Textile Fabric and Rubber.

An experimental protocol is set to carry out first an absolute card-sorting experiment to assess material class discrimination in order to measure user ability to associate a tactile sensation to a given virtual material. The user receives virtual stimuli and makes judgments about which the correspondent real material class is.

Each user is submitted to 10 repetitions for each testing session and experts recorded and observed user's answers and behaviour. The test is carried out as follows: (1) the expert randomly chooses one material and communicates with the operator, (2) the stimulus is submitted to the user for 10 seconds at least (the user can ask for some more time if needed), (3) the user is asked to assign the material class. This procedure is repeated for the channel combination shown in Table 1.

Table 1. Results of Absolute Card–Sorting Test

	1	2	3	4
Touch	●	●	●	●
Auditory		●		●
Visual			●	●
Recognition Rate	**47.20%**	**69.50 %**	**75.43 %**	**83.42%**

The test results are relevant: in the first experiment, combining the sensory channel, the recognition rate increases from 47.20% (only touch) to 83.42% (three channel on). Significant results are the comparison between contributes of auditory and visual feedback (2-3): the visual stimulation reaches a higher recognition rate than auditory one.

Table 2. Results of Comparative Card–Sorting Test

	1	2	3	4
Touch	●	●	●	●
Auditory		●		●
Visual			●	●
Discrimination Rate	**76.30 %**	**79.20 %**	**88.25 %**	**90.37 %**

A subsequent experiment follows a comparative card-sorting procedure. The test is carried out as follows: (1) the expert randomly chooses one or two materials and communicates with the operator, (2) the first stimulus (real) is submitted to the user for 10 seconds at least (the user can ask for some more time if needed), (3) the second stimulus (virtual) is then submitted in the same way, (4) the user is asked to judge if it differs from the first or not.

In the second experiment, the users able to compare real and virtual material up to a maximum of 90% (76% only touch), as shown in Table 2. Trend of Experiment 1 is confirmed, but a reduced discrimination range is evident (40% against 14%). Therefore, This may mean that the virtual stimulation can reconstruct the sensation and interaction with a real object.

5 Conclusions

The study proposes a multisensory system for the simulation of texture surface materials. It allows the reproduction of visual, auditory and tactile sensations during the interaction with a given material. Absolute and comparative card-sorting experiments show that perception increases with the number of involved sensory channels. Moreover, the addition of a mechanical vibration to elicit deep skin mechanoreceptors significantly improves material recognition if compared with [1].

Contribution of each sensory channel on human sensations still remains an open issue. Despite a structured investigation has not been carried out, experiments highlight that visual contribution is more preponderance than the auditory one for tactile perception.

Future work will be focused on the integration of this system into an immersive Virtual Reality Environment and on a deep analysis of the contribution of each sensory channel in tactile stimulation in order to improve the developed technology.

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