Integrated Computer-Aided Engineering 13 (2006) 249–262
IOS Press

A new haptic device for applications in virtual reality and humanoid robotics

Michele Folgheraiter, Giuseppina Gini* and Dario L. Vercesi
Politecnico di Milano, DEI Electronic and Information Department, Piazza Leonardo Da Vinci 32, Milan, Italy
E-mail: {folghera, gini, dario}@blocconote.it

Received 27 February 2006

Abstract. This paper presents an innovative haptic interface that allows to simulate a generic touch sensation thanks to the integration of an electro-cutaneous device and a force-feedback system. After investigating different levels of interaction with the human perceiving system, with the main goal to implement a virtual reality device with high sense rendering capabilities, we developed a special glove. It is controlled with a TENS (Transcutaneous Electric Nerve Stimulation) board that enables electro-cutaneous stimulation on the user fingertip, and a force-feedback system that restricts the user finger movements. To integrate the visual with the touch sensation, we created a 3D virtual model of the environment which is synchronized with the user movements. The user wears the glove and explores the virtual object via a sequence of interactions with it. We conducted different kinds of experiments to find the best pattern of cutaneous stimulations. Then we introduced the visual and force-feedback modalities and evaluated the psychophysical effects of the combination of touch, force and visual feedbacks. We also found that it is possible to generate two kinds of haptic sensations, the beat and the vibration, with appropriate settings of signal amplitude, duty cycle and frequencies.

Keywords: Virtual reality, electro-tactile stimulation, haptic devices, haptic display

1. Introduction

The rapid evolution in the fields of information and communication technologies (ITC), and the theoretical and technological level reached by the human-machine interfaces, have produced instruments to investigate the way humans effectively interact both with real and synthetic worlds. The discipline that studies how to create artificial worlds and how to allow their interaction with human beings, is named Virtual Reality (VR), a term introduced by the visionary scientist Jaron Lanier in 1989.

In order to recreate real sensations, the synthetic environment should be a dynamic system. This means that real-time computational capabilities are needed in order to react on time to a user stimulus. Due to this interaction, the system should modify its inner state and afterwards represents these changes to the user. Therefore a Virtual Reality system should be both immersive and interactive. These two features can be obtained artificially only by a multi-modal interface capable to communicate with the human sensory system. So we can define a Virtual Reality system as an high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, olfactory, and taste [6].

One of the main features of an adaptive living creature, like a human being, is its ability to represent properly the surrounding environment using an internal model. However, the way we build the world model is conditioned by the customized competencies, personal experiences and the specific interactions we made with the objects of this world. For example two people, looking at a painting, may receive different sensations due to the different perception system used, but also, due to the different way that our brain uses to

*Corresponding author.

ISSN 1069-2509/06/$17.00

match real-time information with past recorded data. Each of us builds models of the world in a personal manner. This feature, identified by Burdea and Coiffet [6] like imagination, represents the third component of the Immersion-Interaction-Imagination model of Virtual Reality (VR).

The system we designed takes into account each one of these three concepts. In particular we focused on the tactile sensorial channel and the way we can interact with it in a non invasive way.

The Haptic discipline studies tactile sensation and the way we can generate it through an artificial system. This word arises from the Greek word "hapteshai" that means touch: the human sensibility to feel the surrounding world through body's extensions and tips. Thanks to the touch sensation we can feel the world around us better than that we can feel through any other single sensorial modality [23]. Haptic sense is very important for human beings. Like the vision, the touch sense holds a primary role in human perception, especially during activities that involve objects manipulation. Sometime the touch can also overcome or substitute the vision, as for example in blind people [10] that are able to acquire the object's properties only touching and lifting it. With the haptic sense it is possible to acquire plenty of information: about weight, shape, texture, temperature, consistency etc. Thus if we want to improve the human interaction with a virtual world, we have to take in account the properties and modalities of this fundamental sensorial channel.

While visual Virtual Reality systems grow along 3D computer graphics, haptic devices grow alongside robotics and tele-manipulation systems, in Fig. 1 there is reported the time-line of some important haptic devices of the last thirty years.

The first haptic devices were studied and designed for the tele-control of a manipulator [9].

GROPE-1 was a device [3] with real-time capabilities as a complex human computer interface (HCI). GROPE-1 aimed to develop a bi-dimensional space of molecular docking forces. Later the project was extended to three-dimensional force spaces; a point interaction device operating on a system of strings to be tensed to create forces on a exoskeleton was added.

Another interesting system is the Rutgers Master II [4], that uses four pneumatic actuators to flex or extend the user fingers with a maximum force of 16 N. Each actuator is equipped with a position sensor that allows to control the fingers closure according to a model of the virtual world.

Various haptic systems use robotic manipulators to force the movement of the user in its dextrous space. The PHANToM arm, for example, is a single open chain of joints that realizes a 6-DOF manipulator able to force or guide the user movement during the exploration of the virtual environment. A vibrational device is also included in order to render the touch sensations produced by smooth surfaces. Another similar haptic device is Virtuose from Haption company that is also based on an arm that restricts the operator movements according to the VR world. Based on a different mechanism is the SPIDAR-G [20] that generates force feedbacks by cables connected with the user's hand. The Delta haptic device, by Force Dimension Company, is composed by three serial manipulators that realize a close kinematic chain of 3-DOF. Finally, a cylindrical end-effector adds other 3-DOF. Each joint of the kinematic chain is equipped with sensors and actuated in order to completely control the user movement during the exploration of a virtual world.

The FEELIT mouse, or other advanced gaming control interfaces, may be used to reproduce simple sensations of touch, for example when the mouse pointer collides with other objects of the user screen. Varying the rotation frequency of a small vibrational device these interfaces are able to reproduce different sensations like smoothed or rugged surfaces, metal or wooden materials.

An haptic device must take into account two different effects, since the human tactile sensation can be decomposed into two main components elaborated by two different parts of the central nervous system (CNS): kinesthetic and cutaneous sensations. The kinesthetic sensation is due to the forces that an object generates in opposition to the free movement of the user's articular joints. The receptors involved in kinesthetic touch perception are located inside the muscles. The cutaneous sensation is due to the micro-forces generated during the creeping contact between the user's skin and the object surfaces. The cutaneous sensation is perceived through the mechano-receptors that are located at different depths into the human skin. In Section 2 we will describe, in detail, the human touch system, the skin physiology, and the mechano-receptors principally involved in measuring the mechanical interaction between the object and the user's hand. For each subsystem involved in perceiving a specific touch sensation we can design different devices based on different technology solutions. The kinesthetic touch sensation is often obtained using a mechanical exoskeleton mounted directly over the joints that we want to bind. Servomotors, pneumatic artificial muscles and hydraulic devices are used as actuators of the exoskeleton structure.

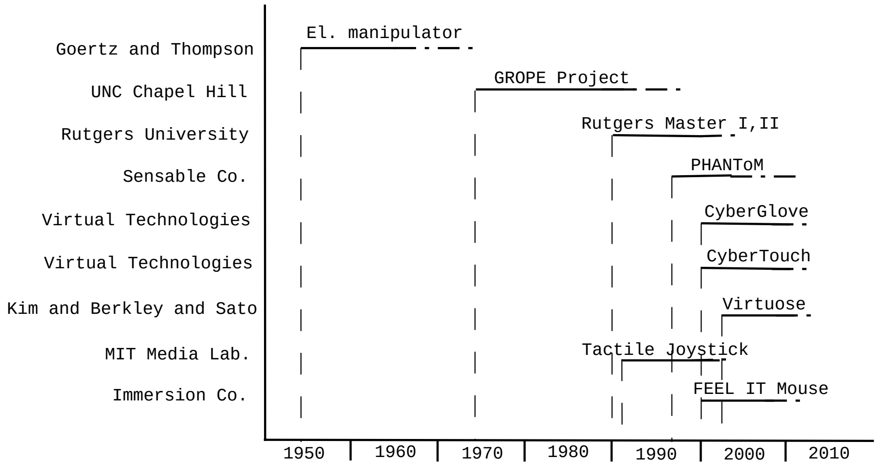

Fig. 1. Time line of the most important haptic devices of the last thirty years.

To generate the touch sensation two different methodologies are possible: to reproduce the physical stimulus that causes the touch sensation, or to stimulate directly the receptor nerve that is involved in perceiving the touch stimulus.

In the first case the goal of the haptic interface is to reproduce the physical stimulus such as the real manipulation of the object can do. The device acts directly on the receptor body through deformation of user's skin and dermis. This causes the membrane depolarization and a consequent train of action potentials that reaches the central nervous system (CNS) via the axon fibers. More details about this approach can be found in [1, 7], where magnetic or pneumatic devices are used to generate a pressure on the user fingertip.

Using the second methodology, it is possible to act directly on the receptor's membrane depolarization, injecting a current inside the tissue. This method, also known as TENS (Transcutaneous Electric Nerve Stimulation), causes the generation of the same action potentials, but this time, without generating the physical stimulus. For more details see Kaczmarek et al. [15,16] and Hiroyuki Kajimoto et al. [17]. Other studies were done to improve the current regulation of an high voltage impulse generators [22] or to optimize the power delivered on the basis of the impulse frequency [21]; the final purpose was reducing the electrodes area and increasing the dynamic range of the haptic device.

The virtual glove that we developed is described in Section 3; it generates a force feedback (kinesthetic sensation) through servomotors connected to the user's fingertips by artificial tendons. The fine sensation of touch (cutaneous sensation) is instead obtained using a custom build TENS board that can generate a biphasic current to induce potential changes in the mechanoreceptors membrane. The sensations evoked on the user are described in Section 4.

2. The human tactile perceiving system

In this section we introduce the basic concepts of the human tactile system, focusing on the hand physiology and its perception structures.

The principal organs involved in the sense of perception are the receptors. A receptor is a biological structure able to identify a stimulus in the internal or external environment and convert it into neuro-electric signals. Frequently the receptor is a modified neuron that is specialized to transduce a specific physical stimulus. The information originated from the external environment are supplied to the nervous system through the sensorial receptors arranged everywhere into the human body. The mechanism of transduction is well know; when a pressure deforms the receptor's membrane some ionic channels open, so ions (Na^+, K^+) cross the channels depolarizing the membrane. If the membrane potential reaches the threshold of a receptor, an action potential is generated and transmitted along the receptor's axon. The action potential acts like a binary signal; the information is modulated by a frequency proportional to the strength of the stimulus. The action potential process is well described by the Hodgkin and Huxley model [11] based on the ionic concentrations of the intracellular solution.

A typical feature of each receptor is the ability to react only to a specific physical stimulus and to be insensible to the other stimuli. Another common feature is

Table 1
Mechano-receptors distribution into the tissue layers and their principal features

Feature	Meissner Corpusles	Pacinian Corpuscles	Merkel's Disks	Ruffini Endings
Rate of adaption	Rapid	Rapid	Slow	Slow
Location	Superficial dermis	Dermis and subcutaneous	Basal epidermis	Dermis and subcutaneous
Response frequency range	10–200 Hz	70–1000 Hz	0.4–100 Hz	0.4–100 Hz
Min. threshold frequency	40 Hz	200–250 Hz	50 Hz	50 Hz
Physical parameter sensed	Skin curvature, local shape	Vibration	Skin curvature, pressiure	Skin stretch

the ability to adapt, differentially or absolutely, to a certain stimulus. Adaptation time may range from the few milliseconds of a Pacinian corpuscle to some days of the arterial baro-receptors. Each afferent fiber is linked to a specific section of the central nervous system [19]. The sensation evoked by the peripheral stimulation is due to the specific brain section excited. The sensation evoked is cause-independent, but depends uniquely to the specific brain section that receives the stimulus information.

All the receptors present in the human body can be divided in five groups depending on their main purpose:

– *mechanoreceptor*: sensible to mechanical deformations
– *termoreceptor*: sensible to temperature variation
– *nociceptor*: tissue harms detection
– *photoreceptor*: sensible to light stimuli
– *chemoreceptor*: sensible to chemical phenomenon like taste and smell

We focus now on the physiology of the mechano-receptors, the receptors able to transduce mechanical stimuli in nervous signals. As said before, we can split the entire tactile perception system into two different channels: kinesthetic and cutaneous. The first one manages information linked to the opposition forces set against our joints movements by the objects we touch. The kinesthetic sense receptors are located into the muscles, tendons, and articular caps. The cutaneous channel receives information about shape, surface patchiness and temperature. The cutaneous receptors are distributed into the three layers of the tissue (Table 1).

The peripheral nerves of the hand contain thousand of axons. We can distinguish 21 fibers with different sites of termination and functions, 8 of which are efferent (signals sent to muscles and some receptors) and 13 are afferent to the central nervous system. Analyzing with more attention the cutaneous mechanoreceptive [13] afferent it is possible to distinguish four fibers that connect with four different receptors: slowing adapting type 1 fibers (SA1) that end in Merkel cells [14], rapid adapting fibers (RA) that end in Meissner corpuscles [24], Pacinian afferent (PC) that end in the homonyms corpuscles and the slow adapting type 2 afferent (SA2) that end in Ruffini corpuscles [8].

Because of their bigger dimension, compared with the other mechano-receptors, Pacinian corpuscles are primarily involved in TENS. Each corpuscle is connected with a dedicated PC fiber; there are about 350 receptors for a single finger. Since they are located very deeply in the skin, they are very sensitive and can detect skin movement of about 10 nm. Due to their location they have no spatial resolution; a single Pacinian corpuscle has a receptive field that can cover also the entire hand. The viscoelastic structure of this corpuscles is able to rapidly adapt to the external deformations of the tissue. The Pacinian corpuscle generates action potentials during the first few milliseconds of deformation and stops its emissions when reaches a new internal equilibrium. When the deforming forces are removed, the corpuscle tends to a new equilibrium and restarts to generate the action potentials along the axon fibers. For this reason these receptors are specialized to detect vibrations that come from object held in the hand [5]. When we are skilled in using a tool, we are able to perceive the events at the working surface, as the tool behaves like and artificial extension of our hand.

3. The virtual system and the computational model

Human body feels the sensation evoked by the external environment as a neuro-electric pulse generated by the sensorial receptors. The goal of a Virtual Reality system is to recreate these stimuli from a virtual world and transmit these information to the user perception system. We can touch a unreal object if the device interfaces are able to recreate it, but we can also touch the same virtual object if the device interface is able to reproduce its presence "directly" into our mind. Increasing the level of the human-machine interaction causes a consequent growth of the reality perceived by the user, but also a growth of the computational and theoretical complexity of the whole system.

In our haptic device we used a mechanical force feedback system, based on servomotors, to recreate the

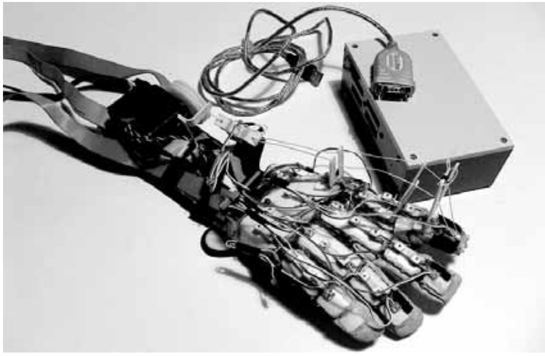

Fig. 2. The virtual glove device and the TENS board box. The glove is connected to the box and to the A/D board installed into a personal computer.

kinesthetic sense of touch. This method realizes an high layer of interaction with the human body, rendering the macroscopic forces that are opposed to the user's fingers movement. The cutaneous sensation instead is obtained by a neural interaction layer based on a custom built TENS board. The information transmitted to the brain by electrical stimulation enables us to feel the shape and texture of the objects, while the force feedback system enables us to feel the object size and extension. Both feedback systems are mounted on a glove that is able to capture and transmit the finger's articular joints position. In the present system there are no sensors to detect the hand position and orientation; we will include some in future developments.

The system detects collisions between the user fingers and the virtual objects and consequently reacts binding the user's dextrous space and sending texture and shape information to the central nervous system.

The entire architecture of the virtual reality system: acquisition, computation-control and feedback process is shown in Fig. 3.

The sensors, placed on the upper side of the glove's fingers (Fig. 2), measure and send the angular joints position to the Virtual Model block; through multiplexing and de-multiplexing we reduce the number of connecting ports needed to transmit these data. The information received is merged with the environment data. The Virtual Model block is charged to determine each collision between the user's hand and the object of the virtual scene, and to communicate the collision entity to the actuator systems. Each block of the Fig. 3 is described by its functional name and the specific implementation technique (software/hardware), described in detail in the next sections.

The same process may be functionally decomposed as described in Fig. 4.

The information acquired by the glove's sensors are routed through two control layers to the user. Each block of the schema communicates with the two next layers only. It receives information from the sub-layer and commands from the upper-layer and, at the same time, it controls the sub-layer and send information to its upper-layer. Another specific feature of the functional block is the different measurement used to represent the whole information streams: voltage and current values in the physical layer, objects and collisions between objects in the Virtual Model block.

The schema in Fig. 4 shows also the three basic loops for the reacting logic we implemented for our device. The first loop acts at the physical layer. This loop controls in real-time the actuators parameters and values in order to keep stable the injected current value, and the servomotors reacting force. After we have fixed the current intensity and the feedback opposition forces, the loop stabilizes these values in a "free-will" way. The second loop shown in Fig. 4 is solved at the virtual model layer. When the VR block detects one or more collisions between the user's fingers and the virtual objects, the system submits all the collision parameters to the physical layer. We introduced the complete V-Collide algorithm [12] into a VRML-C++ simulator to detect collisions between objects. We implemented two different methods to evaluate the collisions and deep penetration between objects. The first method is composed by a custom software able to build the object dependance tree of a VRLM scene and to detect collisions using V-Collide. The second method is based on the exact 3D equation of the object and checks though Simulink the movement of the user hand into the virtual space. If user hand penetrates into the bound space, the system evaluates the penetration deep and then reacts with a force computed according to the object model. For each of these methods we tested different objects as spheres, cubes and simple composition of these forms; in this way we can avoid considering the non-convex hull problem.

The whole system is controlled by Simulink modules running under Matlab. The last loop is closed on the user, which can see all the system's information and set all the parameters in an interactive interface.

3.1. The glove acquisition system

The acquisition system is composed by a glove equipped with 14 angular sensors and 2 force sensors (Fig. 2). Angular sensors measure the joint rotation of each phalanx for every finger, except the little one.

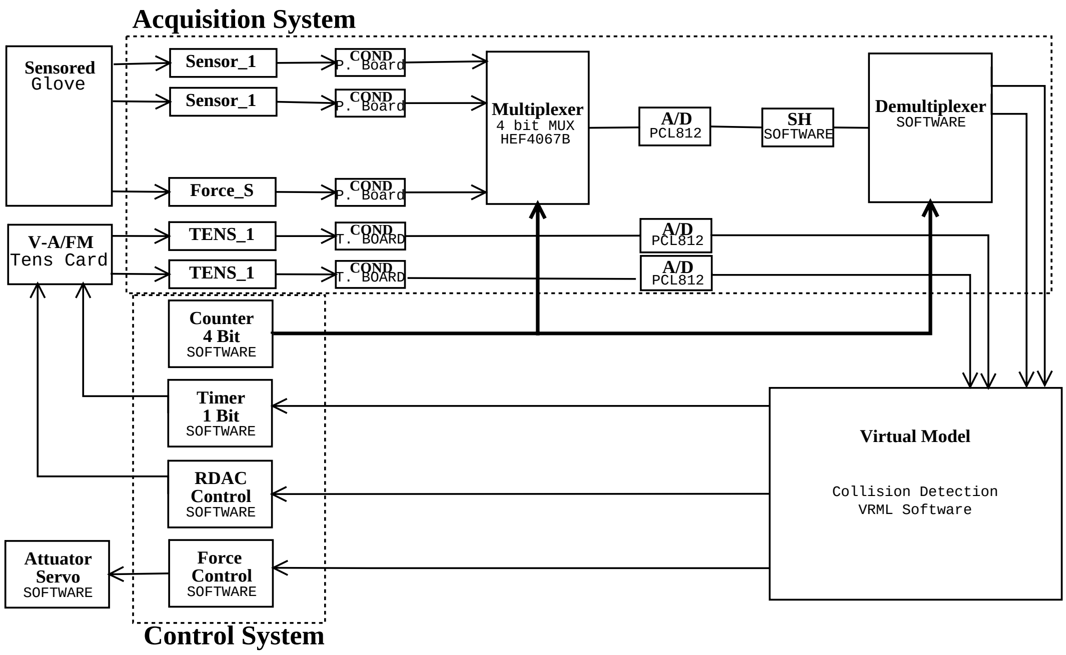

Fig. 3. Architecture of the Virtual Reality system.

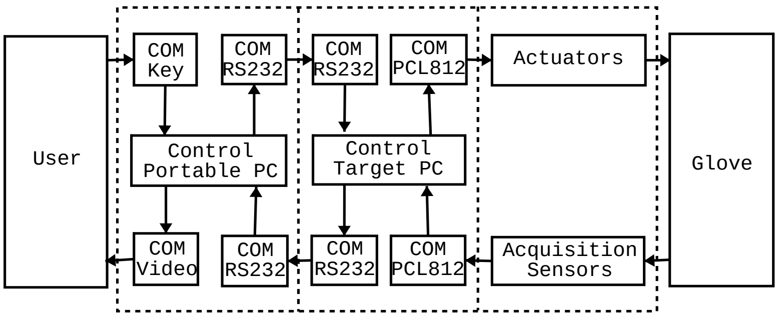

Fig. 4. Functional schema of the acquisition and control system.

Force sensors are connected in series with the artificial tendons that transfer the force from the actuator to the fingertip. Each sensor is composed by a FSE flex sensor (Force Sensor Resistor) able to change its specific resistance value proportionally to an angular flexion. Three angular sensors are mounted on each finger respectively for proximal, middle and distant articular joint. Two sensors are mounted between the thumb and the forefinger to measure the abduction and adduction movement. In addition the thumb and the middle fingertips mount 2 force sensors to detect the contact force with the object during the manipulation. The signals coming from the sensors are limited to a range of 0–5 V, multiplexed on a single analog channel and then send to an A/D board.

3.2. The force feedback system to evoke kinesthetic sense of touch

When the virtual model detects a collision between the scene and the user's finger two kinds of information are sent to the physical layer: the shape of the "texture" and the force entity of the binding reaction. The second one is transmitted from the A/D board to the force actuation system.

The force feedback system consists of a servo motor by **Hitec Company** with a maximum torque of 10 Kg/cm. The servo motor is positioned on a solid arm band and its torque is transmitted to the fingertip by tendons fixed to the solid plastic bands of the glove. The tendons run along the finger length across

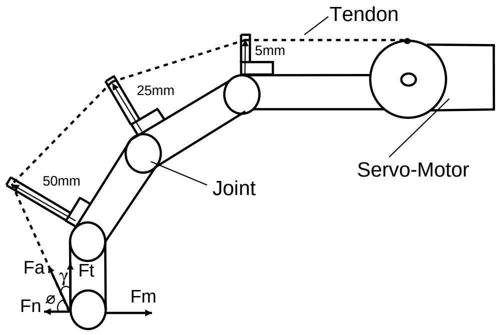

Fig. 5. Schema of the actuation system.

some passings that constrain the movement (Fig. 5). The passing shape and size are developed in order to drive the servo force perpendicularly to the movement path of the fingertip. In this way we increase the force transferred from the tendon to the fingertip, because the normal component of F_a will increase if ϕ decreases.

The force generated by the haptic system depends on the dynamic model of the virtual object and the relative position of the user finger relative to the virtual object. In first approximation we can model the reaction force as in Eq. (1).

$$F_m(t) = K_e x(t) + K_d \dot{x}(t) \tag{1}$$

where K_e is the elastic constant, K_d is a damping constant and $x(t)$ is the penetration rate into the object surface. This model takes into account the static and dynamic force components of the contact.

The force generated by the artificial tendon to the fingertip (F_n) must be equal to the force generated by the virtual object (F_m) (Eq. (2)).

$$F_n = F_m \tag{2}$$

We implemented an algorithm to calculate this force in real time. The physical software interfaces are able to change the servo angular position in order to accomplish Eq. (2). The dynamics described by Eq. (1) is obtained slowing or speeding up the rotational velocity of the servo. Taking into account the mechanical structure of the glove the Eq. (1) can be rewritten as Eq. (3).

$$F_a(t) = \frac{F_n}{\cos\phi} = \frac{K_e x(t) + K_d \dot{x}(t)}{\cos\phi} \tag{3}$$

where ϕ is the angle that the tendon makes with the normal of the last phalanx as shown in Fig. 5. This angle depends on the last phalanx angular position ϖ, its length L_1 and the tendon support height L_2. As we can see from Fig. 5 we can obtain γ by a simple geometrical consideration on Fig. 6.

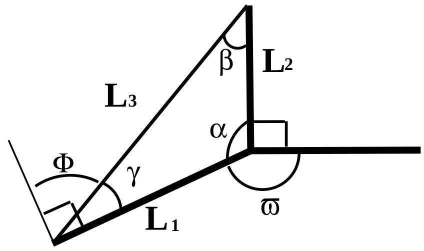

Fig. 6. Angles formed by the two last phalanxes.

$$\phi = \frac{\pi}{2} - \gamma \tag{4}$$

$$\gamma = \arccos\left(\frac{L_3 + L_2 - L_1}{2L_2L_3}\right) \tag{5}$$

In our analysis we neglected the component F_t, because its arm relative to the center of rotation of the last phalanx is smaller than the phalanx lengths.

3.3. *The Electro-cutaneous stimulation device*

As stated before, we intend to study the ability of TENS stimulation to cause “noises” into the neuro-electric system of tissue mechano-receptors. Using a controlled TENS stimulation we can directly evoke sensation by recreating the right sequence of action potential along the axon fibers. The texture shape of the object surface is rendered to the perceiving system through an electrode fixed between the glove and the user’s fingertip. In first approximation [16], we can model the skin-electrode contact as in Fig. 7: where R_{eg} is the resistance between the electrode and the conductive gel, R_{es} and C_{es} are the resistance and the capacity of the the electrode-skin interface. According to previews works and empirical tests [16], R_{eg} results smaller than R_{es} and can be ignored in a first approximation. Therefore, if V is the impulse amplitude applied to the electrode-skin interface, we can write the tension value present on the subject tissue V_{pp} as follow:

$$V_{pp}(t) = V(1 - e^{-\frac{t}{\tau}}) \tag{6}$$

$$V_{pp}(t) = Ve^{-\frac{t}{\tau}} \tag{7}$$

Equations (6) and (7) respectively represent the rising and falling tension characteristic.

As we can see from the electrode-skin interface response the behavior is not linear. This represents a problem for the electro-tactile stimulation because, with fixed tension at the electrodes, the current injected can vary in time and so the touch sensation felt by

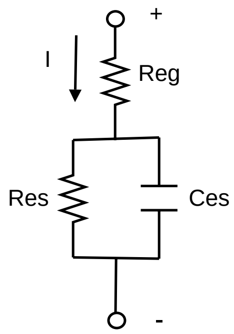

Fig. 7. Electrode model.

the subject. To avoid this problem we can control the current instead of the tension.

Our device can generate a generic biphasic wave varying in frequency (1 Hz–5 KHz) and intensity (0–10 mA). The electrode voltage is controlled by a custom built TENS-board. In order to avoid the electrolysis phenomena, which might cause a permanent tissue damage, the area of the positive pulse is maintained nearly equal to the area of the negative impulse.

The electro-cutaneous signal generation process is divided into two main phases. The first one performs the wave generator task; it works at low power and can interact with the A/D board through 4 dedicated channels. A single digital pulse burst is presented to the gate of a NPN transistor that performs a first small amplification and realizes the frequency base of the stimulation signal. The low power block varies the amplitude of this signal thanks to a digital potentiometer (RDAC) that is controlled through the 3 remaining digital channels.

In the second phase the base signal is amplified through a couple of operational amplifiers (op-amp) and then elevated through a tension transformer connected to the electrode. The transformer elevates voltage from 0–5 V to 0–100 V and generates the biphasic wave we want to obtain. We introduced also some capacitors to uncouple the two phases of the signal transformation. The op-amp outputs has been also stood by a Boucherot block. The TENS-board is fully controlled by digital channels of the same A/D board used for sensor measurements and force feedback control. It can send out the real-time value of the current injected into the fingertip.

When the virtual model detects collisions it sends the signal features to the physical layer. This layer enables the algorithms to set the right values of the digital inputs of the TENS-board, so the injected current is adapted by continuously varying the electrode voltage.

To make different experiments we implemented two electro-stimulation channels of the same kind and electrodes of different shapes and materials. The physical layer is able to control independently both these channels.

4. Electrical transcutaneous/force feedback stimulation experience

The experience done with our haptic device enabled us to assess the accuracy level of the touch sense stimulation and, at the same time, the theoretical base of this kind of research. We divided our experimentations in three main phases. At first we investigated the role of frequency and current intensity in the electrical-stimulation of humans touch sense. A second sets of experiments were done to determine the role of the duty cycle of the stimulation wave. Finally, the last phase involved the force feedback, the cutaneous sense generation and the visual feedback. We prepared standard questions and closed response sets for all the human subjects involved in the experimentation.

4.1. Experience 1: Electro-stimulation intensity and frequency roles

The first experiment has a main role in setting the proper "meaning" of frequency values and current intensities in the electro-cutaneous stimulation process. The test set is composed by seven different frequency layers (from 5 Hz to 400 Hz), each one including four different current intensities (from low to very high) for a set of 28 tested points.

We can then describe the frequency and intensity test sets as in Eqs (8) and (9).

$$I_f = \{5, 10, 20, 50, 100, 200, 400\} \tag{8}$$

$$I_i = \{Low\ Middle\ High\ V.High\} \tag{9}$$

The complete question set is defined by Eq. (10).

$$I = I_f \times I_I \tag{10}$$

The I_i sets are defined by the middle point of the following intervals (Eq. 11). Due to the difficulty in steadying the current intensity during physical experimentations, the whole interval is considered at the same level and described by its label only. For example a Middle value means a current value between 1 mA and 2.5 mA.

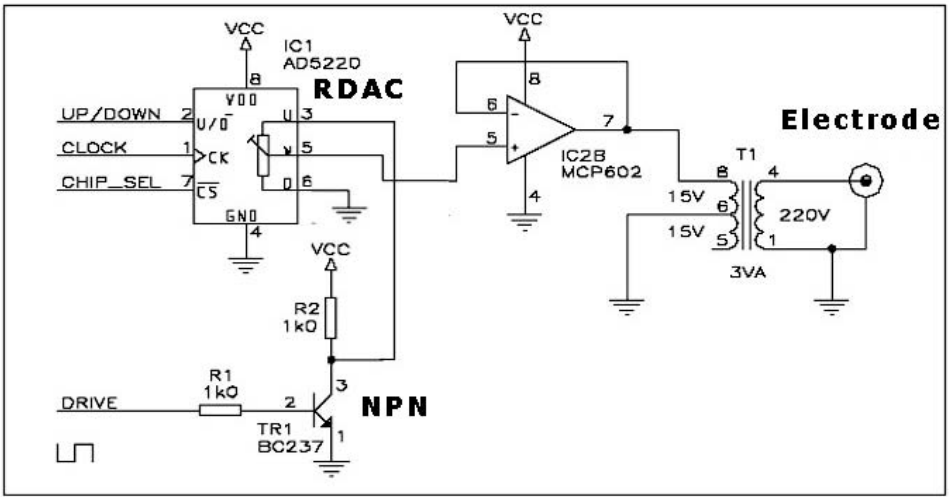

Fig. 8. The electronic circuit of a single channel TENS device.

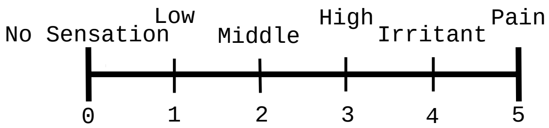

Fig. 9. The current intensity axis.

$$
\begin{aligned}
&I\epsilon Low \Leftrightarrow i \leqslant 1mA \\
&I\epsilon Middle \Leftrightarrow (i > 1mA) \wedge (i \leqslant 2.5mA) \\
&I\epsilon High \Leftrightarrow (i > 2.5mA) \wedge (i \leqslant 4mA) \\
&I\epsilon VeryHigh \Leftrightarrow i > 4mA
\end{aligned}
\tag{11}
$$

Each sensation produced by the electrical mechanoreceptor stimulation has two main components: the felt intensity level and the sensation evoked in the human mind [2]. We prepared two response sets in order to map either components. The first set is composed by six possible intensity responses (from NOSesation to Pain). The second one has seven elements corresponding to seven possible sensations felt by the users. We can write the two sets as in Eqs (12) and (13). Finally we can map the R_i set on the current intensity axis shown in Fig. 9.

$$
\begin{aligned}
R_i = \{&NoSensation, Low, Middle, \\
&High, Irritant, Pain\}
\end{aligned}
\tag{12}
$$

$$
\begin{aligned}
R_f = \{&Beats, Itch, Vibration, Tingle, \\
&Rasping, Warm, NoSensation\}
\end{aligned}
\tag{13}
$$

We tabulated each different sensation to make a common guide for each subject experimentation. The complete answer set is described by the 42 position defined in Eq. (14).

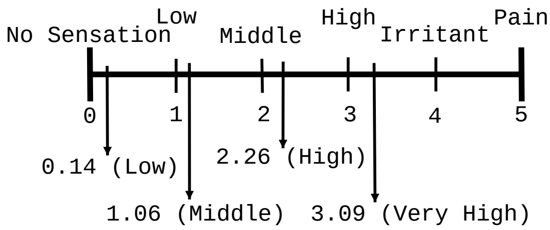

Fig. 10. Mean values (arrows) for the sensations felt by the users at a specific level of current amplitude.

$$
R = R_f \times R_I \tag{14}
$$

This experiment may be described through the resuming Eq. (15). Each subject response is described by a well known intensity and sensation couple.

$$
\forall f \epsilon I_f, \forall i \epsilon I_i \Leftrightarrow Resp(f, i) \epsilon R \tag{15}
$$

For each frequency in the I_f set and for each intensity level in the I_i set we note one response of the R_I set. We tested the same experiment on five different subjects.

The results of the first experiment are described by Table 2, which shows the mean distribution of responses about sensation intensities. These data are obtained connecting the subject response with the corresponding value of the intensity axis of Fig. 9. Each value of the Table 2 identifies the response mean value of the intensity axis for each frequency and intensity level. For example, at a frequency of 20 Hz for a Middle current intensity level (1 to 2.5 mA) the subject probably felt a low sensation (1.00). From the Table 2

Table 2
Mean intensity values of subjects responses

Intensity(Hz)	5	10	20	50	100	200	400	Mean
Low	0	0	0.4	0.4	0	0	0.2	0.14
Middle	1.0	1.0	1.0	1.4	1.0	1.0	1.0	1.06
High	2.2	1.8	2.2	2.4	2.4	2.2	2.6	2.26
Very-High	2.6	2.8	3.0	2.8	3.2	3.4	3.8	3.09

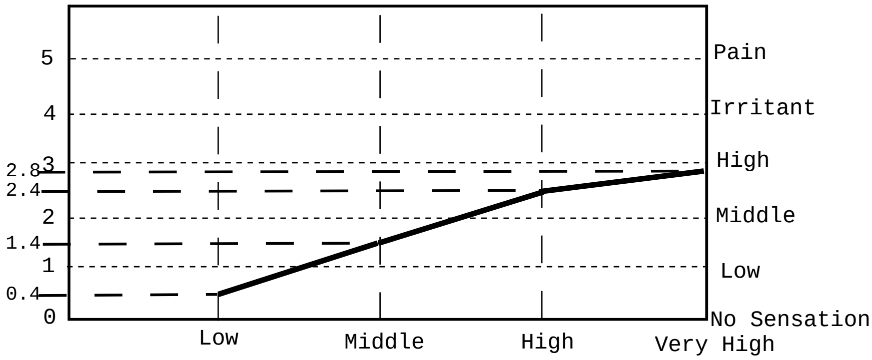

Fig. 11. Subject sensations by electric pulse intensity. This graph identifies the response mean values for the 50Hz electric wave. The curve approximates a logarithmical distribution.

we can observe that values under 1 mA (Low) are inappreciable to most of the subjects. Subjects felt low sensation between 1 mA and 2.5 mA (Middle). At this level they can be distracted by other major stimuli (in accordance with the filter theory). Values between 2.5 mA and 4 mA (High) are strongly felt by the subjects. In this case subjects cannot be distracted by other external stimulus. Values up to 4 mA (Very-High) are considered strong and uncomfortable. The mean trend shown in Fig. 11 logarithmically grows with stimulation intensity according to the the Steven's theory.

In order to study the sensations evoked by the frequency of electrical stimulation, we prepared other tables in which we described, for each f, i couple, the R_f element (Frequency sensation element) of the subject response. In the Table 3 we describe the response number for each element of this set.

The resulting graph shown in Fig. 12 maps the sensation curves evoked by the frequency values of electrostimulation.

The beats sensations are well identified with a frequency of about 10 Hz or less. Around the 50–200 Hz the subjects feel a tingle, and often an uncomfortable sensation. This feeling grows up to a clear vibration near the 100 Hz values. These results prove the typical influence of frequency in different sensation felt by the users, due to the characteristic mechano-receptors attitude to perceive a specific band of sensations and to completely filter the others. In particular the vibration felt around the 100 Hz agrees with earlier findings that Pacinian Corpuscles are sensible to vibration and operate at that frequency [17].

4.2. Experience 2: Duty-cycle role in electrical stimulation systems

The second experience was to explore the role of the duty cycle of the electrical stimulation wave. The wave pulse width affects the felt intensity sensation due to the different value of the injected current, for time unit, into the subject tissue. We tested the device for two significant frequency values (10 Hz – 50 Hz) and two intensity levels $(Middle, High)$. The intensity levels are the same described by the Eq. (11) of the previous experiment. During the experience we asked the subject to describe the differences felt varying pulse width from 10% to 90% of the whole period. The whole test set is composed by the Eqs (16), (17) and (18) and the experience may be described by Eq. (20).

$$I_f = \{10Hz\ 50Hz\} \quad (16)$$

$$I_i = \{Middle\ High\} \quad (17)$$

$$I_w = \{10\%\ 90\%\} \quad (18)$$

Where I_f describes frequency values, I_i is the intensity level set and I_w is the impulse width values of this experiment. Finally, the answer set R_w is described by

Table 3
Subject sensations felt at different frequency values

Frequency	Beats	Itch	Vibration	Tingle	Rasping	Warm
5 Hz	11	1	0	0	0	0
10 Hz	11	2	0	0	0	0
20 Hz	7	1	5	2	0	0
50 Hz	2	5	7	2	0	0
100 Hz	0	1	8	1	3	0
200 Hz	0	6	7	1	0	0
400 Hz	1	2	6	1	0	4

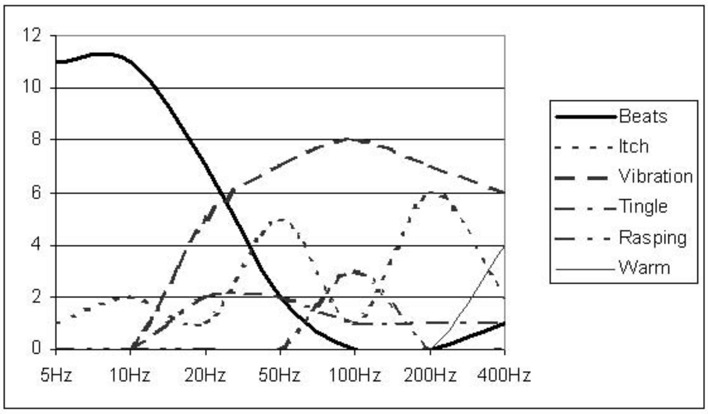

Fig. 12. Distribution of the sensation felt by subjects at different frequency values.

Eq. (19).

$$R_w = \{Low\ Strong\ Soft\ Hard\ Fast\ Slow\ Equal\} \quad (19)$$

To determine the most common answers we built the response set on the base of a first experimentation on ten subjects. Then the recorded experience involves five subjects that choose one of the possible answers. The $Lower$ and $Stronger$ values means that the subject feels the same sensation but perceives some variation in the intensity level. The $Softer$ and $Harder$ values means that subject feels the same intensity of the half width impulse but with a less or more, clear sensations. The $Faster$ and $Slower$ values are connected to the perceived sensation of changed speed. Finally $Equal$ value means that the subject doesn't perceive any kind of change. The complete experiment process may be described by the Eq. (20).

$$\forall f \epsilon I_f, \forall i \epsilon I_i, \forall a \epsilon I_w \Leftrightarrow Resp(f,i,a) \epsilon R_w \quad (20)$$

Results of this data acquisition are in Table 4, with all the answers grouped by intensity and frequency values.

From Table 4 we can observe that subjects feel lower sensation (Lower) for small pulse width (10%) but also a clear sensation was evoked (Harder). For large impulse width (90%) the subjects feel stronger sensation (Stronger) but smoother (Softer) than the first one. We can use pulse width modulation in order to evoke clear or smooth tapping sensation based on the same frequency level.

4.3. Integration of tactile, force and visual feedback

The last experimentation involved together the force feedback, the cutaneous touch generator and the visual feedback. Here we report only preliminary results, since a more intensive experimentation is required to better understand the effects of this multi-modal sensorial stimulation. During this experiments the PCL-812 controls the servo angular position every 10 ms; if a touch position is reached, servo reacts opposing the fingers movement. It is possible to change the servo speed and the touch position in order to simulate hard or soft surface of every dimensions.

At first we applied only force and cutaneous feedbacks. We introduced an electrical stimulation (100 Hz, middle intensity level) on the fingertip when the subject reached the virtual object. After we introduced the visual and the collision detection systems. We presented to the subject a VRML virtual model of the human hand

Table 4
Subject responses about sensation driven by pulse width modulation

f	%	i	Low	Str.	Soft	Hard	Fast	Slow	Equal
50 Hz	10	Mi.	5	0	0	0	0	0	0
10 Hz	10	Mi.	3	0	0	0	0	0	2
50 Hz	10	Hi.	3	0	0	2	0	0	0
10 Hz	10	Hi.	0	0	0	2	0	0	3
–	10%	–	11	0	0	4	0	0	5
50 Hz	90	Mi.	0	2	1	0	1	0	1
10 Hz	90	Mi.	0	1	3	0	0	0	1
50 Hz	90	Hi.	0	3	2	0	0	0	0
10 Hz	90	Hi.	0	3	2	0	0	0	0
–	90%	–	0	9	8	0	1	0	2

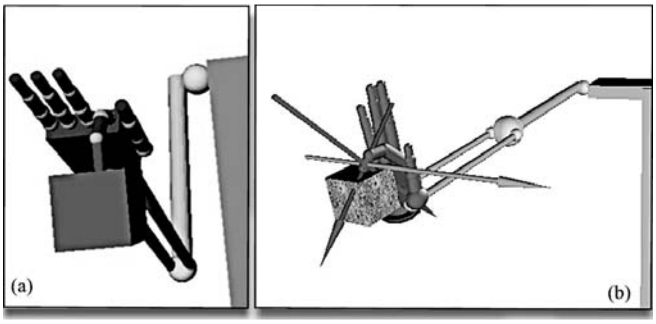

Fig. 13. The Virtual Reality Environment.

and the objects (Fig. 13). When the system detects collisions between the hand and the object the force feedback and the cutaneous stimulation is activated in order to give a fully immersive sensation.

For all the experiments we used two virtual objects of different dimensions. For each object we tested two different force opposition values. We can describe the question set related to the object dimension through Eq. (21)

$$I_d = \{Small\ Big\} \tag{21}$$

and the question set related to the object hardness through Eq. (22)

$$I_f = \{Soft\ Hard\} \tag{22}$$

the resulting question set is composed by the 4 positions table described in Eq. (23)

$$I_n = I_d \times I_f \tag{23}$$

where n is the experimentation number (from 1 to 3). For each part of this experiment, we presented the virtual object to the subject and then we asked to recognize its properties choosing the answer into a response set of the same kind of I_n.

Subjects recognized object hardness and dimensions in each phase, but only when we introduced the visual system they were able to assign a correct shape interpretation for the touched object. Summarizing, with force feedback only, subjects feel a movement opposition force but not a real touching object sensations. Combining force feedback and electrical touch system, subjects can accurately determine the contact position but they do not feel a real detectable touching sensation. When the whole system is tested subjects easily declare to touch an object of the correct shape. This is an important result if we think that in our system there is a severe hardware limitation. Indeed the introduction of the visual system produces a delay in the frame rate of about 50 ms^{-1}, five times higher than the servo impulse ratio. This delay is principally due to the algorithm for collision detection and to the time needed to allow the communication between the different software modules.

5. Conclusions

The device we designed is intended to explore the roles of electro-cutaneous and force feedbacks in virtual reality simulation environments. Its experimentation suggests that it can enable the user to perceive a fine and good sensation of touch during the interaction with a virtual object. We identified the frequencies of best stimulation (10 Hz and 100 Hz), and the current intensity levels, that induces a beat and vibration sensation to the subject. Thanks to this structure we implemented a virtual reality touching system able of an high level of interconnection with the human perceiving system and acting in a completely non-invasive way. The force feedback accomplishes the generic touch sensation supplying also the shapes and dimensions of the touched objects. Finally, a 3D visual feedback increases the realism of the virtual reality environment. Results demonstrated that integrating the visual, fine and macroscopic touch stimuli it is possible to offer to the subject a more realistic interaction with the virtual world.

In comparison with other works [15,18,25] we combined different types of sensorial stimulus with the main goal to increase the realism of the interaction with the virtual object. In comparison with other haptic devices [1,7], we exploit the electro-tactile stimulation in order to recreate the sensation of contact during the interaction with the virtual object. Our device may be used also for other applications, for example as pointing device for blind or motorial disable people.

The main purpose of this research was the exploration of the levels of interaction between the human perceiving system and the machine interfaces. The future effort will be to analyze the electro-stimulation wave characteristics to detail different touch sensations. We want also to increase the resolution of the tactile display, introducing an array of 2X2 electrodes to be independently controlled. We consider this feature very important, especially to use the virtual-touch to explore the object surface. In fact it will be possible to better simulate the edge detection and therefore the object shape. In future we will continue in investigating the effect of the combination of different kinds of stimulus. From our preliminary results it is clear that the integration of force, touch, and visual feedbacks enables a more realistic interaction with the virtual environment.

References

[1] N. Asamura, N. Tomori and H. Shinoda, *A tactile feeling display based on selective stimulation to skin receptors,* Proc. IEEE Virtual Reality Annual International Symposium, March 1998.

[2] P. Bach-Y-Rita, M.E. Tyler and K.A. Kaczmarek, Seeing with the brain, *Internationa Journal of Human-Computer Interaction* **15**(2), 2003.

[3] J.J. Batter and F.P.J. Brooks, Grope-1: A computer display to the sense of feel, *In Information Processing, Proceedings of IFIP Congress* **71** (1971), 759–763.

[4] M. Bouzit, G. Popescu, G. Burdea and R. Boian, *The rutgers master ii-nd force feedback glove,* Proceedings of IEEE VR Haptics Symposium, March 2002.

[5] A. Brisben, S.S. Hsiao and K. Johnson, Detection of vibration transmitted through an object grasped in the hand, *Journal of Neurophysiology* **81** (April 1999), 1548–1558.

[6] G.C. Burdea and P. Coiffet, *Virtual Reality Technology – 2nd ed.*, John Wiley and Sons, Inc., Hoboken, New Jersey, 2003.

[7] D.G. Caldwell, N. Tsagarakis and C. Giesler, Integrated tactile/shear feedback array for stimulation of finger mechanoreceptor, *Proc. IEEE International Conference on Robotics and Automation* **1** (1999), 287–292.

[8] D. Collins and A. Prochazka, Movement illusions evoked by ensemble cutaneous input from the dorsum of the human hand, *The Journal of Physiology* **496**(3) (1996), 857–871.

[9] R. Goertz and R. Thompson, Electronically controlled manipulator, *Nucleonics* **12**(11) (November 1954), 46–47.

[10] M.A. Heller, Tactile picture perception in sighted and blind people, *Behavioural Brain Research Volume* **135**(1–2) (September 2002), 65–68.

[11] A.L. Hodgkin and A.F. Huxley, A quantitative description of membrane current and its application to conduction and excitation in nerve, *Journal of Physiology* **117**(4) (1952), 500–544.

[12] T. Hudson, M. Lin, J. Cohen, S. Gottschalk and D. Manocha, V-collide: Accelerated collision detection for vrml, *Appeared in Proc. of VRML '97*, 1997.

[13] K.O. Johnson, The roles and functions of cutaneous mechanoreceptors, *Current Opinion in Neurobiology* **11**(4) (August 2001), 455–461.

[14] K.O. Johnson, T. Yoshioka and F. Vega-Bermudez, Tactile functions of mechanoreceptive afferents innervating the hand, *Journal of Clinical Neurophysiology* **17**(6) (November 2000), 539–558.

[15] K.A. Kaczmarek and S.J. Haase, Pattern identification as a function of stimulation current on a fingertip-scanned electrotactile display, *IEEE Transaction On Neural System And Rehabilitation Engineering* **11**(3) (September 2003), 269–275.

[16] K.A. Kaczmarek and J.G. Webster, Voltage-current characteristics of the electrotactile skin-electrode interface, *IEEE Proceeding Annual Internetional Conference Eng. Med. Biol. Soc.* **11** (1989).

[17] H. Kajimoto, N. Kawakami, T. Maeda and S. Tachi, *Tactile feeling display using functional electrical stimulation,* In Proc. ICAT'99, 1999.

[18] H. Kajimoto, N. Kawakami, S. Tachi and M. Inami, Smarttouch: electric skin to touch the untouchable. *IEEE Computer Graphics and Applications* **24**(1) (January–February 2004), 36–43.

[19] E.R. Kandel, J.H. Schwartz and T.M. Jessel, *Principle of Neural Science – 4th ed.*, 2000.

[20] S. Kim, J. Berkley and M. Sato, A novel seven degree of freedom haptic device for engineering design, *Virtual Reality* **6**(4) (August 2003).

[21] C. Perez, C. Holzmann and M. Osorio, Optimization of the envelope of a short duty cycle pulse waveform for tactile stimulation, *IEEE Proc. Engineering in Medicine and Biology Society 17th Annual Conference* **2** (September 1995), 1137–1138.

[22] C.J. Poletto and C.L.V. Doren, A high voltage, constant current stimulator for electrocutaneous stimulation through small electrodes, *IEEE Transaction on Biomedical Engineering* **46**(8) (August 1999), 929–936.

[23] M. Taylor, S. Lederman and R. Gibson, Tactual perception of texture, *Handbook of Perception* **3** (1973), 251–272.

[24] H.E. Wheat, L.M. Salo and A.W. Goodwin, Human ability to scale and discriminate forces typical of those occurring during grasp and manipulation, *The Journal of Neuroscience* **24**(13) (March 2004), 3394–3401.

[25] T. Yoshikawa and A. Nagura, A touch force display system for haptic interface. *Presence: Teleoperators and Virtual Environments* **10**(2) (April 2001), 225–235.