A GLOVE INTERFACE WITH TACTILE FEELING DISPLAY FOR HUMANOID ROBOTICS AND VIRTUAL REALITY SYSTEMS

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Keywords: Man-Machine Interfaces, Virtual Reality, Haptic Interfaces, Electro-cutaneous Stimulation.

Abstract: This paper focuses on the study and the experimentation of a glove interface for robotics and virtual reality applications. The system can acquire the phalanxes position and force of an operator during the execution of a grasp. We show how it is possible to use and integrate this data in order to permit the user to interact with a synthetic world. In particular the system we designed can reproduce tactile and force sensation. Electrodes and actuators are activated according to the information coming from the real world (position and force of the user's finger) and from a physical model that represents the virtual object. We also report some psychophysical experiments we conducted on five subjects, in this case only the electro-tactile stimulator was used in order to generate a touch sensation.

1 INTRODUCTION

Human-machine interfaces are very important in order to guarantee a good transfer of information from the human to the machine and vice versa. In many applications the entity and quality of this information exchange can establish the performance and success of the machine operation (Fahn and Sun, 2000),(J.Adams et al., 2001),(Burdea, 1999).

In robotics, for example, these interfaces are applied in order to remotely control the manipulation system. A good example of tele-manipulated robot is the ”Robonaut” designed in the NASA Johnson Space Center's laboratories (Ambrose et al., 2001). This robot has a humanoid shape and it is intended for supporting astronauts during EVA (Extra Vehicular Activity) activities. In this case, the operator is able to govern the robot by a glove interface that measures his arm-hand posture and generates the proper control signals for the robot's limbs. In this system, the operator receives two types of feedback from the robot: the first is a force feedback that allows to calibrate the applied force during an object manipulation, the second is a visual feedback that reproduces the robot environment. For this purpose an HMD (Head Mounted Display) is used.

Another interesting system is the Rutgers Master II developed at the Rutgers University. This haptic interface (Bouzit et al., 2002) permits to flex or extend the subject fingers, with a maximum force of 16 N, using four pneumatic actuators. Each actuator is equipped with a position sensor that allows to control the fingers closure according to a model that represents the virtual world.

The TENS (Transcutaneous Electric Nerve Stimulation) devices are also very interesting in the the field of the haptic interfaces. These systems are capable to generate a touch sensation without recreating the physical stimulus, like many other mechanical devices; this means high energy efficiency and very compact devices. Technically, it consists in changing the membrane potential of some skin receptors with an electric field applied by electrodes on the subject's dermis (Kajimoto et al., 1999). Controlling the current injected in the tissue, it is possible to modulate the receptor nerve activation and so the tactile sensation perceived by the subject.

Thanks to the bigger dimension of the mechanoreceptor nerves (10 μm) with respect to the pain receptor fibers (1 μm), it is possible to evoke the touch sensation and avoid the pain sensation.

Even if big improvements were done in the last decades, many haptic devices are still unable to generate a fully immersive sensation, because they operate outside the human perceiving system. To solve some of these issues, we have built a device that combines

Folgheraiter M., Gini G. and L. Vercesi D. (2005).
A GLOVE INTERFACE WITH TACTILE FEELING DISPLAY FOR HUMANOID ROBOTICS AND VIRTUAL REALITY SYSTEMS.
In *Proceedings of the Second International Conference on Informatics in Control, Automation and Robotics - Robotics and Automation*, pages 353-360
DOI: 10.5220/0001166703530360

visual, touch and force feedback in order to give a more realistic interaction with the virtual world.
In this paper we will show some results obtained with our custom built force feedback and touch sense glove that can be worn and can interact in strict contact with the human touch system. In particular the glove that we developed can be used for three main purposes:

1. To Explore the capabilities of TENS (Transcutaneous Electric Nerve Stimulation) stimulation in combination with a virtual simulation system.

2. To Acquire the grasp positions performed by a human operator in order to train a neural network to make a robotic hand execute the same task (Folgheraiter et al., 2004).

3. To Use the glove as an haptic interface to interact with a virtual world.

We did a first experiment to explore the possibilities offered by the TENS stimulation for the investigation of a virtual world. Using a special electrode applied at the fingertip, we evoked vibration and pressure sensations by injecting an impulsive biphasic current into the skin of the subject, according to the Gate Theory (Melzack and Wall, 1965). We performed different tests changing some stimulation parameters like the current injected, the stimulation frequency and the duration of the impulse. We also introduced a force feedback in opposition to the finger movements in order to emulate the virtual object rigidity.

2 ARCHITECTURE OF THE VIRTUAL GLOVE

The system is composed by a glove equipped with 14 angular sensors and 2 force sensors (figure).

Angular sensors measure the joint rotation of each phalanx for every fingers, except for the little one. Force sensors are connected in series with the tendons that permit to transfer the force from the actuator to the fingertip. We realized them cutting and reshaping commercial sensors, in particular we used flex sensors and FSE (Force Sensor Resistor).

Three angular sensors are mounted on each finger respectively for proximal, middle and distant articular joints. Two sensors, of the same kind, are mounted between the thumb and the forefinger to measure abduction and adduction movements.

The glove is also equipped with a light arm-band, rigidly fixed on it, where we have put the actuator system able to bind the finger movement in its dexterous space.

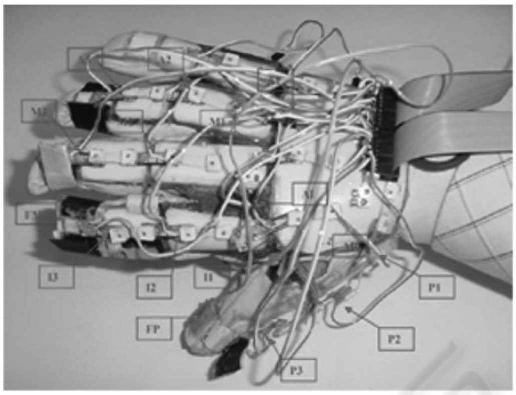

Figure 1: The Glove.

2.1 Force feedback system

The force feedback actuator is composed by a servo connected to the fingertip through two tendons fixed to the solid plastic bands of the glove (Figure 2). The tendons run along the finger length across some passings. We fixed each tendon so that the servo force was driven perpendicularly to the movement path of the finger. In this way we optimized the force transferred along the tendon to the fingertip.

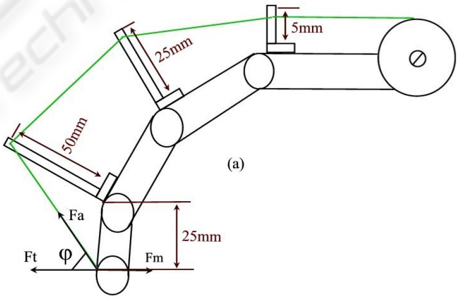

Figure 2: Schema of the artificial tendons.

The virtual object is modelled by its dynamics equations. The force generated by the object depends on its mechanical characteristics, to a first approximation we can write the model as following:

$$F_v(t) = K_e x(t) + K_d \frac{dx(t)}{dt} \tag{1}$$

Where K_e is an elastic constant, K_d is a damping constant and $x(t)$ is the penetration rate into the object surface.

To have the equilibrium, the force generated by the tendon to the fingertip must be equal to the force generated by the virtual object (F_m). We implemented a software to calculate this force in real time; taking into account the mechanical structure of our glove, the equation 1 can be rewritten as equation 2.

$$F_a(t) = \frac{K_e x(t) + K_d \frac{dx(t)}{dt}}{cos\varphi} \tag{2}$$

Where φ is the angle that the tendon forms with the last phalanx (see figure 2).

2.2 Electro-cutaneous stimulation system

The electro-cutaneous stimulation of the fingertip is due to an electrode fixed between the glove and the user's finger. The position of the electrode can be adjusted to choose the specific zone that we intend to stimulate. This is also important to avoid an uncomfortable sensation caused by a bad contact position. Furthermore, we can increase the skin-electrode contact quality using a conductive gel.

To a first approximation (Kaczmarek and Webster, 1989), we can model the skin-electrode contact as following (figure 3).

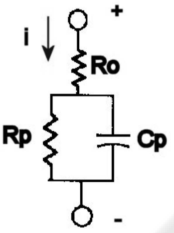

Figure 3: Electrode schema and realization.

Where R_0 is the resistance between the electrode and the conductive gel, R_p and C_p are the resistance and the capacity of the the electrode-skin interface. According to previous works and empiric tests (Kaczmarek and Webster, 1989), R_0 results smaller than R_p and can be ignored to a first approximation. Therefore, if V is the impulse amplitude applied to the electrode-skin interface, we can write the voltage value presented on the subject tissue V_{pp} as following:

$$V_{pp}(t) = V(1 - e^{-\frac{t}{\tau}}) \tag{3}$$

$$V_{pp}(t) = Ve^{-\frac{t}{\tau}} \tag{4}$$

Equations 3 and 4 represent respectively the rising and falling voltage characteristic.

We can see from the electrode-skin interface response that the behavior is not linear. This represents a problem for the electro-tactile stimulation because, with fixed voltage at the electrodes, the current injected can vary with time and so the touch sensation felt by the subject. To avoid this problem, we can control the current instead of the voltage.

In its turn the voltage V_{pp} generates an electric field into the skin surface that causes a potential on the external membrane of the axon fibre.

In their work (Kajimoto et al., 1999) Kajimoto H. et al described the equivalent electric membrane model. They related the potential value of the membrane surface with the corresponding inner value for impulsive stimulus according to the Hodgkin and Huxley theory (Hodgkin and Huxley, 1952).

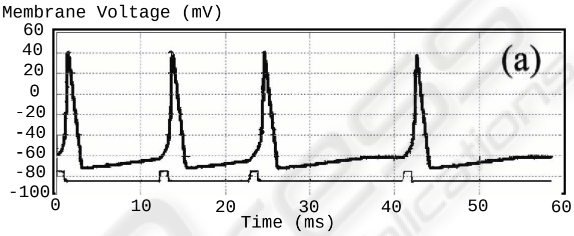

Figure 4: Signal built by membranes of nervous axons according to the Gate Theory. This picture has been built by a Hodgkin-Huxley Model simulator (a).

Electrodes are controlled by a custom built TENS-board able to generate a generic biphasic wave varying in frequency (1Hz-5KHz) and intensity (0-5mA) according to the transcutaneous electrical nerve stimulation theory. The area of the positive pulse is nearly equal to the area of the negative impulse. This is important to avoid that the electrolysis phenomena might cause a permanent tissue damage.

The TENS board is divided into two main blocks. The first block realizes the wave generator; it works at low power and can interact with the PCL-812 A/D board through 4 dedicated channels. An impulsive digital signal is presented on the gate of a NPN transistor that performs a first small amplification, this realizes the frequency base of the stimulation wave. A digital potentiometer (RDAC) varies the amplitude of the voltage signal. The RDAC is controlled through the 3 remaining digital channels.

The second part of the board amplifies the signal thanks to a couple of op-amp (Operational Amplifier) and then elevates it through a voltage transformer connected to the electrode. The transformer elevates voltage from 5V to 100V and generates the biphasic wave.

We completed the board introducing some capacitors to decouple the two phases of the signal transformation. The output of the op-amp has been also stabilized by a Boucherot block.

In this way the board is completely controlled by the digital channels of the same A/D card used for sensor measurements, and can send out the real-time value of the current injected in the finger-tip. We are able to control the current injected, making an instantaneous control loop (via software), both for safety and adaptability to different users.

To make different experiments we used two electro-stimulation channels of the same kind and different kinds of electrodes.

2.3 Acquisition and Control systems

The following schema (figure 5) presents the whole acquisition and control process. Each block is described by a name and its implementation techniques (hardware/software).

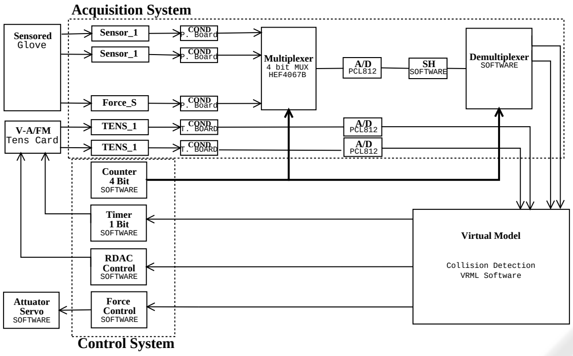

Figure 5: The acquisition and control blocks of the entire process.

All the sensor measurements have been normalized and multiplexed, using an electronic board and then broadcasted through a single analogical channel to an A/D general purpose card (PCL-812) mounted on a PC executing the xPC-target tool of Matlab. Thanks to xPC-Target architecture we can build physical interfaces and control levels and execute them on different calculators, $Target$ and $HostPC$. Target-PC plays also the role of implementing a first control loop to determine and generate the real-time value of injected current. A specific value is assigned by the virtual model according to the object surface characteristics; the control module sends data to the TENS-board in order to stabilize that value. This is important to generate similar sensations in different subjects.

Target-Pc is connected, using a RS232 interface, with a mobile PC that plays the main role in building the world model. The model is realized through a VRML file that can be viewed and analyzed by a proper C++ program with capabilities of collision detection, based on v-collide algorithm. The virtual model simulator is composed by two main parts: a communication module and an external module. The communication module plays the role of interfacing Matlab with the external VRML module. The external module implements the graphical engine and records all the objects into a tree data base that can be sent and parsed in real-time by the v-collide functions in order to determine collisions between objects.

The Host-Pc can realize a second control loop based on angular-sensor measurements, evaluating collisions and then, through the actuator system, binding the finger movement and sending the proper electro-cutaneous stimulation to the finger-tip.

The third and last control loop is made by the user through a visual interface that shows the virtual 3D model (figure 6) and enables controls on every process variables.

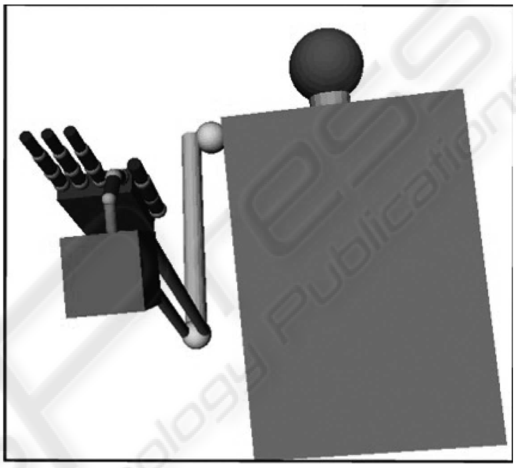

Figure 6: The VRML model permits the user to have a visual feedback.

All the software modules, except to the win32 C++ application for 3D model visualization and collision detection, are built in Simulink and compiled for real-time execution in Matlab.

3 ELECTRICAL TRANSCUTANEOUS STIMULATION EXPERIMENTS

We can divide our experimentation into two main phases. At first we investigated the role of frequency and current intensity with an half period pulse width, then the duty cycle (pulse width) has been varied and we have recorded the differences felt by the subject. For each experiment we have prepared a question set of tested points and a set of possible subject responses.

3.1 Role played by the stimulation intensity and frequency

For the first experiment, we prepared seven different frequency tests (from 5Hz to 400Hz), each of them differentiated in four levels of current intensity (from low to very high). This means we have a global test set of 28 values for each subject.

The two sets can be described by equation 5 (the number values are expressed in Hz) and equation 6.

$$I_f = \{5, 10, 20, 50, 100, 200, 400\} \quad (5)$$

$$I_i = \{\ Low \quad Middle \quad High \quad V.High\ \} \quad (6)$$

Each value of the I_i set is defined by the correspondent peak current interval as following:

- $I \epsilon Low \Leftrightarrow i \leq 1mA$
- $I \epsilon Middle \Leftrightarrow (i > 1mA) \wedge (i \leq 2.5mA)$
- $I \epsilon High \Leftrightarrow (i > 2.5mA) \wedge (i \leq 4mA)$
- $I \epsilon VeryHigh \Leftrightarrow i > 4mA$

The final question set can be described by the 28 position table described by equation 7.

$$I = I_f \times I_I \quad (7)$$

Each sensation produced by the electrical mechanoreceptor stimulation has two main components: the intensity level and the sensation evoked in the human mind (Bach-Y-Rita et al., 2003). We prepared two response sets in order to map either components. The first set is composed by six possible intensity response (from NoSesation to Pain). The second one has seven elements corresponding to seven possible sensation felt by users. We can write the two sets as in equation 8 and equation 9.

$$R_i = \{NoSens., Low, Midd., High, Irrit., Pain\} \quad (8)$$

$$R_f = \{B., I., V., T., R., W.\} \quad (9)$$

Where the sensation evoked values in the set are Beats, Itch, Vibration, Tingle, Rasping and Warm.

To make a common guide for each experimentation we prepared an explicative table in which we described every elements of each sets. The final response set is described by the 42 position described by equation10

$$R = R_f \times R_I \quad (10)$$

In this manner the first experiment can be described as following:

$$\forall f \epsilon I_f, \forall i \epsilon I_I \Leftrightarrow Resp(f, i) \epsilon R \quad (11)$$

For each frequency in the frequency set I_f and for each intensity level in the intensity set I_I we note one response of the response set R.

During the experiment we observed that subjects felt a starting beat when stimulation started. This beat could be uncomfortable in many cases. We recorded subject starting beat sensations at 50Hz and 200Hz for the middle intensity level.

After the data acquisition we prepared a double entering table where we put the mean and variance of R_i elements response. For brevity we present only the shortest version of this table in which we put the whole data grouped by intensity levels. Data is shown in figure7.

Intensity	**Current**	**Mean**	**Variance**
Low	0-1mA	1.14	0.04
Middle	1-2.5mA	2.06	0.02
High	2.5-4mA	3.26	0.06
Very-High	4mA+	4.09	0.17

Figure 7: Mean and variance values of subject responses.

Values under 1mA (Low) are inappreciable to most of the subjects. Subjects felt low sensation between 1mA and 2.5mA (Middle). At this level they can be distracted by other stimuli, like people speaking, and because of that they forget the current stimulation. This is an important consequence of filter theory. Values between 2.5mA and 4mA (High) are strongly felt by the subjects. In this case subjects cannot be distracted by other external stimulus. Values up to 4mA (Very-High) are considered strong and uncomfortable. In some case subjects feel pain. The high variance present for this data group suggests us to increment the number of elements of I_i decreasing steps especially for high values (4mA+).

The graphic in figure 9 shows the subject mean perceived values related to the real intensity of the electrical stimulus. For brevity we present only the 50Hz, 100Hz and 200Hz graphs.

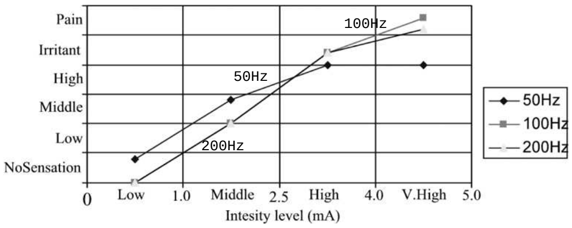

Figure 8: Subject sensations by electric pulse intensity.

As we can see by the graph, the sensation perceived by the subject grows logarithmical with stimulation intensity. This supports the Steven's theory (Darley et al., 1994) according tp which the sensation felt by a subject grows following the equation 12.

$$S = K \cdot I^b \quad (12)$$

Where S is the sensation perceived by the subject, I is the stimulus entity, K and b are two constants that depend on each subject. In the transcutaneous stimulation K and b depend also on the impulse frequency. This is true if we think that the Hodgkin and Huxley relation (Hodgkin and Huxley, 1952), between generator potential and axon activation potentials, suggests a proportionality between frequency of axons potential and stimulus intensity. We can realize an empirical calibration of K and b in order to prepare the personal subject sensation function.

To study the sensations evoked by the electrical stimulation, we prepared a second double entering table in which we described for each f,i couple the R_f element the subject response.

Here we present a shortest version of this table where we describe all the results grouped by frequency values. The table is shown in figure 9.

Frequency	**B.**	**I.**	**V.**	**T.**	**R.**	**W.**
5Hz	11	1	0	0	0	0
10Hz	11	2	0	0	0	0
20Hz	7	1	5	2	0	0
50Hz	2	5	7	2	0	0
100Hz	0	1	8	1	3	0
200Hz	0	6	7	1	0	0
400Hz	1	2	6	1	0	4

Figure 9: Subject sensations by frequency values. Beats, Itch, Vibration, Tingle, Rasping, Warm

From this table we can build a graph related to the sensations evoked during the experiment (Figure 10).

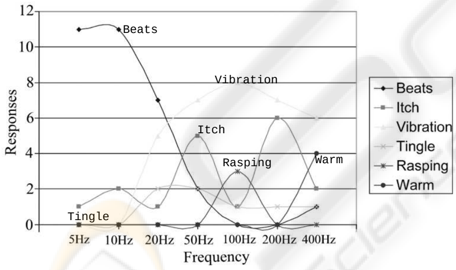

Figure 10: Data graph of subject sensations by frequency values.

We can see that at very low frequency (from 5Hz to 20Hz) subjects feel beats and small pressure sensations. Merkel cells are sensible to that frequency and seem to be specialized in detection of pressure and surface deformations. At middle frequency (from 100Hz to 200Hz) a new sensation of vibration was evoked. Users can't understand, in many cases, the period of the impulsive current but can only perceive a sensation of rapid vibration or grasping object under the fingertip surface. If we think that grasping sensation can be related to hard vibration, we can assure that the 82% of the sensations evoked by a stimulus of about 100-200Hz can be identified as a vibration stimulus. This agrees with the former works that suggested that Pacinian Corpuscles are sensible to vibration and operate at that frequency (Kajimoto et al., 1999).

The starting beat tests produced no interesting data. We could only see that starting beat sensation grows with intensity. This can be connected to the typical adaptability (Guyton, 1987) of each mechanoreceptor in the fingertip.

To determine the maximum frequency that the human mechanoreceptors may perceive, we tried stimulations at 1.2KHz and 5.0KHz. We noted that no subject can perceive impulses faster than 5.0KHz. This value can be assumed as a first upper bound.

3.2 Pulse Width Modulation of the electrical stimulation wave

In the second experiment we tried to demonstrate the role played by the impulse width of the electrical stimulation wave. We fixed the frequency at two significant values (10Hz - 50Hz) for two intensity levels and then we asked the subject to describe the difference perceived varying pulse width from 10% to 90% of the whole period.

Question sets are described by equation 13, equation 14 and equation 15.

$$I_f = \{\ 10Hz \quad 50Hz\ \} \tag{13}$$

$$I_i = \{\ Middle \quad High\ \} \tag{14}$$

$$I_w = \{\ 10\% \quad 90\%\ \} \tag{15}$$

Where I_f describes test frequency values, I_i is the intensity level set and I_w is the impulse width values of the experiment. Response set $\mathbf{R_w}$ is described by table 1

Table 1: Response set

$\mathbf{R_w}$
Lower
Stronger
Softer
Harder
Faster
Slower
Equal

The $Lower$ and $Stronger$ values mean that the subject feels the same sensation but perceives some variation in the intensity level. The $Softer$ and $Harder$ values mean 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 variation.

The whole experience can be described by equation 16.

$$\forall f \epsilon I_f, \forall i \epsilon I_i, \forall a \epsilon I_w \Leftrightarrow Resp(f, i, a) \epsilon R_w \quad (16)$$

Results of the data acquisition are described in table shown in figure 11, where we grouped data by impulse width.

w	L.	St.	So.	H.	F.	Sl.	E.
10%	11	0	0	4	0	0	5
90%	0	9	8	0	1	0	2

Figure 11: Subject responses about sensation driven by pulse width modulation. Lower, Strong, Softer, Harder, Faster, Slower and Equal sensation.

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 HAPTIC USER INTERFACE

The last experiment we made involved the force feedback, the cutaneous touch sense and a visual system. It can be divided into tree main phases. In the first part we used the force feedback system alone. The PCL-812 controls the servo angular position every 10ms; if a touch position is reached, servo reacts by slowing the finger movement. We can change the servo speed and touch position in order to simulate hard or soft surface of every dimensions.

The second experiment involved both force and cutaneous feedbacks. We introduced an electrical stimulation (100Hz, middle intensity level) on the fingertip when the subject reach the virtual object.

The third part of the experiment introduced the visual and the collision detection systems. We present to the subject a VRML virtual model of the human hand and the objects (Figure 6). When the system detects collisions between the hand and the objects, the force feedback and the cutaneous stimulation are activated in order to give to the subject a fully immersive sensation.

For all the experiments we prepared two virtual objects of different dimension. For each object we tested two different force opposition values. We can describe the question set related to the object dimension through equation17.

$$I_d = \{\ Small \quad Big\ \} \quad (17)$$

and the question set related to the object hardness through equation 18.

$$I_f = \{\ Soft \quad Hard\ \} \quad (18)$$

the resulting question set is composed by the 4 position table described in equation 19.

$$I_n = I_d \times I_f \quad (19)$$

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 him to recognize its properties choosing his answers 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 visual system, they were able to assign a correct shape interpretation for the touched object. Summarizing, with force feedback system only, subjects feel a movement opposition force but not a real touching object sensations. Combining force feedback and electrical touch system, subjects can determine the contact position accurately but already they do not feel a real detectable touching sensation. When the whole system was tested, subjects easily affirmed that they were touching an object of the correct shape.

This is an important result if we think that the introduction of the visual system produces a lag into the frame rate of about 50ms (100ms of V-Collide system to 10ms of Simulink model), five times higher than the servo impulse ratio. This lag is due to the algorithm for the collision detection analysis and to the communications between the two interacting software tasks.

5 CONCLUSION

In this paper we presented an haptic interface for application in virtual reality and for tele-manipulation systems.

In the first part we described the model, the hardware and the software used. In the second part we presented three main experiments. The first experiment explores transcutaneous electrical stimulation frequency in order to evoke vibration and pressure sensations. We can determine, by a calibration process, the K and b parameters of the Steven law (Darley et al., 1994) to fix the intensity levels of each subject. Once we found the correct intensity and frequency of stimulations, we explored the pulse width modulation capabilities.

In the last part we tested the force feedback, the touch display and the visualization system in order to simulate a virtual object with different hardness and dimensions. Our results demonstrated how integrating these three kinds of stimulus offered to the subject a more realistic interaction with the virtual world.

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