

Integrating tactile and force feedback for highly dynamic tasks: Technological, experimental and epistemological aspects

Armen Khatchatourov^{a,*}, Julien Castet^b, Jean-Loup Florens^c, Annie Luciani^b, Charles Lenay^a

^a Université de Technologie de Compiègne, EA 2223 Costech, 60200 Compiègne, France

^b ICA(EA 2934)-INPG, 46 av. Viallet 38000 Grenoble, France

^c ACROE, 46 av. Viallet 38000 Grenoble, France

ARTICLE INFO

Available online 20 November 2008

Keywords:

Haptic
Force feedback
Kinesthetic feedback
Tactile
Braille
Virtual environments
Enaction
Closed-loop interaction
Real-time synchronised architecture

ABSTRACT

For hand–object interaction in real situations the interplay between the local tactile interaction and force interaction seems to be very important. In current haptic interfaces, however, two different trends are present: force feedback devices which offer a permanent invariable grip and a resultant force, and tactile devices, which offer variable local patterns, often used for texture rendering. The purpose of the present work is to combine the two types of devices in a coherent manner. In the new device presented here, the tactile stimulation is obtained from strictly the same interaction loop, and obeys to the same physical model, as the force feedback, providing the information on the spatial distribution of forces circulating between the object and the fingertip. An experiment on following sharp edges of virtual object comparing the force feedback alone and different tactile augmentations is presented and discussed, alone with some open epistemological issues.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

1.1. Technological challenges

The aim of this paper is to progress towards haptic interfaces which integrate force feedback and tactile stimulation.

The human haptic system can be characterized by at least three important aspects: (1) it encloses in an interdependent manner several multiform components (kinaesthetic, tactile, thermal); (2) it is intrinsically reciprocal, i.e., a modification of the state of the sensing organ modifies the sensed object and vice-versa, which is not the case with other modalities; and (3) it deals with the topological and morphological complexity of the body. Thus, the haptic system is a complex integrated modality, and an apparatus by which the individual gets information both about the environment and about his own body. Our main conceptual hypothesis is that the three above-mentioned aspects are closely linked; and more precisely, that the tactile-force relationship is closely linked to reciprocal and spatial aspects of the haptic modality.

These aspects are not fully taken into account in most current Virtual Environments (VE). Haptic interfaces for VE are seriously behind the levels of accomplishment of other functionalities of

VE platforms, such as the “computer graphics” for modelling and simulating purely visual aspects of objects. Force feedback devices (FFD) present considerable technological difficulties and issues (frequency bandwidth, stability, etc.) which become critical if one wishes to model highly rigid (large instantaneous forces) or very soft (very weak but very precise forces) interactions with objects, as well as “frictional” interactions where the contact and adherence forces are not necessarily spatially homogeneous. Tactile devices in HCI have been, up until now, poorly developed and are not much used.

Thus, integration of these two devices aims to address one of the major bottlenecks in haptic interfaces, and to progress towards:

- Overcoming the limitations of force feedback devices, e.g., the permanent grasping of the end-effector and the absence of multi-point surface local displacements and forces.
- Overcoming the limitations of tactile devices, e.g., the fact that the action produced by the tactile device is not necessarily directly linked to the action of the user; and that there is no correlation between the action of the user and the local forces which are reproduced by the tactile device.
- Combining local small scale and high spatial resolution multi-point contact area with the larger spatial scale of the force feedback device, which is often limited to one-point interaction.

* Corresponding author.

E-mail address: armen.khatchatourov@utc.fr (A. Khatchatourov).

Moreover, to improve the effectiveness of touch in computerised environments, an ideal integrated system should be able to function so that the two devices (tactile and force) work together in a coordinated manner, in order to reproduce in a coherent manner the physical properties of the virtual object and to respect the physical consistency of the interaction between the user and the object. This would correspond to a complete multi-scale mechanical coupling system which could be the symmetric of the human senses and motricity. At the current stage of technology it seems difficult to produce an integrated tactile-force feedback device (T-FFD) which would work as closed-loop device for both components (see Section 5 below).

These technological difficulties stem from the complexity of touch interaction, both in natural and in computerized environments. The motivation of the present study is to do spadework at the conceptual, technological and experimental levels in order to approach this complexity. The aim of the present study is first of all to work on models of integration and thus to progress towards an integration which will take into account, in a coherent fashion, surface force fields, interaction in a highly dynamic closed-loop, and the tactile modality as an endogenous control for the forces and displacements exerted by the hand.

1.2. Haptic perception studies and haptic interfaces

Within the general studies on haptic perception, it is usual to distinguish between the perception of forces (often associated to the kinaesthetic system) and tactile perception (often associated to the cutaneous sensing system) (Loomis and Lederman, 1986).

These differential associations are not obvious in real situations, where the two systems are mostly activated conjointly: during the haptic perception of an object, there is simultaneously a cutaneous stimulation and a perception of forces.

Tactile and force perception can only be dissociated in certain rare conditions. The typical cases are the experiences by Jansson et al. (1999), Jansson and Monaci (2006) for object recognition, and by Lederman and Klatzky (1999) in particular for roughness perception. In all these studies, the experimental conditions vary the availability of tactile feedback by placing sheaths on the finger. The spatial tactile information is then not available or is constant, whereas the sensation of movement and effort is present. Despite the fact that, even in these cases, the generated vibration may “activate” tactile perception (Lederman and Klatzky, 1999), for the purposes of the studies on human perception, the modalities are considered as in principle separable and studied as such (e.g. Symmons et al., 2007).

Then, it may seem pertinent to use the VE systems (Loomis et al., 1999), in particular haptic devices (Jansson, 1998) in which the components providing force feedback are distinct from the ones providing tactile stimulation. So it may seem easy to artificially combine, or dissociate, the two modalities, and thus to study their functional relation within the general field of haptic perception. This would permit to acquire new knowledge concerning haptic perception for developing models of functional coupling of the two components in the human system.

However, this task suffers from several drawbacks:

First, even in highly controlled experimental conditions, and even if the distinct devices are used, the tactile modality cannot be rigorously separated from the perception of forces, and vice-versa, particularly in physical manipulation tasks. Is it reasonable to suppose that during force feedback interaction the human tactile cutaneous system would not be activated? And conversely, that in tactile skin stimulation, kinesthetic perception would not play any role?

Second, the studies of haptic perception are strongly conditioned by the available haptic devices. As a result, most

implementations can only perform specific aspects of a given task. Moreover, the degree of resemblance with tactile stimulation in a “natural” situation will depend on the computer models employed.

Third, the major difficulty resides in the fact that from a functional point of view, the balance between the relevance of tactile versus force perceptions may vary according to the sensory-motor loops established during a performance of a task (e.g. Lederman and Klatzky, 1999).

These points will be discussed in details later on in the last section. Suffice it to say for the moment that psychophysics studies are closely linked to the technological development of both haptic devices and adjacent computer models, and that such research needs to implement a specific methodology. The major methodological difficulties to be addressed for the integration of Tactile and Force components are symmetrically: (1) on the technological side, the difficulty inherent to this type of integration at the level of devices and computer processes of their control; and (2) on the human side, the lack of knowledge concerning their functional relations.

1.3. Theoretical and methodological aspects

More generally, as discussed in Cadoz and Wanderley (2000) and Sheridan (2002), during the manipulation of a physical object the coupling of the two systems – human and object – leads *de facto* to consider these two coupled systems as a whole. Together they form a third system with new emergent properties which should be taken into account and studied as such. Cadoz and Wanderley (2000) called such situations “instrumental situations”, and named the specificity of this type of coupling “the ergotic function of the human-environment interaction”. In the following we will use the terms “instrument”, “instrumental” and “ergotic” to refer to that type of coupling. In such situations, the knowledge of human action-perception system cannot be considered as independent from the particular situation and particular manipulated object.

This remains true for the computerised situations (Luciani, 2004) (Florens et al., 2006), and especially in manipulation tasks involving integrated tactile-force feedback devices and computer simulations. Thus, technological development is not a direct implementation of the knowledge about human perception, neither is it the direct means to conduct psychophysics studies without taking into account the emergence of new properties of the whole system composed of the human, the haptic device and the manipulated object. Conversely, the question arises: what degree of technical achievements and what degree of genericalness in regard to human performance are really necessary for accomplishing the tasks that these devices are designed for.

One of the ways to hold together psychophysical studies and technological development has been proposed by Lenay et al. (2003). The authors have developed a characteristic approach – a systematic “minimalism” – which makes possible, by progressively increasing the complexity of the technical device and the experimental situation, to identify the “thresholds” of technological complexity for accomplishing a given task. Another way is to develop a priori over-scaled and over-performing systems specified to be used as measurement tools and to be able to catch experimentally relevant psychophysics features (Castagné et al., 2005; Luciani et al., 2007). To identify necessary and sufficient level of technological complexity these two methodologies have to be thought in their convergence.

1.4. Research questions

We are particularly focused on the dynamic effects in haptic manipulation which have not been much explored up until now. By “dynamics effects” we mean effects in which temporal features

play a critical role. For example, in a task of following sharp edges of a virtual highly rigid object, the wide spatial bandwidth, representing the spatial discontinuity, creates critical temporal effects such as very fast variations in velocities. Such properties may make necessary to adopt specific computer architectures (for example, hard real-time synchronized architectures) and dedicated high resolution FFD. The temporal effects may play an important role in haptic manipulation, and can open the way to new investigations on the role of the tactile component in the haptic modality as a whole.

The integration of the two devices involves at least two distinct levels: that of their mechanical integration; and that of their integration at the level of the computer process which controls them. In this study, we leave aside the question of the co-location of the two devices and their mechanical integration: the force feedback involves one hand and the tactile stimulation the other. The process of control of these devices is, for a part, a computer model based on hypotheses about the relation between the two perceptual modalities in humans. We argue that the dynamic and spatial coherence of the behaviour of the two components of the haptic interaction should be also implemented at the level of the computer model. That's why our experiments are based on a simple mechanical hardware association of the devices; and the emphasis is put on the computer models controlling the devices' collaborative behaviour.

Three main hypotheses which guide the implemented computer models (see Section 3) are the following:

- Tactile and force stimulations are produced within the same interaction loop rather than being produced independently.
- Tactile stimulation provides information on the deformation of the exploratory body.
- Tactile stimulation provides information on spatial configurations of the object.

In line with these hypotheses and our focus on dynamic effects, we aim to address two research questions:

1.4.1. *The role of spatial information*

Does the addition of spatially distributed tactile information, combined with the force feedback through the rigid locally invariable end-effector of a FFD, succeed in approaching the spatial distribution of forces in a real situation? The present work addresses this question through the tactile information which informs the user about the spatial configuration of the objects.

1.4.2. *The role of the deformability of the exploratory body*

The deformability of the exploratory body can play an important role in natural (i.e. non-mediated by electrical and computer systems) haptic interaction, since it creates a mechanical constraint for body displacement, and it is also felt as skin stretching. In VE implementations, the deformation of the exploratory body can be addressed at two levels: at the level of modelling the deformation of the object which represents the virtual fingertip; and at the level of the information on this deformation brought to the user through the tactile and/or force actuators. In the present work, the implemented computer models (see the Models and Discussion sections) are designed to inform the user about the deformation of the virtual exploratory body by the tactile stimulation and partly by the force feedback.

We compare the model with force feedback only with the various models of integration with tactile stimulation, in the task of following highly rigid virtual object. We aim to show three things: (1) for the dynamic tasks in question, it is relevant to achieve tactile-force integration; (2) with an identical device, the results depend on the implemented computer model; and (3) the interpre-

tation of the role of tactile perception also depends on the computer models and the underlying hypotheses.

2. Previous work on tactile and force feedback integration

The enrichment of force feedback by tactile stimulators has been initiated in the field of teleoperation for enhancing grip control, for example by putting the pressure sensors on the slave arm and pin-like actuators on the master arm; and more recently in the field of Virtual Reality for surgical simulations and texture rendering.

In the area of surgical simulation, the softness of the modelled object combined with visual control means that the requirements for models and force feedback devices are not very stringent in terms of the dynamics of the coupling. In this field, there are several studies on the integration of tactile and force feedback devices, mainly with the methods of finite elements (Wagner et al., 2005), but they are limited to models for soft tissues and to the exploration of homogeneous stiffness (there are no high thresholds for forces, and no conditions on boundaries). Other works address force feedback interaction with rigid objects with geometrically based haptic algorithms (Morris et al., 2006) but not in the context of tactile and force feedback integration. The integration of T-FF devices in situations with high spatial and temporal bandwidths is still not sufficiently addressed.

In the area of texture rendering, the accent is put on modelling relatively homogeneous textures/fabrics mainly using geometrical haptic algorithms based on collision detection. In this field, the main limitation of tactile devices coupled to force feedback resides in the fact that the tactile loop is disconnected from the main force loop, and functions only in a “display” mode for rendering texture (Takasaki et al., 2005; Summers et al., 2005; Allerkamp et al., 2007; Kyung et al., 2007).

More recently, two other complementary aspects are explored by research in tactile-force integration: (1) the orientation of the forces (“shear” and “tangential” forces) and (2) the spatial distribution of the stimulation:

(1) Concerning the rendering of “shear” and “tangential” forces, several studies address the questions of friction and slippage. Two approaches are used within this aspect: (1a) display of the tangential forces with encountered contact point (Cini et al., 2005; Provancher et al., 2005); and (1b) tangential forces displayed to the user in grasping (Verner et al., 2005) and in slip interaction (Fritschi et al., 2006; Salada et al., 2005; Webster et al., 2005). In these systems a critical issue concerns the control of the motion of the end-effector of the force feedback device, so that it could follow the finger motion without introducing unwanted contact forces as they exist when the finger is tightly attached to the end-effector.

(2) Concerning the spatial distribution of the stimulation, devices such as gloves with air cushions or several vibro-tactile stimulators (Benali-Khoudja et al., 2004) attempt to render the force fields and thus to combine tactile stimulation and kinesthetic stimulation. However, these devices do not have the reactivity of dedicated force feedback devices or dedicated tactile devices. Other devices combine force feedback and tactile spatially distributed arrays such as (Wagner et al., 2004, 2005).

Finally, we would like to discuss in a more extensive manner two other works performed on tactile augmentation of a force-feedback device. In (Declerck and Lenay, 2006), the standard asynchronous PHANTOM FFD was equipped with the standard stylus, and with tactile Braille cells (a 4×4 array of piezoelectric pins) mounted in a box attached to the stylus. The scene was composed of a virtual bridge and of an avatar (exploratory body) controlled by the FFD; the avatar's collisions with the bridge gave rise to tactile and/or force feedback, the task being to follow the bridge

without falling. The implemented model of the virtual scene was based on collision detection approach, and there was no deformation of the exploratory body. Another study by Kuchenbecker et al. (2004) addressed the contour following of the resistant rectangular block with a device composed of PHANTOM and encountered contact thimble-based mechanism attached to its the endpoint (a cylindrical tactile element moves along the fingertip to indicate the position of contact). The computer model was based on the representation of the finger as arc segment and collision detection in order to bring the tactile element to the wanted contact location. These two studies are further discussed in the last section.

To sum up, previous work usually addresses interactions with soft objects where the forces are weak and where there is no high bandwidth (and the corresponding implementations are not always adapted to non-linear closed-loop dynamic interaction); and the tactile stimulators are mainly used as a display, i.e., to present information to the user. Notwithstanding the importance of this work it does not fully embrace the non-linear closed-loop dynamic interaction with physical objects, where the integration of tactile and force feedback may also be pertinent. Thus, the present study is focused on highly dynamic interaction with rigid objects.

Two distinct approaches to the technological implementation can also be deployed: (i) an approach within the “vis-à-vis” interaction paradigm, with the object in-hand. In this paradigm, the device is in front of the user. It has to be at the scale of the human hand, and to be portable to some extent; (ii) an approach which is closer to the immersion paradigm, where the hand is “encapsulated”. These devices are necessarily heavier and are not meant to be portable. The present work explores the interactions with rigid objects within the “vis-à-vis” paradigm.

3. Technological development

3.1. Computer models of the simulated virtual objects

Following the described approach, a novel device for accurate haptic interaction has been developed. The computer models have been developed for the task of following sharp edges of a virtual highly rigid object. The main novelty of this device is that the tactile stimulation is obtained from strictly the same synchronised interaction loop, and obeys to the same physical model, as the force feedback. Thus, it addresses both research questions: it provides information on the spatial distribution of forces circulating between the object and the body, and also informs the user about the physical deformation of the exploratory body.

The scene (see Fig. 1a) is modelled using physical particle modelling, i.e., basically by masses connected to each other by springs. This allows easy modelling of multipoint interactions. The exploratory body (virtual fingertip) is composed of a rigid grid of 16 masses, each of which is in independent interaction with the object of the scene (see Fig. 1b). The resultant force of interaction between the complete set of body masses and the object constitutes a material constraint on displacements of the body, and this resultant force is transmitted to the user through the end-effector of the FFD. Distinct tactile stimulations are realized by 16 tactile pins, each of which corresponds to one of the masses of the exploratory body. Each tactile pin is activated whenever there is the force exerted on the corresponding body mass. The activation of the pins is integrated in the force feedback calculus loop.

In the present study, the grid of masses representing the exploratory body is a rigid non-deformable grid rigidly attached to the FFD. The orientation of the square grid manipulated by the user is always the same (the grid is parallel to the horizontal plane of the user's workspace, and cannot change its orientation around the vertical axis: the model has three DoF). This is schematically represented below. As shown on the picture (Fig. 1a), the grid is square-on to the user, whereas the bridge has a diagonal orientation of 45° to the right (first and third segments) or to the left (second segment).

Four different models have been developed and compared (see also below, Section 4):

3.1.1. Computer model 1 (CM1)

Each pin is independently activated as soon as there is a force between a corresponding mass and the object, i.e., as soon as the contact occurs, without any threshold. The pins are up when there is a contact, and down when the grid is not in contact with the bridge.

3.1.2. Computer model 2 (CM2)

Each pin is independently activated as soon as there is a contact between a corresponding mass and the object, while the force feedback is only activated above a certain threshold. In practice, this has the effect of introducing a delay before the force feedback is felt: when the user is approaching the bridge, she first has a tactile interaction with the object, and then has to make a small additional displacement (of approx. 0.3 cm in user space) in order to feel the resistance of the object. The metaphor of this interaction is similar to the situation of a caress, or gentle stroking of an object in “natural” situation, when the tactile can be seen as the “zero grade” of kinaesthetic interaction, i.e., where the force is not yet felt, as in touching soft tissues or hair.

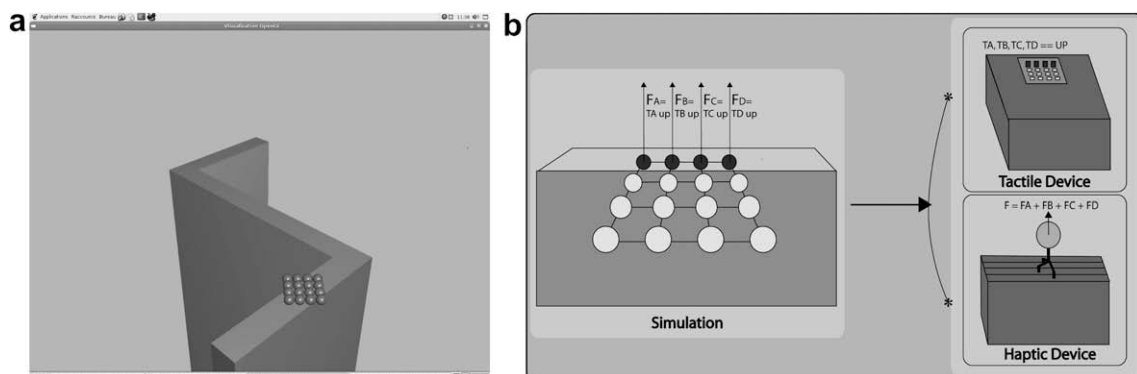


Fig. 1. (a) The model as implemented (screenshot). (b) Schematic representation of tactile and force components: in the model on the left, the black masses (A–D) are in contact with the virtual object, the light ones are not. This situation corresponds to the activation of corresponding tactile pins (TA to TD), and to the resultant force transmitted to the FFD (here the resultant force is equal to the sum of the four forces).

3.1.3. Computer model 3 (CM3)

This model is similar to CM1. Each pin is independently activated as soon as there is a force between the corresponding mass and the object, i.e., as soon as the contact occurs, without any threshold. With respect to the CM1, the pin activation is strictly inversed, that is the pins are up when there is no contact (and no force), and are down as soon as the force interaction occurs. The interest of this model is that the tactile sensitivity may be more sensitive to the upward movement of the pin which occurs here when the user begins to fall off the bridge.

3.1.4. Computer model 0 (CM0, also referred to as FFD-only)

Finally, CM0 is the same computer model as CM1 and CM3 but the tactile feedback is absent.

3.1.5. Deformation effect common to the models

Even though the grid which represents the fingertip is not objectively deformable, there is a deformation-like effect due to two features. (1) The variation in the number of masses in contact with the virtual object leads to a corresponding variation in the number of tactile pins which are raised and which actively stimulate the finger during the course of exploration. This can be considered as simulating a change in the surface contact similar to the change that would be produced by an actual deformation of the exploratory body. Obviously this part of the effect is not present for CM0. (2) The variation in the number of masses produces a modulation of the resulting force transmitted to the end-effector of the FFD, thus inducing an effect of a body which is more complex than that of a single point, or a rigid homogeneous surface. We call the result of these two features (see Fig. 1b) a “deformation effect” (DE).

3.2. Computer architecture

The implementation was done on the modular hardware platform composed of different units, easily adaptable to any particular task. Currently, the platform employs three types of components: multi-processor computers (2 or 4 processors) designed for hard haptic constraints; Digital Signal Processing (DSP) PCI boards; and the force feedback devices (Castagné et al., 2005, 2007). In this experiment, since the requirements were focused on haptic results, simulation required high reactivity, but did not require great computational power (the model of the scene being only composed of

few masses). Accordingly, the platform was employed using the “mobile” configuration composed of one general-purpose host PC, one DSP board on which the simulation runs (Luciani et al., 2007), and the ERGOS force feedback device (see Fig. 2a and b) in 3 DoF joystick configuration (Florens et al., 2004). The ERGOS FFD main characteristics are the workspace of $60 \times 60 \times 25$ mm (in current configuration), max force per slice 200 N (peak)/60 N (continuous), max velocity 1.8 ms^{-1} , peak acceleration 60 ms^{-2} , sensing resolution $1 \mu\text{m}$.

The DSP board is the TORO board from Innovative Integration (TMS320C6711) which is characterized by a computation frequency of 150 MHz. This card provides 16 simultaneous analog inputs and outputs up to 250 KHz each, both at 16-bit resolution for high quality haptics. A/D and D/A converters are synchronized on the same clock signal as the simulation process and are used for the exchange of data with the haptic device. The host PC running Linux is only used to control the global behaviour. A visual feedback is implemented and keyboard input provides parameter adjustment: these two tasks are accomplished by the host and do not interfere with the real-time simulation (they are accomplished between the two calculus steps, when the DSP has finished computing one step of simulation and awaits the next). Major characteristics of this configuration are a high simulation frequency (adjustable between 1 kHz and 44 kHz, 5 kHz for this implementation) and synchronous real-time architecture.

The standard Braille cells for the tactile component were integrated into the above-mentioned real-time architecture. The Braille cells from Metec AG are piezoelectric driven actuators, with dot spacing of 2.45 mm and with dot stroke of 0.7 mm, dot rising time of 24 ms and max clock speed of 500 kHz. They are connected through the 32 binary outputs of the TORO board. A routing board has been designed to adapt the DSP outputs to the analog conditioning of the Braille cells. Up to 32 pins are available, but only 16 pins (4×4 matrix) were used.

In the simulation process, the same physical model running on the DSP controls both the tactile and the FF devices (see Fig. 3). The bi-directional input–output flow with the FFD is synchronized at model's computation frequency and consists in a zero delay closed-loop I/O digital flow. The refreshment of the simulation is done simultaneously at the same calculus step for both the tactile and the force. The tactile digital output flow is down-sampled at a lower rate. This disposition is due to the specific properties of the Braille cells whose response time is about 24 ms. This property is

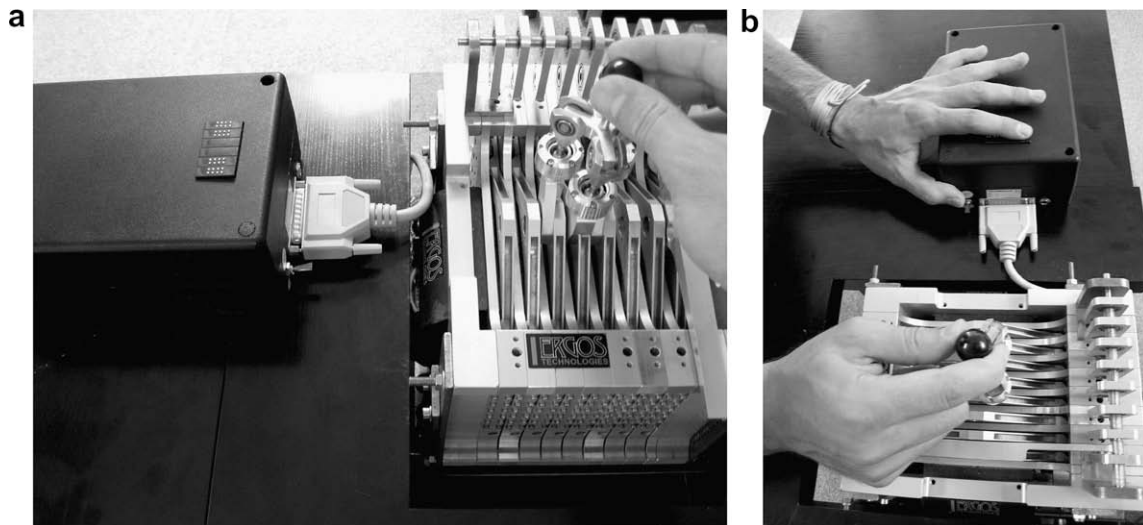


Fig. 2. (a) The device manipulated in FFD-only condition. (b) The device manipulated in FFD + tactile conditions.

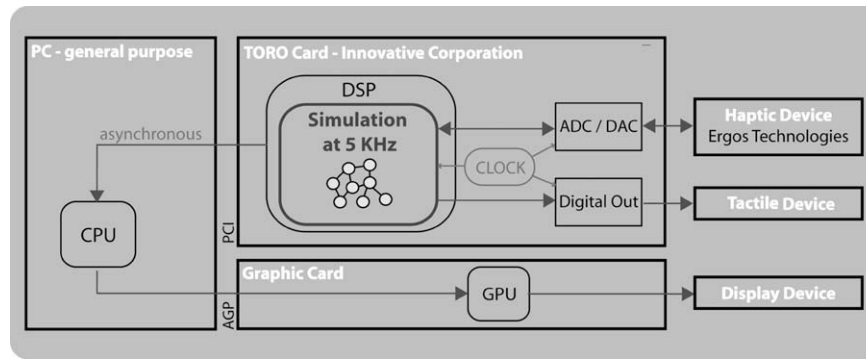


Fig. 3. The computer architecture.

not limiting in the present case since the tactile device works as a simple output device. The resulting average delay for this tactile channel is of 24 ms.

Another important aspect is that in the present development the tactile and the force components are not mechanically integrated, i.e., the interaction requires a bi-manual manipulation.

4. Experiment

4.1. Experimental design

An experiment has been performed, consisting of following the contour of a rigid object with the T-FF device described above.

4.1.1. Task

The subjects were asked to follow the bridge, staying as much as possible on its top surface, in order to reach its end. They were instructed to make small movements to adhere as much as possible to the bridge surface. If contact with the bridge is lost, they were instructed first to make lateral movements to find the vertical wall; then to follow it up to the top; and finally to reposition the exploratory body on the top surface. They were aware of the fact that both their rapidity (total task time) and accuracy (number of falls off the bridge) were measured, and that in the present experimental set-up there is a trade-off between these two criteria (Sribunruangrit et al., 2004), i.e., they have to combine both accuracy and speed. Subjects sat in front of the device, and manipulated the FFD stick with their dominant hand while the finger of the other hand was in contact with the tactile device.

4.1.2. Conditions

There were four experimental conditions corresponding to the four computer models (CM) described in the previous section: condition 0 (CM0, force feedback only); and for tactile and force feedback, condition 1 for CM1, condition 2 for CM2, condition 3 for CM3.

4.1.3. Procedure

At the beginning of each session, the subjects were familiarized with the device during 25 min, including all the four variants of the experimental conditions, both blindfolded and with vision.

Then they ran a “practice test” in a randomized order. In this practice test the four experimental conditions were present (3 min each), the subjects were blindfolded and wore earplugs, but no measurement of the performance was made. The purpose of this phase was to familiarise the subjects with the temporal constraints of the experiments.

Finally the measured session took place, during which conditions were randomized (3 minutes max for each condition). When the subjects missed one of the right-angled turns of the bridge and

got lost, the experimenter repositioned them at the beginning of the bridge, in order to preserve the continuity of the task. The task was considered as accomplished when the subject reached the end of the bridge. There were 12 subjects altogether; each subject performed one registered trial during this measured session. Each subject spent about 1 h in the experiment (familiarization + practice test + trials).

4.2. Experimental results

The results are presented in Fig. 4. The dependent variables measured were: the number of falls off the bridge (falls); the time necessary to accomplish the task (time_total); the time of contact loss (cumulated time of the falls off the bridge) (time_out). We also compared the ratio (time_out)/(time_total). In addition, the subjects were asked to rank the different conditions in order of their subjective preference.

The falls which last less than one second are not included in the cumulative time of loss of the contact; similarly, episodic contact lasting less than one second is not considered as “staying on the bridge”. Thus, when the subject loses contact with the bridge, “finds” it again but for less than one second, and then loses contact again, the situation is considered as a single fall.

Friedman test returned significant results for the number of falls ($p = 0.004$), time spent off the bridge ($p = 0.002$) and the ratio (time_out)/(time_total) ($p = 0.015$). The pairs were then analysed with Wilcoxon signed rank test for paired samples. We can not claim the statistical difference between all the pairs of conditions. In the next section, the p -values obtained with Wilcoxon test, for the null two-tailed hypotheses, are given before Bonferroni correction. The difference between mean values indicates a trend according to which the tactile conditions (and particularly the conditions CM1 and CM3) vs. FFD-only, permit a more accurate following of the bridge.

5. Discussion

5.1. Discussion of the experimental results

5.1.1. FFD-only (CM0) vs. CM1 and CM3

The mean number of falls is significantly lower in both tactile conditions ($p = 0.016$ for CM1 vs. FFD-only, and $p = 0.014$ for CM3 vs. FFD-only). Also, the time spent out of the bridge is significantly lower in both tactile conditions ($p = 0.02$ for FFD-only vs. CM1; $p = 0.03$ for FFD-only vs. CM3). Both of this tactile conditions were preferred by the subjects ($p = 0.002$ for FFD-only vs. CM3).

This indicates that the addition of tactile feedback can allow a more accurate following of the bridge. There is however no significant difference in the total time of task accomplishment. Two

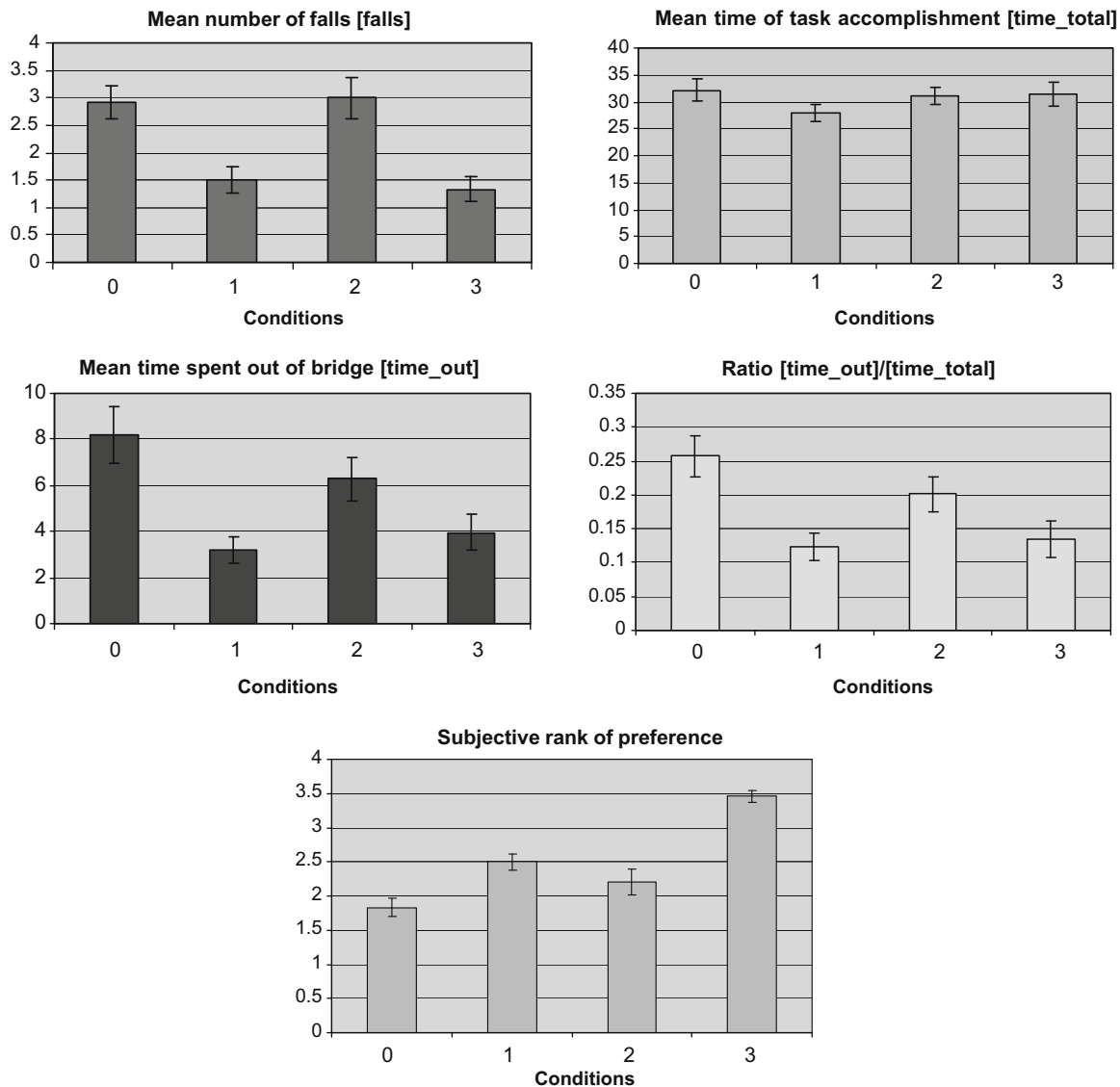


Fig. 4. Experimental results.

aspects can be analysed for this comparison: (a) the presence of the “deformation effect” in *FFD-only* condition and (b) the overall strategy employed.

(a) *Deformation effect in FFD-only vs. tactile conditions.*

In the models we have implemented, information on the spatial discontinuities is already partially available in the *FFD-only* condition through the Deformation Effect. The resultant global force transmitted to the FFD is the sum of the 16 local forces from independently interacting masses. When the user makes a movement and protrudes over the edge, the difference in total force stimulation, resulting from the difference in the number of masses in interaction with the bridge, can be felt. That is, approaching the edge and protruding beyond it leads to the distinct levels in the global resulting force transmitted to the stick of the FFD.

Several participants confirmed a possible use of this strategy while in the *FFD-only* condition, but noticed that this strategy requires very fine and slow manipulation on the edges which is quite difficult to combine with the relatively rapid global movement required by the whole task. Thus, the benefits of the DE in

FFD-only condition are not fully used by the subjects: the overall strategy the subjects employed did not seem completely rely on this effect in *FFD-only* condition.

(b) *Overall strategy employed: number of falls vs. total time of task accomplishment.*

The tactile conditions *CM1* and *CM3* are better than the *FFD-only* (condition 0) in accuracy but not in the total time of task accomplishment. This could be explained by the fact that the strategy employed by the subjects is not the same. In tactile conditions, subjects seem to rely more on fine movements close to the edge, which help to avoid falling off the bridge. However, the counterpart of such a strategy is that the subjects adopt a more cautious strategy which leads them to move more slowly. In the *FFD-only* condition, the gesture seems to deploy a more ballistic strategy of hand movement, relying on the acquired and remembered proprioceptive knowledge of the spatial configuration of the bridge, leading to a rapid but inaccurate task execution.

This analysis is confirmed by the subjective evaluation of participants. It is also confirmed by the fact that the ratio (time_out)/

(time_total) is higher in the case of FFD-only ($p = 0.005$ for FFD-only vs. CM1; $p = 0.037$ for FFD-only vs. CM3). This means that, for the same average time of the task accomplishment, the average time spent off the bridge is bigger in the case of FFD-only, i.e., once the bridge is lost in the FFD-only condition it is more difficult to find it again, which may be due to the higher velocity of the gesture in this condition. Indeed, in order to attain a same average total time while spending more time off the bridge, it is necessary to make faster movements while being in contact with the bridge. By contrast, in the CM1 and CM3 conditions, the gesture is slower and relies more on fine exploration, which makes it possible to rapidly regain the bridge after a fall.

5.1.2. CM2 condition

The relatively poor performances of the CM2 condition can be explained by the fact that the addition of tactile was also combined with the change in the force interaction. This is different from other three conditions in which the force interaction is the same (as described in the section “computer models”).

Indeed, adding the threshold causes the force feedback to be felt “later” with respect to the user movement; and this is equivalent to changing the force interaction, as if the bridge had a non-resistant but tactile-sensitive envelope. But this is equivalent to a narrower and wispier resistant bridge which is much more difficult to follow. Adding the tactile could at best partially compensate this situation. This consideration tends to demonstrate that what is primordial in such tasks is the coherent coupling between force and tactile feedback, and that the results cannot be understood without examining the interaction as a whole, in all its aspects.

5.1.3. CM1 vs. CM3

There was no significant difference in the performance between these two conditions, but the subjects preferred the CM3 condition over the CM1 according to the subjective ranking ($p = 0.024$ for CM1 vs. CM3). They reported: (1) that they felt they were guided by the raised pins, and (2) that they felt more distinctly the upward movement of the pins than the downward movement when the fingertip started to leave the bridge.

5.1.4. Issue of learning

The task we explored is obviously strongly related to the issue of learning. For this experiment, we chose a learning period that did not clearly reveal the effects of adding tactile stimulation for the total time of task accomplishment. Further work could investigate if with more learning the difference between FFD-only and tactile conditions would be bigger, or if on the contrary a shorter period of adaptation can lead to more significant results. In addition, we have explored only one spatial form of the bridge, whereas the “effect of surprise”, confronting subjects with different spatial configurations may also result in a greater role of the tactile component of the interaction.

5.1.5. Role of the spatial information and role of the deformability of the exploratory body (or virtual fingertip)

With regard to these two research questions evoked in the introduction, we have implemented models that combine them in a single interaction situation. In these models the “deformation effect” of the fingertip (DE) is represented both by the tactile feedback and by the force feedback. There is a certain amount of redundancy between the tactile and the force feedback, in the sense that when the finger starts to leave the edge this produces an alteration in both components of the interface. The tactile feedback does nevertheless provide additional information, for the following reason. The grid is always in the horizontal plane, and when the grid is on the top surface of the bridge the direction of the force feedback is always orthogonal to this plane, i.e., vertical. This being so, a quantitative reduction in this force gives a warning that there is a risk of falling, but gives practically no indication as to which direction in horizontal plane should be taken to move fully back onto the bridge; this is because the force feedback gives no indication as to which masses are in interaction with the bridge. In this situation, the tactile component makes it possible to anticipate in which direction to move in order to stay on the bridge. This is confirmed by the observation that the number of falls is indeed less in conditions CM1 and CM3 compared to FFD-only.

A computer model of the fingertip as a virtual deformable object could perhaps give different results. Nevertheless, even if the model of the fingertip were actually deformable, the rigid end-effector of the FFD could only ever provide the overall resultant force; and the tactile feedback could then give a spatial image of this resultant. This could be particularly useful in dynamic situations such as at sharp edges, when the direction of the force is ambiguous, or when there are critical temporal effects such as very fast variations in velocities, i.e., the force direction changes too rapidly.

5.1.6. Conclusion on experimental results

Our findings are in line with the two studies we mentioned in the second section which address the tactile augmentation of the FFD in the task of the following the contour of the resistant structure.

In Declerck and Lenay (2006) blindfolded participants were required to follow the bridge and to maintain contact with it in three different experimental conditions: (P) force feedback but no tactile information; (T) tactile feedback but no force feedback; (PT) both force and tactile feedback (see Fig. 5a). According to the authors, the tactile display of information improves the contour following (there was a substantial decrease in episodes of loss of contact): subjects were able to use the tactile information to efficiently guide their displacements along the resistant surface (see Fig. 5b). Authors assumed that tactile information offers the ability to anticipate the location of the edges of the bridge (exteroceptive function); and that tactile information may also play here a proprioceptive role as it makes possible to perceive the direction of self-displacement relatively to the edges of the bridge.

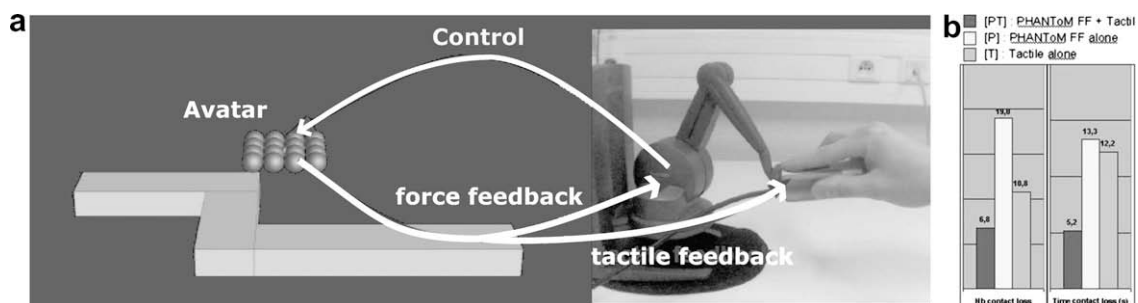


Fig. 5. (a) TactPHANTOM device manipulation and model (Declerck and Lenay, 2006). (b) (Declerck and Lenay, 2006) experimental results.

However in our study the improvement due to the addition of tactile feedback is less marked than in the pilot experiment performed by Declerck and Lenay (2006). This difference can stem from the fact that in Declerck and Lenay (2006) the force interaction results from a single-point contact and the tactile stimulation results from the points surrounding this central single-point (this leading to a very difficult manipulation in FFD-only condition), while in our implementation the entire exploratory body is in physical interaction with the object (this leading to the presence of the deformation affect (DE)).

Kuchenbecker et al. (2004) compared the contour following under the following conditions: providing the contact location (the cylindrical tactile element moves to the location of the contact) and providing force feedback only (the tactile element is stationary). According to the authors, blindfolded subjects employed different sensing strategies between the two conditions, and they argue that the adjunction of tactile element prevents from overshooting when approaching the edge. They reported that subjects were 30.0% less likely to break contact with the environment when provided with contact location feedback, which is similar to our results. On the other hand, average completion time was 39.8% faster when subjects were provided with contact location information, while in our study we did not find a significant difference in the total time of task accomplishment. This discrepancy may be due to the difference in the computer models and in the hardware implementation. Kuchenbecker et al. (2004) provided the contact location of the encountered virtual object in order to give the user the illusion of touching a two-dimensional contour (as if the subject's finger was touching it), while we provided the spatial distribution of the contact forces by means of deformation effect and tactile stimulation. Thus, the similarities in the tasks explored in Kuchenbecker et al. (2004) and in our study still do not remove the fact that the analysed aspects of the haptic interaction are of distinct nature.

Jansson and Monaci (2006) reported that the spatial distribution of stimulation at the contact area for the haptic identification of manufactured objects is more important than the number of distinct contact points. The improvement of the accuracy of the contour following in our experiment is in accordance with these findings. Although the task was different in this study (identification vs. contour following), we may suppose that it included edge following of the rigid objects. In addition, our FFD-only condition is almost equivalent to the finger with sheaths condition, where the information on the contact area was constrained. In this sense, we think our approach may be more promising and less complex than a multifinger haptic device. To further address this question, it would be interesting to compare the two conditions (multifinger vs. one spatially distributed contact area) within a single experiment with the same T-FFD.

In our experiment, subjects noticed that tactile stimulation produces an effect of slowing down the gesture when approaching an edge. We may therefore suppose that the tactile feedback functions here as a control loop for adjusting the effort applied by the subject. This is confirmed by a large number of studies where, for complex tasks such as grasping an object, being deprived of tactile sensitivity leads to applying an excessive effort (Westling and Johansson, 1984; Masataka et al., 2006). In our opinion this confirms that, in future work, it will be advantageous to combine components which provide information on the spatial configuration with other components which provide information on deformability.

On the basis of this discussion, we argue that the augmentation of FFD with spatially distributed tactile arrays is indeed of interest. We further argue that the integration of tactile and kinesthetic components in interfaces requires a coherent choice of the computer model which controls them. We have shown that with a

well-chosen computer model, the integrated device permits an improved performance in the task we have studied.

5.2. Some open epistemological issues

The fact that the results of experiments depend on the way in which the devices are controlled, in other words on the computer model, is quite obvious (e.g. Choi and Tan, 2003). Nevertheless, it must not be forgotten that the computer model is an implementation of underlying theoretical assumptions about the functional relation between the tactile and kinesthetic modalities in humans. This leads us to sketch open questions on the relation between psychophysical and cognitive studies on one hand, and T-FF (tactile–force feedback) devices on the other. In our view, this relation is in no wise trivial and raises some open issues which deserve consideration in future research.

Psychophysical studies on the tactile–kinesthetic relation usually assume that tactile perception can be studied by means of devices that produce tactile stimulation, and perception of forces – by means of FF devices. In other words, FF devices are not considered as stimulating human tactile system (or only to a negligible extent). Similarly, it is assumed that tactile devices do not a priori stimulate the kinesthetic system. The studies which seek to differentiate these two modalities can be considered as methodologically valid only on this condition of “separability”.

Then, the studies on the functional relationships between the tactile and kinesthetic modalities in humans, assume that the integration of the two devices on the side of the machine is equivalent – or at least closely approaches – to the combination of the two modalities on the human side. It is thus implicitly assumed that there is symmetry between two terms: first, the functional relation between the tactile and force components as it has been implemented in the devices employed; and second, the tactilo–kinesthetic relations in humans which are purportedly the object of study.

However, such equivalence is not necessarily possible, even in principle. Three levels of implementation which seem to intervene are discussed below: (1) mechanical integration of the devices; (2) the computer model that controls the devices; and (3) the modalities of this control in terms of input–output relationship.

(1) Mechanical integration is not neutral.

As we have emphasized in the introduction, in the natural situation of bio-mechanical interaction the two tactile and kinesthetic modalities cannot a priori be rigorously dissociated (except in very special cases).

When the interaction is mediated by computerized systems, the three main configurations of integration are: (a) parallel integration, one for each hand, without co-location (present study); (b) parallel kinematics integration for one hand without co-location (Kammermeier et al., 2004); and (c) serial kinematics integration with co-location (Kammermeier et al., 2004).

In the configurations (a) and (b) it is clear that the strong separation between the tactile and kinesthetic stimulations removes us from the natural situation. As for the configuration (c), the prospects for a “neutral” separation between the modalities are scarcely improved. In a device with serial integration, tactile perception is also evoked via the rigid arm or the part of the device attaching the finger to the FFD end-effector (e.g. Donlin et al., 2007), which produces tactile stimulation of the parts of the hand which are not in contact with the tactile stimulator itself.

In other words, whatever the mechanical implementation, tactile stimulation is never absent from a FFD, and vice-versa, even though the stimulations may be transduced differently. This distortion or reorganisation with respect to the natural haptic interaction

may be not problematic for achieving the tasks for which the integrated device was designed. However, it raises a methodological problem when it comes to drawing conclusions concerning the tactilo–kinesthetic relation in humans.

- (2) *What is meant under the term “tactile” in a computer interface is essentially dependent on the implemented model that controls the behaviour of the device.*

The “tactile” in real situations is tightly linked to force perception but there is manifestly a lack of knowledge on the exact relation between tactile and force perception in humans. Given that the tactile device cannot reproduce exactly the natural situation, the relationship between the tactile and force components as implemented in the computer algorithm is a model of the relationship postulated to exist in humans. This model can be functional, or physiological, or a mix of both. For example, the CM2 (Computer Model 2) assumed that in natural situations (i.e. non-computer-mediated), tactile perception can be present without a significant perception of a resistant force, as when a material is softly brushed before its hard resistance is felt. However, the experiment showed that this computer model was not adapted for the task studied.

For the very same integrated device, the way in which the two components are dissociated or combined in the computer model influences the user’s interaction with the virtual object when using the device. Thus the results of experiments on the functional relation between tactile and force components in humans may depend on the computer model and underlying hypotheses. The problematic nature of this dependence is not sufficiently taken into account in most implementations.

- (3) *In current integrated T-FF devices, the tactile stimulator part is based on an open-loop implementation of the input–output systems paradigm.*

In natural interactions, the dynamic attributes of the object address simultaneously the tactile and kinesthetic senses via a relation of mechanical coupling with the hand. Considering the interface between the hand and the object, there is no privileged direction of causality, be it from hand to object or conversely from object to hand (Sheridan, 2002; White, 2006). This is true both for the kinesthetic system and for the tactile system. The coherent way to address this type of ergotic situation (Cadoz and Wanderley, 2000) in computerized environments is to consider the joint sensor–actuator couple. For the tactile devices (Wall and Brewster, 2006) and the integrated T-FF devices, the most current approach is to implement the tactile part as an actuator. If it is legitimate to consider the energetic coupling between the action (e.g. the position of the finger, or the pressure exerted by the finger) and the tactile stimulation produced on the finger in return as negligible, then the tactile part can be supported by an “open-loop” implementation (Fontana, 2007) of the relation between the inputs and outputs of the device. In the opposite case, if the devices are to be used for experimental purposes, this approximation might no longer be valid and could become a methodological bottleneck.

The integration of T-FF devices is thus a composite situation of the three levels described above. From a methodological point of view, this disqualifies the postulate that there is equivalence between the functional T-FF relations on the side of the machine and those on the side of the human subject; although this equivalence is implicitly assumed by current studies on perception.

In view of these considerations, we could go so far as to say that the separation between the tactile and the force modalities can be accomplished in the mediation devices, rather than in actual human subjects. In natural perception, tactile feedback and force feedback always go together, so that at the level of perception their

roles are *a priori* almost impossible to separate. Thus, the categorical differentiation between these two components in the human system is largely an artefact of the devices at the disposal, which aim to explore the role of the tactile dimension by partially separating it from kinesthesia.

If the understanding of the sense of the touch itself is conditioned by studies using specific interfaces, then the interfaces play the role of “categorisation devices”. In a certain sense, the situation is similar to the well-known metaphor of the “telephone exchange” which was used to “explain” the functioning of the central nervous system (Kirkland, 2002), as well as to the metaphor of the computer in the computational paradigm of cognitive processes. However, the T-FF devices go beyond a simple metaphor or an explicative model of touch in humans, as they also serve to quantify measurements of the human sensory-motor and cognitive system.

This situation is not epistemologically neutral because, as we have just seen, there is no *a priori* symmetry between the integrated tactile-force device and the human sensory-motor system. In addition, precisely in this situation, the behaviour of the devices and the behaviour of the human who manipulates the device are interdependent (Florens and Urma, 2006): when a human being is equipped with an integrated device an entirely new system is set up. T-FF integration amounts to constructing a new, specific situation of interaction which is relatively distant from the natural situation. This requires a shift in the object of study: we are not studying human beings with the aid of neutral non-invasive measuring instruments; rather, we are studying a typical situation of instrumental action. The knowledge which may be acquired is thus not knowledge of human system as such; it is rather knowledge, local and partial, of situations of interaction which are relative to the particular T-FF devices.

In this sense, our approach relies on the enactive epistemological paradigm. Enaction in a strong sense, as we understand it (Khatchatourov et al., 2007) – i.e. co-arising of the subject and the world; grounded on phenomenology as thematisation of lived experience, and “completed” by a recognition of the role of technical artefacts in the process of “enacting” of a world of lived experience) – could provide a shift necessary to approach haptic interaction.

In an enactivist framework, the relation to the environment, as well as knowledge about this relation, are both constructed. The senses, understood not only as physiological but also as cognitive relation to the environment, are the instantiation of structural coupling of the organism and the environment (which is “a historical process leading to the spatio-temporal coincidence between the changes of state” of the participants (Maturana, 1975)). If we consider that the structural coupling can be affected by the means of such coupling (here the interfaces), then the enactive paradigm conceives the senses as something constructed, both in the sense of their historical evolution and in the sense of knowledge about them. In this way, the epistemological ambiguity between the use of interfaces in cognitive studies and the necessity of such studies for the design of interfaces can be resolved; and an epistemological coherence of the complementarity between such studies and the technological development of the interfaces can be guaranteed.

6. Conclusion

The paper presents the technological development of an integrated tactile–force feedback device. The main novelty of the device consists in the integration of the spatially distributed tactile stimulation and the force feedback, obtained strictly from the same synchronized interaction loop. This implementation addresses the

particular situation of highly dynamic haptic manipulation, on the example of the virtual bridge contour following.

Through the analysis of the force feedback alone and three alternative computer models for tactile stimulation this study tackles the research questions on the role of spatial information and the role of deformability of the virtual fingertip. In comparison with the force feedback alone, for two tactile conditions the experiment showed an increased accuracy while there was no significant improvement in the rapidity of the task accomplishment. The fact that only certain computer models of tactile interaction give better results (with an identical device, the results depend on the implemented computer model) led us to underline the importance of the work on the computer models which are the key element to guarantee the consistency of the interaction with virtual objects.

We argue then that providing the user with the *both* spatialized information on the contact surface and deformability (or at least the deformation effect) of the virtual fingertip is pertinent for the task under consideration.

Notwithstanding these promising results, we further argued that it may be difficult to draw more generic conclusions on the relation between tactile and kinaesthetic components in human perception from such experiments because the results and their interpretation are model- and device- dependent. This raises epistemological issues on the status of the computer model and adjacent devices in psychophysics studies. We believe it is necessary to carefully take them into account. We think that the adoption of an enactivist framework in cognitive sciences is a promising way to hold together psychophysical studies and technological development.

Acknowledgements

This research has been supported by the FP6 European Network of Excellence Enactive Interfaces IST-2004-002114-ENACTIVE, the French ministry of Research and the French ministry of Culture. Thanks to John Stewart (Costech) and to anonymous reviewers of the paper for helpful comments and suggestions.

References

- Allerkamp, D., Böttcher, G., Wolter, F.-E., Brady, A.C., Qu, J., Summers, I.R., 2007. A vibrotactile approach to tactile rendering. *The Visual Computer*, Vol. 23. Springer, Berlin/Heidelberg, no. 2, pp. 97–108.
- Benali-Khoudja, M., Hafez, M., Alexandre, J.-M. and Kheddar, A., 2004. Tactile interfaces: a state-of-the-art survey. In: *ISR 2004, 35th International Symposium on Robotics*.
- Cadoz, C., Wanderley, M., 2000. Gesture and music. In: Wanderley, M., Battier, M. (Eds.), *Trends in Gestural Control of Music*. IRCAM – Centre Pompidou.
- Castet, J., Couroussé, D., Florens, J.-L., Luciani, A., 2007. A real-time simulator for virtual reality conceived around haptic hard constraints. In: *Proceedings of the 4th international conference on Enactive Interfaces (Enactive'07)*.
- Choi, S. Tan, Z., 2003. An experimental study of perceived instability during haptic texture rendering: effects of collision detection algorithm. In: *Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS'03)*.
- Cini, G., Marcheschi, S., Salsedo, F., Bergamasco, M., 2005. A novel fingertip haptic device for display of local contact geometry. In: *Proceedings of IEEE World Haptics 2005*, pp. 602–605.
- Declerck, G., Lenay, C., 2006. The role of tactile augmentation of a PHANTOM FFD studied on a task of goal-oriented displacement. An enactivist contribution to the study of modes of control of haptic interactive displacement. *2nd Enactive Workshop*, Montréal.
- Donlin, G., Leuschke, R., Hannaford, B., 2007. Experimental Evaluation of Attachment Methods for a Multifinger Haptic Device. *EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. *World Haptics 2007*. Second Joint Volume, Issue 22–24, pp. 439–445.
- Florens, J.-L., Luciani, A., Cadoz, C., Castagné, C., 2004. ERGOS: multi-degrees of freedom and versatile force-feedback panoply. In: *Proceedings of EuroHaptics 2004*, pp. 356–360.
- Florens, J.-L., Urma, D., 2006. Dynamical Issues at the Low Level of Human/Virtual Object Interaction. In *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS'06)*.
- Florens, J.-L., Voda, A., Urma, D., 2006. Dynamical issues in interactive representation of physical objects. In: *Proceedings of the EuroHaptics 2006 Conference*, pp. 283–288.
- Fontana, M., 2007. Channel, afferent/efferent. In: Luciani, A., Cadoz, C. (Eds.), *Enaction and Enactive Interfaces, A Handbook of Terms*. Enactive System Books, France.
- Fritsch, M., Ernst, M., Buss, M., 2006. Integration of kinesthetic and tactile display. A Modular Design Concept. *TOUCH-HapSys Report*.
- Jansson, G., 1998. Haptic perception of outline 2D shape: the contributions of information via the skin, the joints and the muscles. In: Bril, B., Ledebt, A., Dietrich, G., Roby-Brami, A. (Eds.), *Advances in Perception-Action Coupling*. Editions EDK, Paris, pp. 25–30.
- Jansson, G., Billberger, K., Petrie, H., Colwell, C., Kornbrot, D., Fänger, J., König, H., Hardwick, A., Furner, S., 1999. Haptic virtual environments for blind people: exploratory experiments with two devices. *International Journal of Virtual Reality* 3 (4), 8–17.
- Jansson, G., Monaci, L., 2006. Identification of real objects under conditions similar to those in haptic displays: providing spatially distributed information at the contact areas is more important than increasing the number of areas. *Virtual Reality* 9 (4), 243–249.
- Kammermeier, P., Kron, A., Hoogen, J., Schmidt, G., 2004. Display of holistic haptic sensations by combined tactile and kinesthetic feedback. *Presence: Teleoperators and Virtual Environments*, Vol. 13. MIT Press, 1.
- Khatchatourov, A., Stewart, J., Lenay, C., 2007. Towards an Enactive Epistemology of Technics. In: *Proceedings of the 4th international conference on Enactive Interfaces (Enactive'07)*, pp. 373–376.
- Kirkland, K.L., 2002. High-tech brains: a history of technology-based analogies and models of nerve and brain function. *Perspectives in Biology and Medicine* 45.2, 212–223.
- Kyung, K.-U., Lee, J.-Y., Park, J.-S., 2007. Comparison of force, tactile and vibrotactile feedback for texture representation using a combined haptic feedback interface. In: Oakley, I., Brewster, S. (Eds.), *Haptic and Audio Interaction Design*, Vol. 4813/2007. Springer, Berlin/Heidelberg.
- Kuchenbecker, K., Provancher, W., Niemeyer, G., Cutkosky, M., 2004. Haptic display of contact location. In: *Proceedings of the International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS'04)*.
- Lederman, S., Klatzky, R., 1999. Sensing and displaying spatially distributed fingertip forces in haptic interfaces for teleoperator and virtual environment systems. *Presence* 8 (1), 86–103.
- Lenay, C., Gapenne, O., Hanneton, S., Marque, C., Genouëlle, C., 2003. Sensory substitution, limits and perspectives. In: Hatwell, Y., Gentaz, A., Streri, E. (Eds.), *Touching for Knowing, Cognitive psychology of haptic manual perception*. John Benjamins Publishing Company, Amsterdam/Philadelphia, pp. 275–292.
- Loomis, J.M., Lederman, S.J., 1986. Tactile perception. In: Boff, K., Kaufman, L., Thomas, J. (Eds.), *Handbook of Perception and Human Performance*. Vol. II, Chapter 31.
- Loomis, J.M., Blascovich, J., Beall, A., 1999. Immersive virtual environment technology as a basic research tool in psychology. *Behavior Research Methods, Instruments, & Computers* 31 (4), 557–564.
- Luciani, A., 2004. Dynamics as a common criterion to enhance the sense of Presence in Virtual environments. *Proceeding of Presence 2004 Conference*. ISPR, Valencia, Spain, pp. 93–103.
- Luciani, A., Florens, J.-L., Couroussé, D., Cadoz, C., 2007. Ergotic sounds: a new way to improve playability, believability and presence of virtual musical instruments. *Proceedings of the 4th international conference on Enactive Interfaces (Enactive'07)*, 373–376.
- Masataka, N., Konyo, M., Maeno, T., Tadokoro, S., 2006. Reflective grasp force control of humans induced by distributed vibration stimuli on finger skin with ICPF actuators. In: *Proceedings of IEEE International Conference on Robotics and Automation, ICRA 2006*. pp. 3899–3904.
- Maturana, H., 1975. The organization of the living: a theory of the living organization. *International Journal of Man-Machine Studies* 7.
- Morris, D., Sewell, C., Barbagli, F., Blevins, N., Girod, S., Salisbury, K., 2006. Visuo-haptic simulation of bone surgery for training and evaluation. *IEEE Computer Graphics and Applications* 26 (4), 48–57.
- Castagné, N., Florens, J.-L., Luciani, A., 2005. Computer platforms for hard-real time and high quality ergotic multisensory systems – requirements, theoretical overview, benches. In: *Proceedings of the 2nd international conference on Enactive Interfaces (Enactive'05)*.
- Provancher, W.R., Cutkosky, M.R., Kuchenbecker, K.J., Niemeyer, G., 2005. Contact location display for haptic perception of curvature and object motion. *International Journal of Robotics Research* 24 (9), 691–702.
- Salada, M.A., Vishton, P., Frankel, E., 2005. An experiment on tracking surface features with the sensation of slip. *Proceedings of IEEE World Haptics*, 132–137.
- Sheridan, T., 2002. Some musings on four ways human couple: implication for systems design. *IEEE Transactions on System, Man, and Cybernetics – Part A: Systems and Humans* 32 (1).
- Sribunruangrit, N., Marque, C., Lenay, C., Hanneton, S., Gapenne, O., Vanhoutte, C., 2004. Speed-accuracy trade-off during performance of a tracking task without visual feedback. *IEEE Transaction on Neural Systems and Rehabilitation Engineering* 12 (5).
- Summers, I.R., Brady, A.C., Syed, M., Chanter, C.M., 2005. Design of array stimulators for synthetic tactile sensations. *Proceedings of IEEE World Haptics*, 586–587.
- Symons, M., Richardson, B., Willemin, D., 2007. Intrasensory attention: kinaesthetic versus cutaneous inputs. *Perception* 36 (6), 880–887. 2007.

- Takasaki, M., Sakurada, T., Kotani, H., Mizuno, T., 2005. A surface acoustic wave tactile display on phantom. *Proceedings of the 2005 international conference on Augmented tele-existence*, Vol. 157. ACM International Conference Proceeding Series.
- Verner, L., Jeung, K., Okamura, A., 2005. Effects of Gripping and Translational Forces on Teleoperation. In: Barbagli, F., Prattichizzo, D., Salisbury, K., (Eds.), *Multi-point Interaction with Real and Virtual Objects*, Springer Tracks in Advanced Robotics, Vol. 18, pp. 231–242.
- Wagner, C., Lederman, S., Howe, R., 2004. Design and performance of a tactile shape display using RC servomotors. *The Electronic Journal of Haptics Research* 3. www.haptics-e.org.
- Wagner, C.R., Perrin, D.P., Feller, R.L., Howe, R.D., Clatz, O., Delingette, H., Ayache, N., 2005. Integrating tactile and force feedback with finite element models. *Proceedings of IEEE International Conference on Robotics and Automation. ICRA*. pp. 3942–3947.
- Wall, S., Brewster, S., 2006. Sensory substitution using tactile pin arrays: human factors, technology and applications. *Signal Processing* 86 (12), 3674–3695.
- Webster, R., Murphy, T., Verner, L., Okamura, A., 2005. A novel two-dimensional tactile slip display: design, kinematics and perceptual experiments. *ACM Transactions on Applied Perception* 2 (2).
- Westling, G., Johansson, R.S., 1984. Factors influencing the force control during precision grip. *Experimental Brain Research* 53 (2), 277–284.
- White, P., 2006. The causal asymmetry. *Psychological Review* 113 (1), 132–147.