A Framework for Building Haptic Interactions for Teleoperation Systems

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ABSTRACT

From the nano/micro-manipulation domain to the intervention in the nuclear field, haptics has become essential in actual teleoperation systems. The active property of this modality makes gestures more reliable and accurate. Nowadays, there is much research concerning the integration of haptic modality. The proposed solutions give, according to the adopted approaches, various efficiency levels. However, this work doesn't integrate generally and systematically psychophysics studies and ergonomics considerations. These elements are very important if we want to include effectively the human operator in any teleoperation system. Otherwise, various new applications present to the human operator several unfamiliar phenomena (e.g., nano-environments, underwater environments and the outer space environments). It's thus necessary in this type of application to transform virtually the remote environment to present to the operator nature-like haptic interactions. In this paper, we present a framework for building haptic interactions for teleoperation systems. This framework integrates the psychophysics studies and ergonomics elements, and presents a method to project the remote environment in the intuitive perception space.

Categories and Subject Descriptors

H.5.2 [**User Interfaces**]: Ergonomics, Haptic I/O, Theory and methods.

General Terms

Design, Human Factors.

Keywords

Haptic interaction, Teleoperation.

1. INTRODUCTION

During interaction with a remote or local environment, humans exploit several active or passive action/perception couplings. Each of them is adapted to particular contexts, data, or interaction types. For instance, visual feedback is more adapted to perceive and interact with data shared in the spatial domain. Furthermore, this modality is dominant compared to the others [13] [15]. Nevertheless, this modality presents a passive coupling between perception and action. When an active coupling is required in the application, we have recourse to the haptic feedback. This modality complements moreover the visual feedback by providing local and physical information about manipulated data or objects (texture, weight, viscosity, etc.) [5]. These information are very important for accurate gesture and efficient motion thus, this modality is very important in the teleoperation context. Recently, haptic interfacing has attracted much interest in the scientific and industrial communities. Unlike traditional human-machine interfaces usually coming with visual displays and sometimes with auditory information, interfaces with haptic feedback can enhance the realism of interactive systems through more intuitive interactions [8], [13]. Along with the development of interfacing technology and the strong trend to include haptics in multimodal interfaces, there are more and more haptic research and applications in many sides of life (e.g., vibration on cell phone is the most known haptic application cited). For instance, in telesurgery applications, haptics is researched and applied to improve the surgeons' performance in suturing and knot-tying tasks, which are very time consuming [17], [18]. Besides, there are situations in which human visual and auditory channels are heavily loaded, or the visual and auditory information is limited (i.e., undersea navigation in zones having high density of planktons, teleoperation with various information being sent through the visual channel like in a pilot training cockpit) the presentation of haptic channels is very important. Thus developing haptic interfaces is believed very important to consider [13], [15].

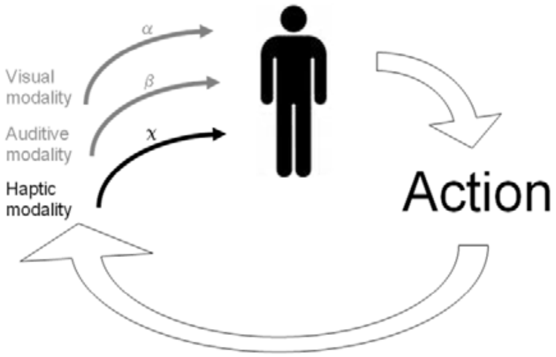


Figure 1. Haptic interaction

There are two main families of haptic applications: virtual reality and teleoperation reality. In both families, haptics, together with vision and audio, is being research for approaching more or less a state of "full immersion" [16]. In the virtual reality family, force-reflecting devices with graphical user interfaces can be used in games, education and training, medicine (i.e., rehabilitation) engineering [19], [20]. Applications in rehabilitation help people who have had illness or impairments to regain as much function as possible with haptic exercises [21]. In the teleoperation reality family, human operators interact with real environments through multimodal interfaces including haptics, vision and maybe audio. In telesurgery, as mentioned above, there are more and more applications of haptic to improve the surgeons' performance. In macro world, supplying the operator with both visual and haptic sensory feedback can help the operator perform the task as naturally and fluently as possible and as though physically present at the remote site [23]. In nano-scale manipulation, haptic interaction can allow the operator to sense and touch the surface and nanoparticles during the manipulation [22].

Nevertheless, we are still facing with many problems in integrating haptics into teleoperation. First, these are problems in hardware construction such as material characteristics, mechanical properties, actuators. The second category of problems is about software designing like real-time requirements, stability, rendering algorithms. The third category includes problems in user-interaction modeling like ergonomic and psycho physic criteria [13]. There are many situations in which the human operator is not familiar with the phenomena in remote environments so the challenge is to represent these phenomena in ways that the operator can understand or learn quickly. For instance, with teleoperation tasks in environments like underwater or outer space, the present of micro-gravity, which gives direct and indirect effects to the slave interface and the mechanical phenomena [28], [29], with different scales in the remote environment will more or less affect on the operators' performance. In nano-scale environments, the physics is totally different from the macro-scale environments. For instance, adhesion forces like van der Waals, capillary and electrostatic forces are much more important than gravity and inertia forces [6], [24]. It is very difficult to represent this information because humans are not familiar with the phenomena in such environments. Thus there are challenges of representing the remote environment in the best habitual haptic interactions (with complementary feedbacks like visual and auditory) to the operator.

Further, despite increasing widespread of haptics, frameworks for designing haptic interactions are still lacking, especially in teleoperation. This paper proposes a framework for building an efficient haptic interaction for teleoperation systems. In section 2.1, we propose a representation space of remote environment's properties in which a natural haptic mapping, presented in section 2.2, will be performed. The framework of this mapping – or interactions building – is divided into 3 steps. Section 2.3 deals with the first step of the framework: analyzing the data in the environment. Section 2.4 is the second step - analyzing the haptic displays. The last step, building the haptic interaction, is explained in section 2.5. Finally, section 3 is on conclusion and discusses about future work on the framework.

2. APPROACH

In our approach, we consider a space to which the information in the remote environment belongs. In this space we will present the intuitive mapping, the representation of the information in the environment in ways that the operator can quickly understand and learn in a natural way.

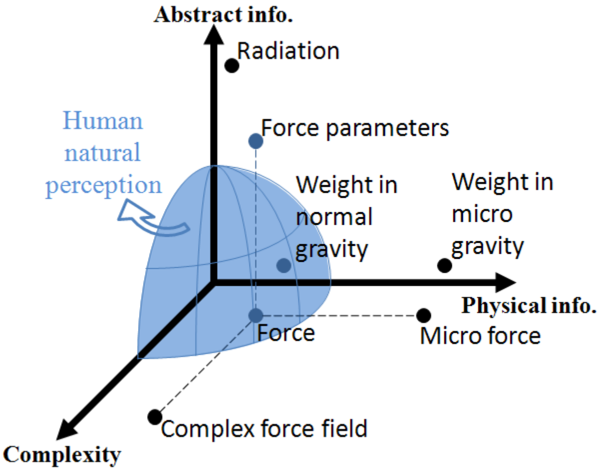


Figure 2. Properties representation space

The proposed space, presented in Figure 2, has 3 axes:

- Physical information: this axis deals with properties that mechanically affect interactions in the environment. These are forces, motions, viscosity, gravity, etc.
- Abstract information: this axis is for displaying properties that do not produce mechanical effects on the interactions in the environment. For example, the forces will mechanically affect interactions but the parameters (orientation, gradient, etc.) of these forces do not produce mechanical effects. Other examples of abstract information are sound frequency, radioactivity, etc.
- Complexity of information: this axis presents the abundant of the information in the environment. This can be understood as the amount of effort that operators must give to perceive the environment information.

In this space, the zone called human natural perception (HNP) (Figure 2) represents the perception that humans have learnt and developed through daily life activities. The environment's properties will be displayed in this 3-D space depending on their characteristics. If the properties are familiar to humans such as normal gravity ($g=9.81ms^{-2}$), dimensions from several millimeters to several meters, standard air viscosity ($mu=1.73x10^{-5}$ Ns/m^{2}), etc., these properties will be displayed inside the HNP zone. On the contrary, they will be outside of this zone. For example, in Figure 2, an object's weight in normal gravity condition is display inside the human natural perception zone, while the object's weight in micro gravity conditions, such as in underwater environment and outer space environment, $g<9.81ms^{-2}$, will be located outside of the natural perception volume. Because the micro gravity will directly affect on the mass of an object, it is displayed around the Physical information axis. For another example, let's consider a force which is a function of time $F=f(t)$ with the range from *2-4 N*. This force is easily sensed by humans and can give some mechanical interactions, will be displayed in the HNP zone, around the Physic information axis. The function $f(t)$, one of the parameters of this force, is only a math function which does not give any mechanical interactions. So it will be displayed along the Abstract information axis like in Figure 2. If we have a distribution of various values of force in space – complex force field, we suggest displaying this field around the Complexity axis.

Figure 3 presents the proposed approach for an intuitive mapping. In this Figure, only the haptic channel of HNP called human nature haptic perception (HNHP) is presented. The aim of this study, in the context of teleoperation, is to represent the properties of the remote environment, with existing haptic display technologies, in the best habitual haptic interactions thus enhancing the performance of the human operator like precision, execution time, comfort. We call this representation the intuitive mapping. Figure 3 shows an example in which we map information in an environment to display properties in the natural haptic perception space. Both environment's information and haptic display properties will be explained more in the sections 3 and 4. Normally, there is more than one property in one environment. For example, in undersea environment, where teleoperation tasks like seabed navigation and fishing out are performed, there are properties like micro gravity, viscosity, field of flows, etc.

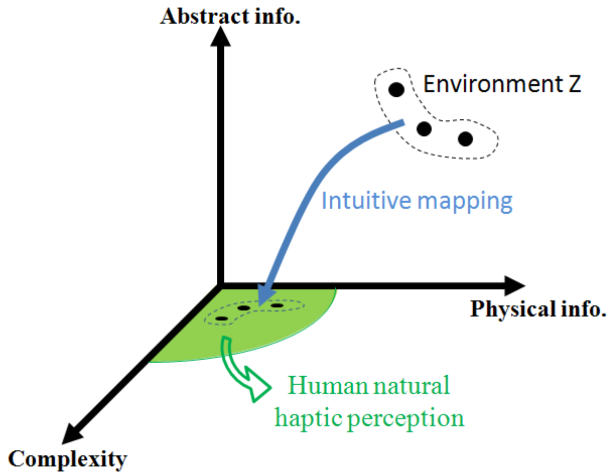


Figure 3. The intuitive mapping

To make the intuitive mapping, we propose a framework with three steps shown in Figure 4. In step 1, we analyze the information in the remote environment to extract the information in the relation with the carried out task and according to the operator's performance (execution time, trajectory). Next, in step 2, we investigate the haptic devices for possible displays. Finally, basing on the learnt information of the environment analyzed in step 1 and haptic displays investigated in step 2 we build the haptic interactions in step 3. In this step, we will apply studies about usability engineering and ergonomics [5], [26], [30].

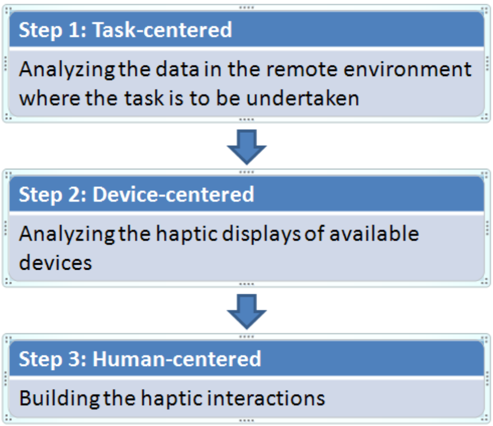


Figure 4. Three steps of the framework

In the following parts, we will go through step by step of the framework.

3. STEP 1 - DATA ANALYSIS

In teleoperation, understanding remote environment's properties helps not only to optimize the settings for equipments (i.e., setting parameters for master, slave devices) but also to find optimal strategies for manipulating objects or navigating in that environment. In [7], [14], a method for automatic estimation remote environment properties was investigated. The method described has 3 sub-problems: task decomposition, data segmentation and property estimation. The aim is to estimate the geometric properties of the manipulated object and its environment using the remote robot's sensors and knowledge of the task being performed.

In this paper, we are not focusing on how to technically measure the information of remote environment. We suppose that all the information (e.g., forces, geometric parameters, etc) are known. We study how to analyze and extract the information that is important to the performance of the task from the properties. It means constraints between the properties and task's performance (e.g., the effects of adhesion forces on the precision of objects manipulation tasks in micro/nano worlds) are considered. The analyzing employs a sequence of two sub-steps described below.

3.1 Sub-step 1.1 – Task decomposing

In fact, one certain task can be separated into many phases – sub-tasks – during its operating time. In one phase, there is a set of properties that are important for assuring the performance; and in another phase, there can be another set of important properties. In other words, the important of the properties can vary from phase to phase. Thus, to obtain a good performance of the whole-task, we need to divide the task into many sub-tasks and investigate every of these to have good selections of important properties for each.

There are many models of task analyzing. They are input-output diagrams, flowcharts, Hierarchical Task Analysis, Petri networks, etc. In [12], Plos employed the Petri network (for the method called Multimodal Decomposition of the Activity) to decompose tasks in elementary sub-tasks. Using this method, they can insert new perceptive and motor modalities into the diagrams. In this paper we develop a simple method, a flowchart-like one, for tasks dividing. The task is separated into a series of finite sub-tasks. There are at least two possibilities to decompose the task. In the first method, basing on the functions of different internal parameters, we study the changes of the parameters and related phenomena to decide the separation point. For example, in micro-nano manipulation tasks, when the distance between the tip and objects is from 0.10 – 1.00 µm, the dominating forces are electrostatic forces; when the distance is from 10 to 20 nm the capillary forces dominate the others. In this case we can separate the moving of the tip, basing on the function of distance between the tip and objects, into 2 phases. The second method bases on the "gesture" of the end effector. For example, in macro-manipulation, grasping a tool/object can be separated into 3 phases: opening the gripper; moving the opened-gripper to the position where it can grasp the object; closing the gripper until it hold the object with enough force without breaking it.

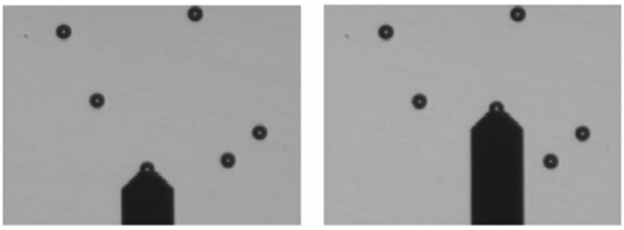


Figure 5. Micro-balls manipulation by adhesion forces

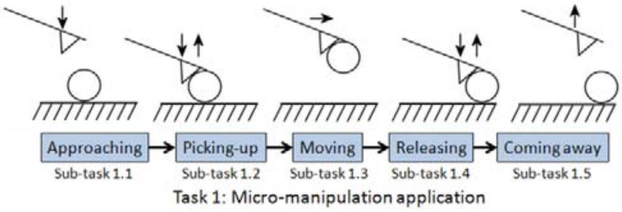


Figure 6. Dividing one task into sub-tasks

Figure 5 shows a micro-world task where the micro-balls are manipulated by adhesion to desired positions [2]. In Figure 6, the task of micro-manipulating is broken down into five sub-tasks. In sub-task 1.1, the goal is to approach the target ball. During approaching phase, the end effector must not hit or capture other objects. In sub-task 1.2, the tip must be able to capture and lift the ball away from the substrate by adhesion forces. After capturing the object, the aim of sub-task 1.3 is to move the object to the desired position without dropping, hitting or capturing new objects. In sub-task 1.4 and sub-task 1.5, the tip must release the ball at the desired position and then come away from the ball without hitting other objects. It is obviously that every sub-task has its own performance criteria. The next sub-step presents our approach in identifying the important properties in the environment for every sub-task.

3.2 Sub-step 1.2 – Selecting properties

We will study among the known properties in the environment, which are important to the performance of the sub-task. For doing that, first, we list all of the properties in the environment which are interesting to teleoperation tasks. Then among the properties listed, we select the important ones for every sub-task. In the remote environment of a teleoperation task, we will consider the spatial scale (i.e., macro or micro scale) of the task, the presents of kinds of forces, the properties of the objects, the tip, the substrate, and the medium, etc. For that purpose we present our classification of the properties as below:

i. Local properties (Table 1) – including properties of the objects to be manipulated and the slave manipulator (tip);

ii. Global properties (Table 2)- including properties of the substrate and the medium.

Table 1 – Local properties

Local prop.	Objects' elements	Tip's elements
Conductivity	☐ Electrical conduct. ☐ Thermal conduct.	☐ Electrical conduct. ☐ Thermal conduct.
Dimension	☐ Height ☐ Length ☐ Width ☐ Radius	☐ Height ☐ Length ☐ Width ☐ Radius
Electrostatic	☐ Electrostatic	☐ Electrostatic
Force	☐ Electro-magnetic force ☐ Van der Waals force	☐ Electro-magnetic force ☐ Van der Waals force
Friction	☐ Dynamic friction ☐ Static friction	☐ Dynamic friction ☐ Static friction
Hardness	☐ Deformable ☐ Hardness ☐ Rigidity	☐ Deformable ☐ Hardness ☐ Rigidity
Mass	☐ Mass	☐ Mass
Motion	☐ Acceleration ☐ Orientation ☐ Position ☐ Velocity ☐ Vibration	☐ Acceleration ☐ Orientation ☐ Position ☐ Velocity ☐ Vibration
Lifetime	☐ Time	
Shape	☐ Polygon ☐ Round ☐ Sphere ☐ Cube-like	☐ Polygon ☐ Round ☐ Sphere ☐ Cube-like
Temperature	☐ Temperature	☐ Temperature
Texture	☐ Texture	
Volume	☐ Volume	☐ Volume
…	…	…

Table 2. Global properties

Global prop.	Medium’s elements	Substrate’s elements
Conductivity	☐ Electrical conduct. ☐ Refractive index ☐ Thermal conduct.	☐ Electrical conduct. ☐ Refractive index ☐ Thermal conduct.
Density	☐ Density	
Electro-magnetic wave	☐ Amplitude ☐ Frequency ☐ Phase ☐ Source position	
Force	☐ Capillarity force ☐ Electro-magnetic force ☐ Gravity	☐ Capillarity force ☐ Electro-magnetic force ☐ Van der Waals force
Friction		☐ Dynamic friction ☐ Static friction
Pressure	☐ Pressure	
Sound	☐ Frequency ☐ Loudness ☐ Phase ☐ Source position	
Surface roughness		☐ Surface roughness
Temperature	☐ Temperature	☐ Temperature
Viscosity	☐ Viscosity	☐ Viscosity
…	…	…

Table 1 and Table 2 presented above are not exhaustive, other properties will be easily added for different environments. Using these tables as references, for a certain environment of teleoperation task or sub-task, we select the interesting properties by making checklists of corresponding global and local properties of the environment. Each of the selected properties is also given a score for its importance to the performance (execution time, precision, etc.) of the task. For doing that, the usability heuristics are used. There are several definitions of usability. In general, usability can be understood as studies about human psychological matters for assuring the effectiveness, efficiency and satisfaction for specified users in a specified context of use [26], [27]. Thus tables (i.e., global and local) for selected properties with importance-scores are made by either referring to relative research, experiments, or collecting an expert evaluator’s responds from a series of questions. In our approach, the scores are given from 1, the least important, to 10, the most important.

In the case of micro/nano world, the phenomena are different from those at macro scale. In [2], [6], some main features relating micro-manipulation are discussed. First, adhesion forces like van der Waals (vdW) forces, capillarity and electrostatic have higher magnitudes than the gravitational effects. These forces make it difficult to release a gripped object as it adheres to the tip of the end effector. We can reduce adhesion forces by using rough surfaces. Second, an initial acceleration, which is affected by the slope angle of the gripper and the mass of the object, of the end effector can cause releasing. Referring to these works, we propose in Table 3 and Table 4 the interesting properties of a typical micro-manipulation environment.

Table 3. Local properties in picking-up phase of a typical micro-manipulation environment

Objects’ elements	Score	Tip’s elements	Score
☑ Radius		☑ Radius	
☑ Electrostatic		☑ Electrostatic	
☑ Electro-magnetic force ☑ Van der Waals force		☑ Electro-magnetic force ☑ Van der Waals force	
☑ Acceleration ☑ Orientation ☑ Position		☑ Acceleration ☑ Orientation ☑ Position	
…	…	…	…

Table 4. Global properties in picking-up phase of a typical micro-manipulation environment

Medium’s elements	Score	Substrate’s elements	Score
☑ Capillarity force ☑ Electro-magnetic force		☑ Capillarity force ☑ Electro-magnetic force ☑ Van der Waals force	
		☑ Dynamic friction ☑ Static friction	
☑ Pressure			
		☑ Surface roughness	
☑ Viscosity		☑ Viscosity	
…	…	…	…

In various situations, beside the information that is important to the task’s performance, a selected property may contain noise or vain information. In these cases, we propose to simplify or/and decompose the properties for useful information. This helps to understand the key elementary information in the properties to the performance of the task; and further to save the bandwidth of the communication channel, which also strongly affects the performance of the task. Besides, if the value ranges of the properties are greater than haptic devices’ capacity ranges (i.e., ranges of rendering forces, frequency, etc.), simplifying or/and decomposing the properties helps to prevent the haptic display devices from overload.

Usually, the properties containing noise, from the environment or from the measurement, or vain information are functions of time or space (e.g., vibration of the AFM tip when surfing on the surface [33]). Techniques for simplifying of decomposing these properties can be employed are filtering or Fourier transforming. With filtering, we can apply the low-pass filter (Figure 7), band-pass filter, band-stop filter or high-pass filter for selected properties to have desired information. The Fourier transform is used to extract the useful information from the data such as the frequency or amplitude of a certain decomposed basic function.

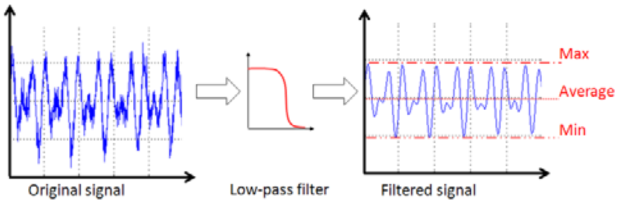


Figure 7. Applying a low-pass filter to the signal with noise

In summary for this step – data analysis, we study the circumstance in the approaching phase of a micro-manipulation task. We suppose that the sizes of spherical objects are from 10 to 50 µm; the task is undertaken in vacuum; the substrate is flat (no roughness) and dry (no capillary forces); there is no static charge on the objects, tip, and substrate. We propose 2 tables for local and global properties with importance-scores as below:

Table 5. Local properties in approaching phase of a typical micro-manipulation environment

Objects' elements	Score	Tip's elements	Score
☑ Radius	9		
☑ Van der Waals force	8	☑ Van der Waals force	8
		☑ Acceleration ☑ Orientation ☑ Position	7 6 10
…	…	…	…

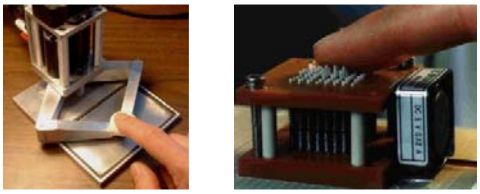
Table 6. Global properties in approaching phase of a typical micro-manipulation environment

Medium's elements	Score	Substrate's elements	Score
		☑ Van der Waals force	8
…	…	…	…

4. STEP 2 – DEVICES INVESTIGATION

In attempts of representing the haptic stimulus to humans, many kinds of haptic devices were developed or are under developing. There are two important parts of a complete haptic interface: several electromechanical transducers applying and measuring mechanical signals on different body areas, and the computational system driving the transducers [8]. The signals can be forces, vibration, displacements, combinations of these, etc. Thus, investigating a haptic interface, we must study the information about types of mechanical signals that the device can apply and measure, and the description about these signals (i.e., ranges of magnitude, frequency, workspace, etc.) In [3], the haptic devices are classified into 2 groups: operator-mounted devices and non operator-mounted devices. Stanney et al. [26] mention that haptic devices are suggested to give two types of feedback: *(1) kinesthetic – information sensed through movement and/or force to muscles and joints; (2) tactile – information received through nerve receptors in the skin (e.g., at the finger pad), which convey shapes and textures*. Inspired from this, in our approach, we classify the haptic interfaces in two categories: (1) tactile and (2) kinesthetic-tactile interfaces.

The tactile interfaces category deals with devices that produce and measure the stimulus on the operator's finger pad. These devices can be either passive or active. Hayward [9] describes three devices for experiencing of haptic shape, each at a different scale. To display large objects, a rolling plate in contact with the finger tip to provide the moving patterns of normal finger deformation according to exploratory movements is used. For medium objects, display is given by the Pantograph haptic device (Figure 8.a). By locally stretching and compressing the skin on the finger tip, we can display small objects shapes. Further, other haptic object attributes such as friction could be displayed using analogous approaches.



a) Pantograph haptic device from McGill University

b) Braille display from Forschungszentrum Karlsruhe

Figure 8. Tactile interfaces

The second category – kinesthetic-tactile interfaces – includes devices that allow the operator to interact with the remote environment by their arm(s) or body. Beside kinesthetic rendering, these interfaces can also give tactile rendering (e.g., rendering texture, vibration). Usually these are active devices. These devices can give haptic feedback to the arm/leg through the handle/wheel/pedal or to various location of the body [25] or give a whole-body kinesthetic like in flight simulators. Figure 9 show two examples of this category.

a) Virtuose™ 3D15-25 from Haption

b) Logitech Wingman Formula Force

Figure 9. Kinesthetic-tactile interfaces

For every category, we propose a table for investigating the display capacities. Table 7 deals with tactile interfaces. Referring to this table, we will make a checklist of available displays and descriptions for tactile interface devices. On the left column we have the displays such as texture, hardness, vibration, etc. For example, in [9], Hayward described a haptic interface that can display the object shape with a rolling plate; in [1], Allerkamp et al. use vibrotactile to display the surface texture. The displays are in alphabetical order. On the right column we have the description for each display. For a specific device we will have specific descriptions. For example, with a vibrotactile display, we need descriptions about ranges of amplitude, frequency, display functions (square, triangle, sine, etc).

Table 7. Tactile interfaces

Tactile interfaces	
Displays	Description
☐ Friction	
☐ Shape/size	
☐ Texture	
☐ Vibration	
…	

Table 8. Kinesthetic-tactile interfaces

Kinesthetic-tactile interfaces			
Stance		Force	
Displays	Description	Displays	Description
☐$F = f(\ddot{x}_H)$		☐$F = f(\ddot{x}_M)$	
☐$F = f(\dot{x}_H)$		☐$F = f(\dot{x}_M)$	
☐$F = f(x_H)$		☐$F = f(x_M)$	
☐$F = f(\ddot{\theta}_H)$		☐$F = f(\ddot{\theta}_M)$	
☐$F = f(\dot{\theta}_H)$		☐$F = f(\dot{\theta}_M)$	
☐$F = f(\theta_H)$		☐$F = f(\theta_M)$	
…		…	
Constraint		Others	
Displays	Description	Displays	Description
☐ Point		☐ Vibration	
☐ Line		☐ Inflation	
☐ Zone		☐ Contraction	
☐ Rotation		…	
…			

Table 8 is proposed for kinesthetic-tactile interface devices. There are 4 small groups of displays in this table. In the stance group, which relates to the displacements of the human operator, the forces feedback can be a function of the human operator's body position ($F = f(x_H)$), a function of operator's velocity ($F = f(\dot{x}_H)$), etc. This is similar in the Force group. Instead being functions of operator's displacements, the feedback forces are functions of the master manipulator position (to display, for example, attraction/repulsion forces), velocity (to display viscosity, for example), rotation, etc. Some devices can also produce motion constraints in point, line, zone; or they limit the rotation of some axis. These are in Constraint group. Besides, some other devices can be employed for interacting like a vibration ring for lower arm, an inflatable balloon. These kinds of devices will be listed in the group of others. For every display we also have the description about its parameters. For example, investigating the display capacity of Virtuose™ 3D15-25, we can have the result like in Table 9.

Table 9. Display capacities of Virtuose™ 3D15-25

Force		Constraint	
Displays	Description	Displays	Desc.
☑$F = f(\dot{x}_M)$	-Category: kinesthetic-tactile	☑ Point	
		☑ Line	
☑$F = f(x_M)$	-Force feedback in 3 DOF -Workspace: 250 *mm* -Force max: 15 N -Force continue: 5 N -Hardness: around 800 N/m -Internal loop: 300 Hz (kinesthetic) to 1000hz (kinesthetic + tactile) …	☑ Zone	

5. STEP 3 – BUILDING THE HAPTIC INTERACTIONS

From the data analyzing in step 1 (Section 3) and devices investigation in step 2 (Section 4), we have prepared the "materials":

- Tables of important local and global properties to the performance of that sub-task/task. Each of the properties has its score for its importance to the performance of the sub-task/task. The performance is evaluated on the execution time, precision, and trajectory.
- Tables of display capacities of the facilities. The displays are listed in two tables of tactile interfaces and kinesthetic-tactile interfaces with detailed description.

In this step, we study how to build the haptic interactions for a sub-task/task from these "materials". The aim of this building is to transform and represent the remote environment to the operators in ways which are similar to human everyday interactions or at least in ways that the operator can understand or learn quickly. Further, we propose likewise to the operators some additional functions that do not exist in the real world like virtual fixtures to help improve the efficiency of operational gesture [2], [34].

Swindells et al. [30] suggests that good representations must support human goals, capacities, and desires. In [8], the quality of haptic representation is defined as a function of the human perceptual system and the characteristics of the devices, such as dynamic range, resolution, and appropriateness of the generated signals. To this function, in the context of our approach, we already had the characteristics of the devices (i.e., tables in step 2 – devices investigation). Thus understanding the human haptic perceptual system is an important and essential step toward building intuitive haptic interactions for enhancing the performance in time executing, precision, trajectory of the task, and comfort, satisfaction of the operator. Considering the human operator the center of this step, we propose a building method using ergonomics and psychophysics [5], [26], [27].. Ergonomics concerns the research and the analyzing of the practice and the procedure of deducting the mechanisms involved in performing a task. In our approach, ergonomics is used to choose the appropriated haptic displays (described in Section 4) for the properties of the environment (described in Section 3). After choosing haptic display for a property, psychophysics studies, dealing with physical stimuli and their subjective percepts, are used to obtain the best way for representing the information. For instance, to Allerkamp et al. [1], any vibration frequency distribution can be simulated by appropriate combinations of only two vibration frequencies (40 and 320 Hz).

In our proposed method, we choose the haptic displays for the select properties starting from the most important property to the least important one in the global and local properties lists. For each of the properties, the ergonomic study is carried out to give weights to haptic display for the quality of representing. Table 10 and Table 11 give an example of giving the scores to the quality of displaying the properties. The weights in the example are given from 0 to 10. Number 10 is for the very good quality of representing and number 0 is for the representation that is meaningless to humans. In Table 10 the position of the tip, having the best score for the performance of the approaching phase of micro-manipulation, is the first property to be consider the quality of representing through the displays. As stated in Section 3.1, to assure the performance (in precision and trajectory) of the approaching, during this phase, the end effector must approach the wanted object without hitting or capturing any other object. As mention above, the aim of this building is not only to make an intuitive representation of the remote environment to the operator but also to help improve the efficiency. For a good performance of manipulating micro-balls, in [2], Ammi used the planning path to avoid unexpected collision. With the planning path, the performance of the sub-task and the quality of the representation are assured. We propose to give the weight 10 for representing the position of the tip, which is closely linked to the position of the master end effector; and the weight 5 for representing this position with the force, which is a function of the tip's position $F = f(x_M)$. For the other displays, we put weights 0 because the meaningless or impossible links (e.g., link the position of the tip to the point constraint which allows the rotation of the tip but limits the translation) (Table 11).

Table 10. The combination of local and global properties in approaching phase of a typical micro-manipulation environment

Tip's elements	Score
☑ Van der Waals force	9
☑ Acceleration	7
☑ Orientation	6
☑ Position	**10**
Objects' elements	Score
☑ Radius	8
☑ Van der Waals force	9
Substrate's elements	Score
☑ Van der Waals force	9

Table 11. Modified table for display capacities of Virtuose™ 3D15-25. The weights of the displays are proposed for the quality of representing the tip position, the most important during approaching phase, in Table 10

Displays of Virtuose™ 3D15-25	
Displays	Weight
☑$F = f(\dot{x}_M)$	0
☑$F = f(x_M)$	5
☑ Point constraint	0
☑ Line constraint	10
☑ Zone constraint	0

Table 12. Calculating the final score for the interactions between the properties and the haptic displays in approaching phase of micro-manipulation

Properties	Displays	Final score
☑ Position	☑$F = f(\dot{x}_M)$	0
☑ Position	☑$F = f(x_M)$	50
☑ Position	☑ Point constraint	0
☑ Position	☑ Line constraint	100
☑ Position	☑ Zone constraint	0
☑ Van der Waals force	☑$F = f(\dot{x}_M)$	0
☑ Van der Waals force	☑$F = f(x_M)$	90
…	…	…

Table 13. Build interactions table for the approaching phase of a specific micro-manipulation (described in Section 3.2)

Tip's elements	Displays
☑ Van der Waals force	☑$F = f(x_M)$
☑ Acceleration	
☑ Orientation	
☑ Position	☑ Line constraint
Objects' elements	Displays
☑ Radius	
☑ Van der Waals force	☑$F = f(x_M)$
Substrate's elements	Displays
☑ Van der Waals force	☑$F = f(x_M)$

After giving the weights for quality of the interactions, we calculate the final score for all interactions. The final score is calculated by multiply the score (the importance of an environment's property) by a weight (the quality of representing a property by a certain display) like in Figure 10. Table 12 shows partly the result of the final scores for the interactions in a proposed circumstance (described in Section 3.2). The final interactions are decided basing on the final scores. The interaction with the biggest final score is recorded first, then the ones with smaller final scores. We propose in Table 13 the final interactions for the approaching phase of a specific micro-manipulation.

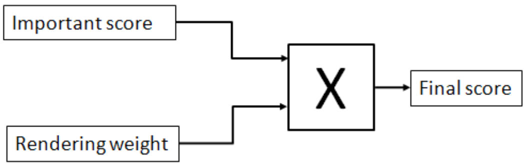


Figure 10. Final score calculation

In some cases, because it is lacking of haptic displays, not all of the properties can be mapped. However, a teleoperation system does not come only with haptic interactions but also with visual or/and auditory interactions. Therefore, the un-mapped elements by haptic interactions can be displayed by other interfaces.

6. CONCLUSION AND OUTLOOK

In this paper, we presented a framework to transform virtually the remote environment to present to the operator nature-like haptic interactions for teleoperation systems. This framework integrates the psychophysics studies and ergonomics elements in one side, and presents a method to project the remote environment in the intuitive perception space.

The outlook for this study is applying the framework and carrying out the experiments for specific teleoperation tasks. For the first approach to this framework, we are developing a simulator for micro-manipulation tasks in Matlab/Simulink®. The future work is to apply this framework to the tasks and study the performance of the task (in execution time, precision, trajectory of the manipulation, and the comfort, satisfaction of the operator).

7. REFERENCES

[1] Allerkamp, D., Böttcher, G., Brady, A., Qu, J., Summers, I. and Wolter, F.-E. 2005. Tactile Rendering: A Vibrotactile Approach. Proceedings of the HAPTEX'05 Workshop on Haptic and Tactile Perception of Deformable Objects, Hanover, December 2005.

[2] Mehdi Ammi. 2005. PhD thesis at University of Orléans, 2005.

[3] Casiez, G. Meseure, P. 2003. Interface Homme-Machine Le retour haptique. Université des Sciences et Technologies de Lille I Copyright © 2003.

[4] Debus T., Dupont P., Howe R. 2000. Remote environment property estimation during teleoperation. Proceedings of IEEE ICRA, 2000.

[5] Kelly S. Hale, Kay M. Stanney. 2004. Deriving Haptic Design Guidelines from Human Physiological, Psychophysical, and Neurological Foundations. IEEE Computer Graphics and Applications, vol. 24, no. 2, pp. 33-39, Mar/Apr, 2004.

[6] D. S. Haliyo, Mehdi Boukallel, Gentiane Venture and Stéphane Régnier. 2002. Manipulation of Micro-Objects using Adhesion Forces and Dynamical Effects. Proceedings of the 2002 IEEE ICRA, 2002.

[7] R. Howe, T. Debus and P. Dupont. 1998. Haptic Identification of Remote Environment Properties. SPIE International Symposium on Intelligent Systems and Advanced Manufacturing, Proceedings of the SPIE, Vol. 3524, Boston, MA, November, 1998.

[8] V. Hayward, O. R. Astley, M. Cruz-Hernandez, D. Grant, and G. Robles-De-La-Torre. 2004. Haptic Interfaces and Devices. Sensor Review, vol. 24:1, pp. 16-29, 2004.

[9] V. Hayward. 2004. Display of haptic shape at different scales. Proceedings of Eurohaptics, 2004.

[10] Laurent Mignonneau, Christa Sommerer. 2005. NanoScape Experiencing Aspects of Nanotechnologies Through a Magnetic Force Feedback Interface. ACE05Conference SIG CHI, Polytechnic University of Valencia, Valencia, Spain, 15 June 2005.

[11] Keith V. Nesbitt. 2001. Modeling the Multi-Sensory Design Space. Proceedings of Information Visualisation, Australian Symposium on Information Visualisation, 2001.

[12] Plos, O., Buisine, S. 2006. Décomposition Multimodale de l'Activité : Vers un outil d'aide à la conception. ErgoIA'06 Colloque francophone sur l'Ergonomie et l'Informatique Avancée, 2006.

[13] Robles-de-la-Torre, Gabriel. 2006. The Importance of the Sense of Touch in Virtual and Real Environments. IEEE Multimedia. Vol. 13, No. 3, pp. 24-30. Jul-Sept, 2006.

[14] Schulteis, T., Dupont, P., Millman, P., and Howe, R. 1996. Automatic Identification of Remote Environments. Proceedings of the 1996 ASME International Mechanical Engineering Congress and Exposition, DSC-Vol. 58, ASME, New York, NY, pp. 451-458, 1996.

[15] Van Erp, J. B. F. 2002. Guidelines for the use of vibro-tactile displays in human computer interaction. In Proceedings Eurohaptics 2002, Edinburgh, S. A. Wall et al., Eds. 18—22, 2002.

[16] Ferreira, A., Mavroidis, C. 2006. Virtual reality and haptics for nanorobotics. IEEE Robotics Automation Vol 13 N° 03, September 2006 Page(s): 78- 92.

[17] Okamura, A. M. 2004. Methods for haptic feedback in teleoperated robot-assisted surgery. INDUSTRIAL ROBOT, 2004, VOL 31; NUMBER 6, pages 499-508.

[18] H. Mayer, I. Nagy, A. Knoll, E. Braun, R. Bauernschmitt, and R. Lange. 2007. Haptic Feedback in a Telepresence System for Endoscopic Heart Surgery. PRESENCE, MIT Press, Volume 16, Issue 5, 2007

[19] Xunzhang Wang; Seet, G.G.L.; Lau, M.W.S.; Low, E.; Tan, K.C. 2000. Exploiting force feedback in pilot training and control of anunderwater robotics vehicle: an implementation in LabVIEW. OCEANS 2000 MTS/IEEE Conference and Exhibition. Volume 3, Issue , 2000 Page(s):2037 – 2042.

[20] Nahvi A., Nelson D.D., Hollerbach J.M., Johnson D.E.1998. Haptic manipulation of virtual mechanisms from mechanical CAD designs. Proceedings of the 1998. IEEE. International Conference on Robotics. &. Automation.

[21] Bardorfer, A.; Munih, M.; Zupan, A.; Primozic, A. 2001. Upper limb motion analysis using haptic interface. IEEE/ASME Transactions on Mechatronics. Volume 6, Issue 3, Sep 2001 Page(s):253 - 260.

[22] Fok, L.M.; Liu, Y.H.; Li, W.J. 2004. Haptic Sensing and Modeling of Nanomanipulation with an AFM. ROBIO 2004. IEEE International Conference on Robotics and Biomimetics. Volume , Issue , 22-26 Aug. 2004 Page(s): 452 - 457.

[23] Richard Lee Thompson. 2001. The Integration of Visual and Haptic Feedback for Teleoperation. DPhil Thesis, University of Oxford, 2001.

[24] Quan Zhoua, Pasi Kallioa, Fumihito Araib, Toshio Fukudab and Heikki N. Koivoc. 1999. A Model for Operating Spherical Micro Objects. Proceedings of the 1999 International Symposium on Micromechatronics and Human Science, MHS'99, Nagoya, Japan, 1999.

[25] Lindeman, R.W., Page, R., Yanagida, Y., Sibert, J.L. 2004. Towards Full-Body Haptic Feedback: The Design and Deployment of a Spatialized Vibrotactile Feedback System. Proc. of ACM Virtual Reality Software and Technology (VRST) 2004, Nov. 10-12, 2004, Hong Kong, China, pp. 146-149.

[26] Kay M. Stanney, Mansooreh Mollaghasemi, Leah Reeves, Robert Breaux, David A. Graeber. 2003. Usability engineering of virtual environments (VEs): identifying multiple criteria that drive effective VE system design. International Journal of Human-Computer Studies archive, Volume 58 , Issue 4 (April 2003) Pages: 447 - 481.

[27] Nosper, A., Behr, K.-M., Hartmann, T., & Vorderer, P. 2005. Exploring the relationships between the usability of a medium and the sense of spatial presence perceived by the user. In Slater, M. (Hrsg.), Proceedings of the 8th International Workshop on Presence ("Presence 2005", S. 261-268). London: University College.

[28] S.C. Venema and B. Hannaford. 1995. Miniature telerobots in space applications. Proc. Int'l Conf. on Integrated Micro/Nanotechnology for Space Applications. Oct. 30, 1995, Houston, TX, USA.

[29] Commission on Physical Sciences, Mathematics, and Applications, Space Studies Board. 2000. Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies. National academy press. Washington, D.C. 2000. Chapter II, pages: 17-19. Chapter IV, pages: 111-165.

[30] Swindells, Colin, Smith, Jocelyn D., and MacLean, Karon E. (2005) An Exploration of Representations to Aid Design of Haptic Behaviours. In Proceedings of Conference on Human Factors in Computing Systems (CHI) Workshop -- Hands-on Haptics: Exploring Non-Visual Visualization Using the Sense of Touch, ACM Press, pp. 5-8.

[31] David A. Denby. 2006. The Distinction between Intrinsic and Extrinsic Properties. Denby Mind. 2006; Volume 115, Number 457; Pp. 1-17.

[32] Theodore Sider. 2001. Maximality and Intrinsic Properties. Philosophy and Phenomenological Research 63 (2001): 357-364.

[33] Cha'o-Kuang Chen; Bin-Hao Chen; Yue-Tzu Yang. 2004. Atomic force microscopy tip noise induced by adhesion, nanoindentation and fracture. Nanotechnology, Volume 15, Number 12, December 2004, pp. 1771-1778.

[34] Jake J. Abbott and Allison M. Okamura. 2003. Virtual Fixture Architectures for Telemanipulation. Proceedings of the 2003 IEEE. International Conference on Robotics & Automation. Taipei, Taiwan, September 14-19, 2003.