Improving Perception and Understanding of Nanoscale Phenomena Using Haptics and Visual Analogy

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Abstract. This paper introduces a new pedagogical tool using haptic feedback and visual analogy, to improve perception and learning of nanoscale phenomena, for people without prior knowledge of nanophysics. This tool is a haptic and virtual-reality simulator of a foremost one-dimensional nanophysical phenomenon: the approach-retract cycle of an Atomic Force Microcope (AFM) probe, with a force-feedback device and two graphic representations. One representation is a virtual AFM cantilever and the other one is a virtual magnet-spring system, whose haptic behavior is analog. Preliminary results from an experiment conducted with forty-five students seem to show a better efficiency with the combination of both haptic feedback and visual analogy.

Key words: Haptic feedback, Visual analogy, Computer-assisted instruction, Atomic force microscopy

1 Introduction

Recent developments in the nanotechnology field have brought new knowledge of intangible phenomena at the nanoscale. One of the foremost tools for imaging, measuring and manipulating matter at this scale is the atomic force microscope (AFM).

The AFM consists of a microscale cantilever with a sharp tip (probe). Its deflection and its twisting give forces between the tip and the sample. The nanoprobe can be used to manipulate nano-objects, but this technique is limited by the lack of real-time visual feedback, inherent to scanning probe imaging, and by scaling effects on the nanoworld physics. In order to overcome these difficulties, virtual reality (VR) techniques and haptic feedback are currently being explored as a way to enhance the operator's perception. In this way, several telenanorobotic systems have been developed over the recent decade, combining an AFM with a haptic device and an augmented reality human-machine interface such as [1].

However, using such a symbolic representation for nanoscales is far from intuitive because the ratio between surface and volume forces differs from the one at our scale; adhesion and friction dominate gravity and inertia, resulting in sticky effects and huge acceleration. Rendering those effects to the user with linear scaling ratios would lead to large misunderstandings. That is one of the reasons why accurate telenanomanipulation is still a challenging issue [2].

In this perspective, we propose a haptic and VR simulator to explore and evaluate the impact of using haptics and a new visual analogy on the perception and the understanding of a nanophysical phenomenon, for persons without prior knowledge of nanophysics. Another benefit of this work lays in pedagogical aspects for a new generation of engineers who would deal with emerging micro- and nanotechnologies. An interactive VR tool may make them instantly aware of different aspects of nanoscale phenomena and increase considerably their understanding.

The next part presents an overview of previous works in the field of VR for pedagogical approach in nanosciences. The experimental system, set up for the evaluation of the force feedback and the visual analogy, is then described. Furthermore, the experimental procedure and the first results are described and discussed.

2 Related work

A growing research community is exploring the effectiveness of VR simulations in the enhancement of students' understanding of complex science topics. Some recent works investigated the impact of VR, mainly haptic augmentation, in nanosciences-learning contexts, such as virus morphology in biology [3], approach-retract phenomenon in microscopy [4] or protein-ligand docking in biomolecular [5].

In biology, Jones et al. [3] used the nanoManipulator, a VR platform with Phantom connected to an AFM, to assess the addition of different types of haptic feedback (a 6D Phantom device and a 2D joystick) on students' understanding of virus morphology. As well as in other investigations on using haptics in educational settings, they found that the more immersive environment provided by the haptic feedback makes the instruction more interesting and engaging. Moreover, they noticed some differences according to the type of hands-on tool: the more sensitive the haptic tool used, the more students used haptic terms and spontaneous analogies to describe the virus.

In microscopy, Marchi et al. [4] developed a multisensorial (visual, auditory and haptic) platform equipped with a real-time physically based modelling engine. They used it to teach a one-dimensional nanophysical phenomenon, the "approach-retract" (AR) force measurement, at the master level. Students reported more efficient description of AR than with a classical AFM. This may be due to the fact that VR simulation eases the observation of the parameters' influence by modifying them easily and choosing extreme values. Notwithstanding, their experimental plan did not directly compare the benefit of using a haptic feedback for the understanding process.

In addition, the visualisation of the geometrical appearances, as in the traditional AFM display, is not necessarily the most appropriate visual representation for understanding. For instance, the AR interaction in [4] used an atomic representation, made of a triangular tip interacting with an elastic layer of atoms depicting the sample surface, and a vertical line with zero free length symbolizing the cantilever. As Podolefsky [6] pointed out, analogies can be used to promote students' learning in physics. However, in the context of nanomanipulation by AFM, there exists no evaluation of the gain of possible visual metaphors.

Our study focuses on the AR phenomenon as it involves most noticeable phenomena in nanomanipulation. In this work, we aim to explore the benefit of using haptic interfaces and of providing an analogical visual representation on subjects' performance related to the understanding of the phenomenon. In the following, performance is analysed both in terms of speed and accuracy of the comprehension.

3 Experimental platform

3.1 Approach-retract phenomenon

The experimental system aims at simulating the AR phenomenon according to the different haptic and visual feedback cases of the evaluation. This phenomenon stands for the mechanical behavior of the AFM probe when it touches a sample surface in the vertical direction.

The profile of a force-distance curve of a silicon tip touching a polystyrene surface in ambient conditions is shown in Fig. 1. Examples of experimental AR curves can be found in [7]. The adhesion forces lead to a hysteretic behavior, with two thresholds.

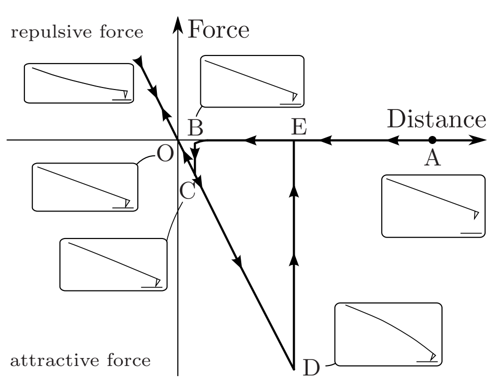


Fig. 1: Force-distance curve of an AR phenomenon

Away from the surface, distant forces do not act on the tip, so the cantilever is undeformed (point **A**). Approaching near point **B**, attractive forces rapidly increase and bend the cantilever. However, this bending is much smaller (more than one hundred times in ambient conditions) than those during the retract phase and thus, it is not visible at the scale of the whole curve. This behavior goes on until point **B** is reached, where an instability appears because the attractive force gradient overcomes the cantilever stiffness. The tip curtly snaps on the substrate; this "snap-in" matches the BC segment on the curve.

From this point, the tip is repelled by contact forces depending on the contact mechanics. During retract, the tip stays stuck to the substrate and the cantilever bends until the force applied by the cantilever reaches the "pull-off" force (point **D**). Then, once the equilibrium is broken, the second fast force variation of the AR curve occurs, snapping out the tip (point **E**).

3.2 Haptic and virtual reality system

The experimental system as illustrated in Fig. 2 comprises a real-time simulation of the AR phenomenon, along with a computer graphics interface and a force-feedback device. The simulation calculates the cantilever state, which can be sent to the visual and haptic feedback.

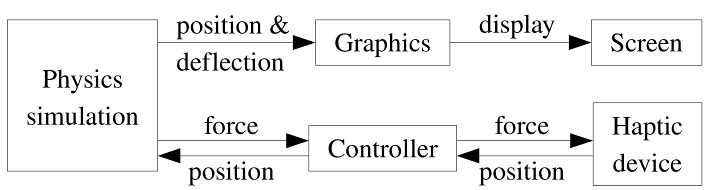


Fig. 2: Haptic and virtual reality system overview

Haptic simulation. The natural frequency of contact mode cantilevers is typically higher than 10 kHz. Therefore, at the time scale of a human teleoperation, we can assume the probe behavior quasi-static. Consequently, the AR simulation consists in calculating the cantilever deflection for each position.

The elongated form of the cantilever has a linear behavior in the small deformations domain, so the probe is modeled, as illustrated in Fig. 3, as a spring without mass. Therefore, the cantilever deflection is $\zeta = F/k$ with F the force applied by the tip on the cantilever and k the cantilever stiffness.

The simulation considers that there is no electrostatic force. Thus, during the approach phase, the equilibrium equation, in using the Derjaguin approximate expression of sphere/plane Van der Waals forces, is

$$k\zeta + \frac{HR}{6h^2} = 0 \tag{1}$$

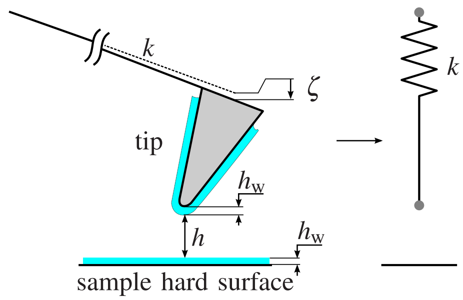


Fig. 3: Spring model of the contact mechanics

where h the distance between the tip and the substrate (between the water layers), H the Hamaker constant and R the tip radius. The cantilever base position z is defined as $z = h - \zeta$. Equation (1) is a cubic polynomial and its solution is given by

$$\zeta = \frac{2z}{3}\left(-1+\cos\left(\frac{1}{3}\arccos\left(1-2\frac{z_{\mathrm{si}}^3}{z^3}\right)\right)\right), \qquad z > z_{\mathrm{si}} \tag{2}$$

$$z_{\mathrm{si}} = \frac{3}{2}\left(\frac{HR}{3k}\right)^{\frac{1}{3}} \tag{3}$$

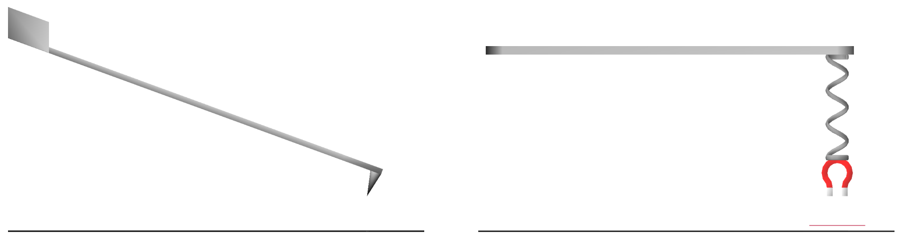
where z_{si} is the height of the snap-in threshold.

From the moment when $z = z_{\mathrm{si}}$, the tip snaps on the substrate which is assumed not deformable. Then, the deflection ζ is proportional to z. The simulation returns to the approach phase when the applied force reaches the pull-off force F_{po}. The latter is calculated according to the Maugis-Dugdale contact model [8].

For the experiment, the simulation used a supple cantilever with stiffness $k = 0.2\,\mathrm{N/m}$, a silicon tip interacting with a polymer sample surface, through a water layer of $h_{\mathrm{w}} = 8\,\mathrm{nm}$ on each surface. Resulting thresholds are $z_{\mathrm{po}}+2h_{\mathrm{w}} = 125\,\mathrm{nm}$, $F_{\mathrm{po}} = 25\,\mathrm{nN}$, $z_{\mathrm{si}} + 2h_{\mathrm{w}} = 18\,\mathrm{nm}$, $F_{\mathrm{si}} = 0.13\,\mathrm{nN}$. The force at the snap-in instant is two hundred times weaker than F_{po}. With linear scaling factors between the nanoscene and the haptic device, the friction of the haptic device masks this snap-in force, which, as a result, cannot be discernable.

Visual feedback. Two virtual representations are provided as illustrated in Fig. 4. The first one is a cantilever beam, although it is shorten (about 10x) relative to a real one in order to be able to see the cantilever deformation. It is angled by 20 degrees like in a real AFM to avoid that the cantilever base touches the sample surface.

The second representation is a behavioral analogy: the AFM probe similarly behaves like a zero-mass magnet attached to a spring touching a metallic surface. Indeed, attraction forces such as Van der Waals ones are in h^{-2} at close distance, like the magnetic force in the air gap between a magnet and a metallic surface. Moreover, the magnetic force is more familiar to our daily life.



(a) (b)

Fig. 4: Virtual representations of the AFM probe: cantilever (a) and magnet-spring (b)

Moreover, two visual marks locating the snap-in and pull-off thresholds are provided, close to the watched area. The snap-in mark appears during approach and is located between the magnet and the sample, at the height where the magnet snaps. Whereas the pull-off one, which is related to the cantilever base position, appears during retract and is placed above the horizontal bar, at the height where the magnet takes off.

Force feedback. The simulation is coupled with a force-feedback device working in an impedance way: the device sends to the simulation its vertical position, and receives the vertical force to render. This force is the one applied by the tip on the cantilever, F, with a constant scaling ratio. This ratio is determined by the rendered pull-off force, which is fixed at 7 N. In addition, an intermediate PC controller ensures the stability of the device.

4 Experiment

The aim was to explore the impact of haptics and visual analogy on students' understanding of the AR phenomenon. The study explored two research questions: (a) Does using the visual magnet-spring analogy representation improve learners' understanding of the AR phenomenon ? and (b) Does adding haptics enhance it as much, less or more than using the analogy ?

4.1 Method

Experimental apparatus. The experimental setup used a 3.2 GHz Pentium 4 PC, with the free and open-source software Blender [9] for the visual rendering and a C/C++ simulation of the AR phenomenon. The haptic device was a Virtuose3D from Haption. The system was designed in a multithreaded way. Graphics rendering was of 60 Hz and haptic control was updated at a rate of 1 kHz.

Participants. Forty-five voluntary students (41 men and 4 women), aged from 20 to 30, took part in this experiment (m=24.2, sd=2.3). They had no prior knowledge on nanoscale mechanics.

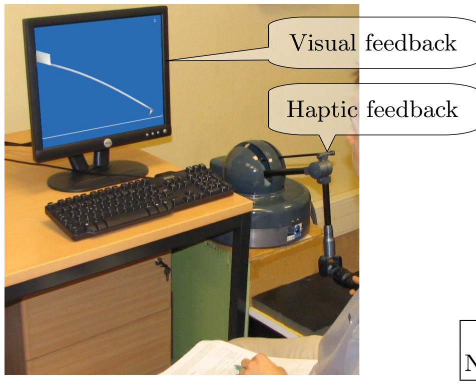


Fig. 5: Experimental set up

	Cantilever	Metaphor
Haptics	C1	C2
No haptics	C3	C4

Table 1: Experimental conditions

Design and procedure. As illustrated in Fig. 5, the participants were seated next to the haptic device, in front of the visual display.

The participants were randomly divided in four groups. Each group of participants was associated with one experimental condition to be used in the first phase of the experiment. The experimental conditions combined two haptic conditions (use of haptics; no use of haptics) and two visual conditions (use of visual metaphor; use of cantilever display), as displayed in Table 1. There was no time limitation.

The experiment was divided in two phases. During the first phase, the participants tried the AR simulation, consisting in approaching and retracting the virtual cantilever on four samples, and were asked several written questions about the AR phenomenon.

In the second phase, each participant was able to test the four conditions successively in a random order. They were then asked to fill in a second subjective questionnaire. They were asked to grade the four experimental conditions using a seven-point Likert scale, from 1 (very bad) to 7 (very good) and according to three subjective criteria: the *comprehension* of the AR phenomenon, the *perception* of forces and the global *appreciation* of the feedback.

4.2 Preliminary Results

Performance related to how subjects understand the AR phenomenon. To assess the effect of visual and force feedback conditions on subjects' understanding performance, we distinguished between the subjects' initial understanding performance in the first sample they tested and the actual understanding performance as measured in the subsequent three samples.

On the first sample tested by subjects, we expected no difference between experimental conditions due to the initial phase of the understanding process. To evaluate this hypothesis, we calculated a global indicator for sample 1 by summing all the correctness indicators applied to the answers of the subjects.

We ran an ANalysis Of VAriance (ANOVA) with the Visual display (Metaphor vs. Cantilever) and the Haptic feedback (Haptic vs. Non-haptic) as between-subjects factors. The test showed no significant effect for the Visual display ($F(1,42) = 0.51$, n.s.), the Haptic feedback ($F(1,42) = 1.52$, n.s.) and the two-way interaction ($F(1,42) = 0.95$, n.s.).

The correctness scores for the three subsequent samples tested during the first phase of the study were aggregated to evaluate how subjects actually increased in their understanding differently across the four experimental conditions. We conducted an ANOVA on this score with the Visual display and the Haptic feedback as between-subjects factors on this comprehension. The results show a main significant effect of Haptics ($F(1,41) = 6.52$, $p < .0145$) and no significant effect for the Visual display ($F(1,41) = 0.87$, n.s.) and for the two-way interaction ($F(1,41) = 1.79$, n.s.). From a descriptive viewpoint, we observed that subjects exhibited highest scores when being provided with Haptics (mean for Haptics (mH)=2.41, standard deviation (sd)=.67; mN=1.83, sd=.89), whereas a smaller (indeed not significant) difference was observed within the Visual display (mM=2.23, sd=.75; mC=2.00, sd=.85).

Time. All phases of the test being summed, the total time of the subjects' performance showed to be different depending on the group conditions. We computed an ANOVA on the total time with Visual display and Haptic feedback as mixed between-subjects factors. Subjects took slightly more time with the Cantilever than with the Metaphor displays (in minutes, mC=55.52, sd=12.18; mM=54.77, sd=13.04). Comparatively, we observed a large difference in the total time between subjects in the Haptic condition (mH=59, sd=14.89; mN=51.48, sd=8.40). A significant main effect of Haptics is found ($F(1,41) = 4.24$, $p < .0485$) whereas no significant effect of Visual display ($F(1,41) = 0.06$, n.s.) neither two-ways interaction between the two factors is found ($F(1,41) = 0.02$, n.s.).

Subjective evaluations. Table 2 presents the scores of the three subjective ratings for each condition and each criterion. A first result is the strong correlation between the three dimensions, with $R > .80$ systematically between each of the three.

To address subjects' evaluation of the conditions, we computed a Multivariate ANOVA on the three evaluated dimensions with Evaluated Condition as within-subjects factor and Initial Group Condition as between-subjects factor. Both factors and the two-way interaction were tested significant: Evaluated con-

Table 2: Means and sd of the three subjective evaluations (graded from 1 to 7)

	Comprehension		Perception		Appreciation	
	cantilever	metaphor	cantilever	metaphor	cantilever	metaphor
Haptics	5.67 (1.11)	6.51 (0.59)	6.04 (0.77)	6.36 (0.65)	5.98 (0.75)	6.31 (0.70)
No haptics	3.20 (1.42)	4.22 (1.66)	3.02 (1.54)	3.62 (1.59)	3.29 (1.38)	3.71 (1.52)

Table 3: Means and sd of global appreciation ratings for each of the four conditions as a function of the initial condition of the experiment

	Evaluated cond.				
Initial cond. group	Haptic + cantilever	Haptic + metaphor	No haptic + cantilever	No haptic + metaphor	Total
Haptic + cantilever	6.45 (0.69)	6.00 (0.77)	2.45 (1.29)	2.54 (1.04)	4.36 (2.11)
Haptic + metaphor	6.00 (0.63)	6.45 (0.69)	3.00 (1.48)	3.36 (1.50)	4.70 (1.91)
No haptic + cant.	5.58 (0.79)	6.33 (0.65)	3.75 (1.22)	4.42 (1.38)	5.02 (1.44)
No haptic + meta.	5.91 (0.70)	6.45 (0.69)	3.91 (1.14)	4.45 (1.37)	5.18 (1.44)
Total	5.98 (0.75)	6.31 (0.70)	3.29 (1.38)	3.71 (1.52)	4.82 (1.76)

dition (Wilks' lambda = 0.2718, F(9.0,394.4) = 31.02, $p < .0001$), Initial group condition (Wilks' lambda = 0.8305, F(9.0,394.4) = 3.48, $p < .0004$) and the interaction Evaluated condition * Initial group condition (Wilks' lambda = 0.7767, F(27.0,473.8) = 1.59, $p < .0324$).

Subsequent analyses confirm the result for each dimension[1]. For example, considering the global appreciation (cf. Table 3), we found that the best rated was Haptic+Metaphor (m=6.31) followed by Haptic+Cantilever (m=5.98). The worst ratings were Nohaptic+Metaphor (m= 3.71) followed by Nohaptic+Cantilever (m=3.29).

Subjects evaluated differently the various feedback depending on the experimental condition they were initially confronted with. The best ratings were found for subjects that were initially in the Nohaptic+Metaphor condition (m=5.18) whereas ratings were lower for subjects that were initially in the Haptic+Cantilever condition (m=4.36).

4.3 Discussion

Globally, the participants were significantly better in understanding the AR phenomenon when provided with force feedback than with only visual feedback. Furthermore, they preferred using haptics and the visual analogy rather than the cantilever representation. The highest influence of haptics was observed on the perception. The highest influence of the metaphor was on the understanding. This seems consistent with the aim of each technique.

The participants seemed more influenced by the presence of force feedback than by the visual metaphor. However the groups with haptics required more time; the reason may be eiher the more engaging simulation, or the additional information brought by the haptic modality.

A third of the participants of the groups without the visual metaphor spontaneously elaborated orally or by written the magnet-spring analogy. This suggests that our visual analogy could be useful for explaining the AR phenomenon to people without prior knowledge.

[1] Not reported here, individual ANOVAs performed for each dimension were significant for both factors and the two-way interaction.

This result seems inline with [6] who suggested that analogies can promote learning in physics in large-scale introductory physics courses. They found that "*representations play a key role as a mechanism of analogy use. Representations appear to cue students to focus on particular characteristics of physical phenomena.*" In our case, the magnet-spring analogy representation could help in focusing on the hysteresis behavior and the linear deformation of the cantilever.

5 Conclusion

This paper described an experimental platform set up to evaluate the benefit of using force feedback and visual analogy on the understanding of the approach-retract cycle of an AFM probe, for participants without prior knowledge.

First results showed that both studied parameters were appreciated and had an influence on students' perception and understanding. Further analysis is needed to detail these results, nonetheless the magnet-spring analogy appears to be a good candidate for AFM teaching in an introductory course. Our results suggest that future pedagogical tools on nanoscale phenomena should combine both haptic feedback and visual analogies.

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