Interactive Learning of Nanophysics Phenomena

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This paper describes a new method of teaching and experimenting nanophysics effects using a nanomnipulator. This nano-manipulator is formed by a multi-sensory platform connected to an AFM and/or to virtual nano-scenes produced by a real-time simulator. The first objective of this work is the evaluation of a custom-made nanomanipulator compared to the use of a classical Atomic Force Microscope (AFM) interface. These instruments are used to teach one-dimensional nano-physical phenomenon, the approach-retract (AR) one, to university students at master level. The second objective is to determine the role of each sensorial rendering (force, visual and sound) and their combination, in the understanding process of the AR phenomenon. These two objectives have been evaluated quantitatively and qualitatively by analysing student practical work reports.

Keywords: teaching, nanomanipulation, approach-retract interaction, multisensory, virtual reality

1. Introduction and state of the art in VR learning nanosciences

In the nano-world the object manipulation is not intuitive because the dominant phenomenon is not anymore gravity but adhesion and friction forces [1]. Forces that have different origins as capillarity, Van der Waals, electrostatic attraction, depending on the environment, produce these phenomena. The strategies and tools used in nano-worlds to move and interact with an object or a surface cannot be simply transferred from the macroscopic scale. One of the main instruments to explore surfaces and manipulate objects at the nanometer scale is the atomic force microscope (AFM) [2]. An AFM probe is based on a sharp tip localized at the free end of a micro-cantilever. A piezoelectric component is attached to this cantilever allowing it to move in the spatial directions. When the tip apex interacts with a surface, it induces cantilever deflexion. By recording this deflexion, information about tip-surface force interaction can be obtained. This technique finds its limits in the lack of real-time interactivity. Besides, interpretation of topography image or curves data is not so intuitive and requires time and solid theoretical background.

Some previous educational approaches have used virtual reality applications with haptic, visual, and/or auditory feedback in different ways to improve scientific learning in molecular biology [3], chemistry [4]. In nanophysics education, Murphy [5] has implemented a method of using atomic and magnetic force microscopy to led the students in differentiating ranges and origin of forces involved in imaging, while Ringlein [6] has developed simulations to describe and illustrate the atomic origins of friction. Their works even if students-oriented are based especially on visual rendering and does not include full immersion of the student at the nanometre scale. For research use, some groups have combined an AFM with haptic devices and virtual reality interface to facilitate nano-manipulation [7,8]. All these studies improve the AFM capabilities for nano-manipulations but do not facilitate the nano-scene phenomena understanding. In order to improve students understanding we used

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our custom-made nanomanipulator as educational tool. The present work focuses on the understanding of the approach-retract phenomenon that is required in local surface force spectroscopy and in most of the nano-object manipulations with an AFM probe. Firstly, this physical phenomenon studied during the practical work is explained followed by a brief description of the nanomanipulator chain. Secondly, we expose the practical work methodology and finally the results and discussions issue from the analysis of the student reports.

2. Approach-retract phenomenon

When two atoms approach to each other in vacuum, they interact and form a bond stabilised at the atomic-scale. The force given by the derivative of the Lennard-Jones (LJ) potential U_{LJ} represents the intensity of the bonding as a function of the distance, z [1].

$F = -grad(U_{LJ}) = \dfrac{12B}{z^{13}} - \dfrac{6A}{z^{7}}$ (1) ; A and B are respectively Van der Waals and Coulombien constants. The curve given by this force, represented in fig. 1 in classical line, is constituted of an attractive branch for long-range interactions (z^{-7}) called Van der Waals interaction, and a repulsive branch for short distances (z^{-13}). During an AR process in contact mode, which can be described roughly as a nano-palpating mode, the AFM tip apex interacts with the surface following a LJ potential. This interaction induces the deflexion of the cantilever free end that is related to its spring constant K [9]. The elastic behaviour of the cantilever is represented in fig 1 in dashed line. The global behaviour resulting on the AFM tip of the two combined forces, Lennard-Jones and elastic ones, is given by the expression (represented in fig 1 in bold line):

$$\vec{F}_C + \vec{F}_{LJ} = \vec{0} \text{ where } F_C = K\Delta z \text{ (2) with } \Delta z = z_T - z_P \text{ (Tip and Piezo positions)}$$

The hysteresis illustrated in fig. 1, bold line, is characteristic of the AR phenomenon. It presents two thresholds: one fast force variation in the approach phase called 'snap-on' (S1) of the tip to the surface and a second one in the retract phase called 'snap-off' (S2).

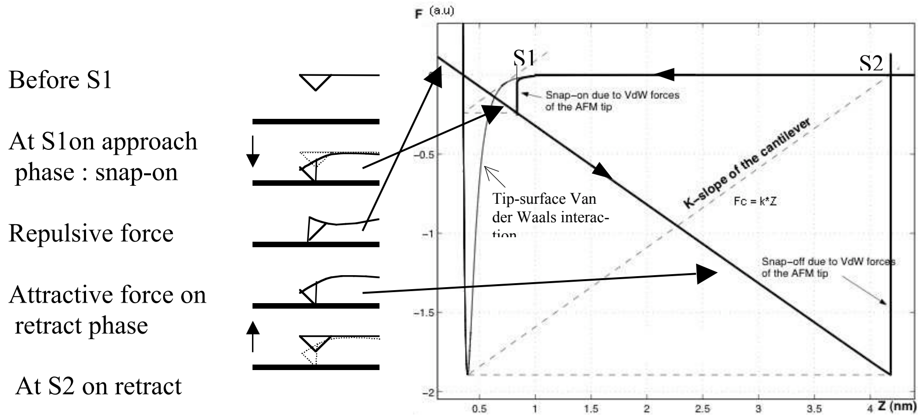
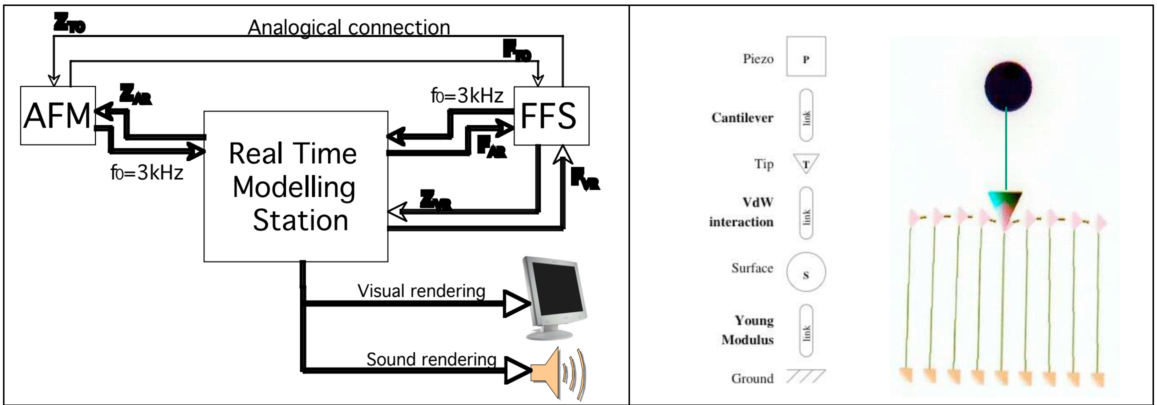


Fig. 1. AR phenomenon also called force

Analysing a force curve, students do not understand straightforward the physical origin of these two main specificities. From this observation, we have decided to use our custom made nanomanipulator to facilitate the student understanding.

3. Presentation of the educational platform

The designed educational platform (Fig. 2a) brings together an Atomic Force Microscope, Real-Time Modelling station, Force Feedback System working following 3 possible connexions: (a) teleoperation, when the real space of the user (force feedback system) is linked directly to the real space of the tasks with a simple scale change (there is no virtual simulation).; (b) virtual reality: real space of the user (force feedback system) is linked through one or many input/output points to a virtual space; (c) Augmented Reality: real space of the user (force feedback system) is linked to the real space of the tasks through the virtual space.
To ensure an accurate rendering of the contact with a very stiff object, at a mechanical level of human perception, the nanomanipulator chain has to work with a high working frequency and signal bandwidth. The main values of our nanomanipulator chain are indicated in the fig2 and the full description can be found in ref [10]. The justification of these values could be found in the ref [8]. The real-time modelling station placed between the experimentalist and the nano-world assures the support for implementing multi-sensory metaphors defining the active visual and auditory displays. The real-time modeling engine runs on the fundamental principles of physical-based simulation. The formalism, called Cordis-Anima [11] is based on two basic modules from which any mesh structure can be created: a module representing a pin-point mass, and another that sends two opposite forces, according to action-reaction principle. By modifying the parameters of each element: mass, spring constant, viscosity, a wide spectrum of real phenomena can be designed.



a) Nanomanipulator chain composed of the AFM, RTMS and FFS with a working frequency f_0

b) 1D Virtual nanoscene (left) and its associated Cordis-Anima model (right)

Fig. 2. Multisensorial platform

By means of the Cordis-Anima modelling and simulation system, a minimal representation of the real and complex phenomenon of AR interaction is implemented. The components involved in this interaction: the piezoelectric tube, the tip and the sample surface defined at an atomic level, are modelled like material objects with their specific mass, that are permanently in interaction with the external environment as well as among them. The equivalent schema is presented in Fig. 2b, where the cantilever is represented as a spring with a zero free length and driving the tip on the Oz axis, while the tip-surface bond is treated as a non-linear atom-atom interaction and implies energy exchanges between the elements involved in interaction. These exchanges are captured at the atomic layer of the surface and used to modulate the sound. The sound varies in frequency and intensity according to the evolution of the global elasticity and inertia of the system that is composed from the surface to the AFM probe. The force feedback translates the cantilever deflexion that is proportional to the force acting between the tip and the sample. Thanks to the multi-sensory rendering, the user can see and hear the interaction evolution and at the same time feels the involved forces.

4. Methodology description

Students of physics master and nanotechnology master followed an AFM practical work of 3 hours. All these students have a theoretical background in physics and basic concepts in AFM but no experience in multi-sensorial renderings and VR. In practice, sixty students have been separated in thirty couples; each couple followed the three hours practical work focused on the study of approach-retract (AR) phenomenon. Half of the couples has used a classical AFM interface while the other half has used the nanomanipulator. The PW using the classical AFM interface is divided in two steps. The first one is dedicated to the realisation of a classical topography image in order to get use to the AFM interface, and the second one is dedicated to the study of force curve spectroscopy mode. With a classical interface in spectroscopy mode, it is possible to set-up the tip velocity and the piezoelectric tube extension before the automatic run executed by the software and electronics of the microscope. It is also possible to apply a voltage between the tip and the sample that induces a capacitive force and, thus, a long-range interaction. The example of electrostatic forces is used to underline the possible variations of snap-on and snap-off thresholds. The only way to display the recorded spectroscopy data is to plot the cantilever deflexion in function of the piezoelectric tube position or time. This method does not provide real time information and is not interactive. Students recorded several force curves in different conditions and have to analyze them after in order to understand the AR phenomenon. The nanomanipulator PW is divided in two parts; the first one, after a short presentation of the nanomanipulator chains and its components, is dedicated to the realization of an AR phenomenon using a basic teleoperation connexion between the FFD and the AFM probe. Students can move and control the piezoelectric tube via the FFD and fell the force produced by the cantilever deflexion. The second part is dedicated to the study of AR effect using virtual nanoscenes linked to the multi-sensorial platform.

Two kinds of aspect have been evaluated from the written report compiled by the students after the practical work: (1) the comparison in the understanding of the AR effect using classical AFM interface or using the nanomanipulator; (2) The role of each rendering (haptics, visual and sound) in the learning process of the AR effect. In order to evaluate the efficiency of the nanomanipulator in the understanding process compared to the classical AFM interface, we have determinate from all the students' written reports (the ones written by students who have use the classical AFM interface as well as the ones written by students who have used the nanomanipulator) the degree of correct and complete answers to these following questions: (a) What is the snap-in and snap-off in the AR phenomenon? (b) What is the origin of the hysteresis behaviour? For the determination of the role of the three different renderings, the protocol during the practical work consists of running the same AR model and using the FFD for controlling the piezoelectric tube z position, but with different feedbacks 'on' as summarized in the table 1. After each AR run, students have to draw the graph (in arbitrary unit) of the elastic cantilever deflexion force in function of the piezoelectric tube position and to write their associated comments.

Configuration	1	2	3	4	5	6	7
FORCE rendering	X	-	X	-	-	X	X
SOUND rendering	-	X	X	-	X	-	X
VISUAL rendering	-	-	-	X	X	X	X

Table 1

5. Results and discussion

Firstly we compare the understanding of the AR phenomenon between the group of students (group 1) that used the classical interface and the group that used the nanomanipulator (group 2). The group 1 has to describe from the classical force curve the associated tip behaviour and tip-surface interaction. The group 2 has to associate and use their feelings and senses to describe the tip behaviour by drawing the associated force curve. A qualitative analysis of the written report of these two groups, allow to observe two major differences: (a) in the understanding of the snap-on (S1 on fig.1) and snap-off (S2 on fig.1), (b) in the explanation of the hysteresis origin.

In the group 1, most of the students have well described the position and force intensity evolution of the thresholds S1 and S2 with the evolution of the tip-sample interaction: LJ force alone or LJ force coupled to capacitive force but not with the value of the cantilever spring constant. The explanation of the hysteresis origin was not complete because they only underline that the intensity of the adhesive force is stronger in the retract phase that in the approach one. They did not link this hysteresis behaviour with the exploration of the full attractive part of the tip-surface potential. In the group 2, most of the students have described the position and force intensity evolution of S1 and S2 with the tip-sample interaction but also they underline the role of the value of the cantilever spring constant. Their explanation of the hysteresis behaviour is detailed and they associate the hysteresis with the exploration of the full attractive part of the LJ potential. From these observations, we can conclude that students of group 2, have understood more deeply the AR phenomenon and more precisely the role of the cantilever spring constant in the exploration of the tip-surface interaction. These understanding differences can be attribute to the flexibility of the virtual nanoscene to explore a wide range of situation. Indeed, the virtual nanoscene allows generating extreme behaviours that are not possible in the real one, and associate them with the evolution of the multisensorial renderings. As example, increasing the value of the cantilever spring constant in order to reduce or even eliminate the hysteresis area. Such extreme situations cannot be done with a classical AFM interface because such high spring constant value are not available on the market and also because it would be time consuming.

In order to evaluate the role of each sensorial rendering, we have designed a set of basic questions with three possible answers: YES, NOT or Undefined. From these basic questions, we obtained a series of data. The preliminary statistical data treatment, reveals the following points on the role of each rendering and their coupling: (a) 80% of the students, after using only force rendering, can distinguish different kinds of force in the approach phase and in the retract one (attractive and repulsive regime). The combination of the force with the visual or /and the sound rendering augments the distinction of the two regimes, up to 90%. (b) 50% of the students detect a different maximum in force intensity in attractive regime between the approach and the retract phases just using the force or visual rendering. Their combination augments this perception up to 90%. (c) 90% of the students determined only with visual rendering, that the ‘snap-on’ and ‘snap-off’ do not occur for the same piezo-tube position, this percentage drops to 50% if using only force or sound rendering. (d) 50% of the students detect a rapid force variation during the approach phase and the retract phase using only sound rendering, the coupling of the sound with force or visual rendering reaches 75%.

From these data, we can deduce firstly, that each rendering plays a specific role in the understanding process as: the sound in the perception of the fast force variation; the force rendering in the detection of the nature of the tip-surface force (attractive or repulsive); the visual rendering for distinguish that the snap-on and the snap-off do not occur for the same piezo-tube (cantilever) position. Secondly when the majority of students is not able to associate correctly their perception to the tip behaviour, the coupling between two well chosen renderings improve significantly their understanding. In most cases, the association of two renderings allows at least to 75% of the students to translate and associate correctly their dual perceptions to a specific behaviour of the AFM probe or to the nature of the tip-surface interaction. From these first tests on the role of the renderings in the understanding process, still a lot of information has to be extracted and analysed as example the evaluation of the rendering coupling on the reduction of the wrong or undefined answers. On the future works, a new protocol would have to be set up where the apparition of the rendering in the different configurations would be randomly defined. This approach should eliminate the effect of the rendering order on the understanding process.

6. Conclusion

The presented works show an improvement in the learning process of the AR phenomenon using the nanomanipulator rather than a classical AFM interface. As the student handles directly the nano-scene, a change in the physical interaction is transferred in a variation perceived by human sensorial channels, thus the student is no more oblige to make an effort of interpretation from symbolic graphic representation to sensed information. In addition, since in the virtual nanoscene the parameters values

can be changed easily, the role of each elements involved in the studied interaction can be explored. This leads to a better understanding of the studied phenomenon.
From the statistical treatment of the data issue from the student report, we have established the main role of each multisensorial rendering: sound rendering plays a crucial role in the perception of the fast force variation, visual one is crucial to determine the threshold instabilities, and finally the force rendering allows the determination of the nature of the force.

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