

NANOWORLD Practical Works 2010

FORCE FEEDBACK NANOMANIPULATOR

PUT YOUR HAND IN THE NANOWORLD THANKS TO HAPTICS
LEARN PHYSICAL PHENOMENA THROUGH VIRTUAL REALITIES

SCHEDULE

MORNING SESSION : 08:00 – 12:00
AFTERNOON SESSION : 13:30 – 17:30

PLACE

PHELMA - CIME NANOTECH

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TABLE OF CONTENTS

A - CONCEPTS AND DESCRIPTION OF THE SYSTEM (TO READ BEFORE THE SESSION)

- A1. Introduction
- A2. Components and functional principles of the VR Platform

B - EXERCISES and QUESTIONS

- B1. Atomic Force Microscope (AFM)
- B2. Preliminary analysis of the AFM probe
- B3. Physical-mechanical analysis

C – PRACTICAL WORK

- C1. Approach-retract effect on a 2D virtual nanoscene
- C2. Phenomenon analysis by graphical and descriptive methods
- C3. Stick-and-slip effect on 2D virtual nanoscene

INDIVIDUAL WORKS

PREPARATORY WORK

Read and prepare the part A before coming to the practical work session.

REPORT AFTER SESSION

Send back the report maximum 2 weeks after your session, by email (castet@imag.fr).

The report is individual.

A –CONCEPTS AND DESCRIPTION OF THE SYSTEM

A1. Introduction

The nanomanipulator designed by the ACROE-Institut Néel team aims to bring the nanometric phenomena at a human scale and to allow a direct manipulation in the nanoworld. Three kinds of system configuration have been realized around this work.

The *Teleoperation* configuration: the user manipulates a real AFM through a teleoperation system that links directly the AFM to the force feedback device. Real space of the user (force feedback device) is linked directly to the real space of the tasks with a simple scale change (there is no virtual simulation).

The *Virtual Reality* configuration: the user manipulates a 2D virtual nanoscene, metaphor of AFM system, through the force feedback device. Real space of the user is linked through one or many input/output points to a virtual space.

The *Augmented Reality* configuration: real space of the user is linked to the real space of the tasks through a virtual space.

This practical work focused on the *Virtual Reality* configuration aims to apprehend with fingers two phenomena observed during AFM experiments. The approach-retract phenomenon in contact mode and the friction phenomenon of nanometric scale, called « stick and slip ».

A2. Components and functional principles of the Virtual Reality Platform

The nanomanipulator has been realized on the Virtual Reality platform conceived by ACROE around hard haptic constrains (time determinism and high frequency of simulation). It is composed of a real-time physically based platform for multi-sensory interactive simulation (TELLURIS) and a force-feedback device (ERGOS-Technologies haptic device). (Fig. 1). This part presents the main features of the platform.

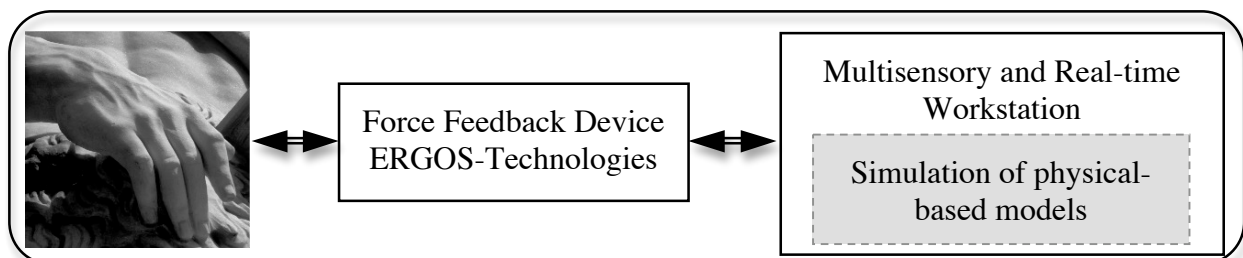


Fig. 1 - Instrumental chain of the nanomanipulator

a. Real-Time physically based platform (TELLURIS)

Concerning the modelling framework, the ACROE team has designed since 1984 computer formalism, called CORDIS ANIMA system, based on discrete mass-interaction modelling. A physical object or a set of physical objects are modeled and simulated as a network where the nodes are the smallest modules representing inertia (the MAT elements) and where the links (the LIA elements) represent physical interactions between them. The modules are all implemented with explicit algorithms, allowing for deterministic computation. Thus our multi-sensory simulation is based on one model composed of a large number of simple algorithms allowing a regular computation synonymous of determinism.

The input/computation/output sequence can also be easily synchronized on an external clock. Simulation frequency can be adjusted between 1 and 50 kHz according to the bandwidth of the physical phenomenon targeted.

Depending on the expected task and circumstances of platform use, simulation requirements are variable. This platform is also conceived like a modular hardware platform composed with different computation units.

One of the hardware components is multi-processor computer (bi or quadri) from Concurrent Computer Corporation. Processors used are AMD Opteron 2 GHz with cache of 1Go and 64 bits architecture. A DSP board from Innovative Integration, called TORO board, is the second main component of the platform. The DSP embedded is the TMS320C6711 characterized by a computation frequency of 150MHz. 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 (ERGOS panoply).

Considering that commercial sound boards present non negligible latencies, we have also chosen to take benefit of the 16 bits precision D/A converters for sound outputs (up to 4 channels, for quadrasonic sound), allowing for very short latencies (less than 5 us for a simulation frequency of 44,1 kHz).

These hardware components could be used together or independently providing a range of configurations for various performances.

The current nanomanipulator uses configuration that is only based on the DSP-board with high channel of analog I/O. This module is particularly adapted to be used for models requiring hard reactivity and a low computation power. The simulation runs on the DSP and its host, a general-purpose computer, is only used for simulation control and for visualization.

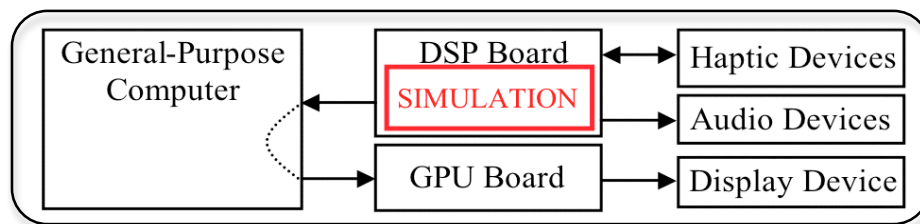


Fig. 2 – Configuration of platform with DSP for Practical work

QUESTIONS

- A2.1. Find different definitions of virtual reality. What is it and where is it used?
- A2.2. Give the frequency scale of each sensitive phenomenon: sound, visual, and haptic.
- A2.3. What do you know about real-time computation?
- A2.4. The DSP is synchronized at 5kHz. The computation time of one simulation step is 2 microseconds for one « element » (see CORDIS). How many elements can be simulated to respect strictly the synchronisation?

b. The formalism CORDIS

The formalism called CORDIS is based on two elements or basic points: the M point, respectively the L point. From these assumptions, two types of basic modules MAT and LIA have been set up (Fig. 3), from which any mesh structure can be created.

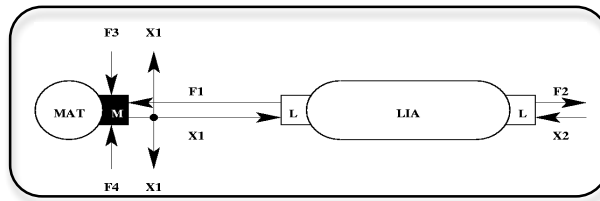


Fig. 3 - MAT/LIA link with forces and positions

The MAT module, representing a pin-point mass, is made of a single M point and its algorithm in discrete time is calculated from the fundamental relation of dynamics:

The fundamental relation of dynamics : $\sum F = m\vec{a} = m\ddot{X}$

$$X(n) = 2X(n-1) - X(n-2) + \frac{F(n-1)}{M} \quad (1)$$

- $F(n) = f(n \cdot \Delta t)$ is the sum of the forces received by the M point,
- $X(n) = x(n \cdot \Delta t)$ is its position,
- f, x are the corresponding continuous measures,
- $M = m/\Delta t^2$,
- Δt is the sampling interval.

The LIA module is composed of two L points sending two opposite forces, according to action-reaction principle. The elastic link follows the discrete-time algorithm, with K the spring constant:

$$F_2(n) = -F_1(n) = -K \times [X_2(n) - X_1(n)] \quad (2)$$

The interaction models for AFM-tip and sample surface created in *TELLURIS* can be directly developed (in C language with integrated parameters).

c. ERGOS-Technologies Haptic Device (HD)

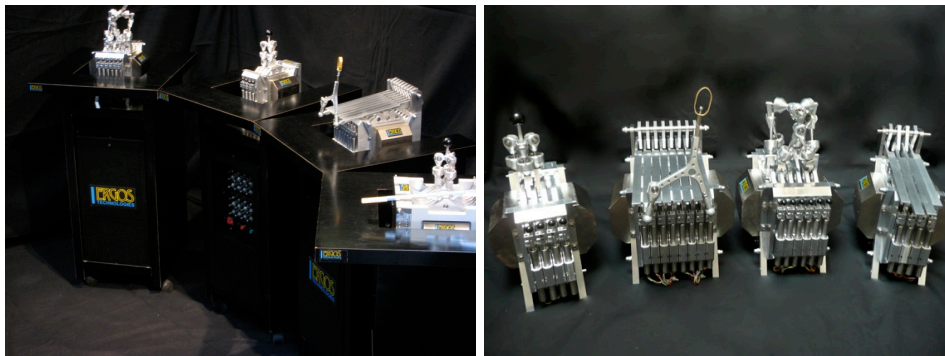


Fig. 4 - Haptic device from ERGOS-technologies panoply

The retroactive gestural transducer is a haptic manipulator composed of independent slices, each of them can be moved of an electromagnetic actuator and is linked with a high-resolution LVDT position sensor (2mm), as shown on Fig 4. Besides the easy modularity of this morphology, its power is so far unmatched in the commercial force-feedback architectures. With a 20-mm vertical displacement and a 10-kHz cut-frequency, it delivers a 50N permanent force, extensible to a 200-N transitory force for a maximum speed of 2 m/s, since most of the commercial architectures hardly reach the 10 to 20 N.

Two forces are applied on the real key of the HD: one force induced by the user during her/his manipulation and one force send by the virtual space through the input/output M point when the key is linked. At each moment the HD key reacts and finds an equilibrium position eventually according to the resultant of these 2 forces. Correspondingly, at each moment the position of the HD key is sent to the virtual space through the same input/output M point. The HD key has the same statute as the other virtual point-masses (MAT) from simulation.

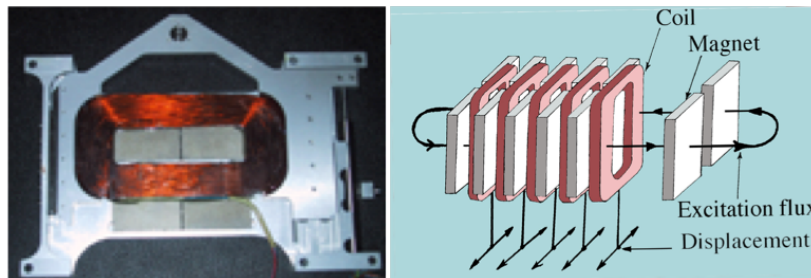


Fig. 5 - 1DOF force-feedback slice and the shared Excitation flux system

Note :

Most of beginners in using a haptic device do not take care much about the device since they assimilate it to a simple video-game joystick. But :

- this device is responding with 50N of force, it is much powerful than a usual joystick,
- this device is connected to a virtual simulation, that is to say a world as physical as the real one.

For these reasons, **never release** the haptic end-effectors as a (real or virtual) manipulation is running!

A haptic device is a tool, *release it is equal to drop it ...*



B – EXERCICES and QUESTIONS

This practical work takes place in the experimental environment of a laboratory, using a prototype. It brings out the concept of multisensory and instrumentation, and is thus quite qualitative. You are welcome to ask questions about the architecture, the models, the results, and the impact of such a tool on applications.

B1. Atomic Force Microscope (AFM)

An **AFM** (Fig. 2) is based on a sharp tip supported by a cantilever – assembly that constitutes the AFM probe, an optical detector for the cantilever deflexions and a piezo-electric positioning system allowing 3-dimensional moves. Generally, the sample is set on the positioning system and can be moved along x and y while the AFM probe is not moving.

The forces between the tip and the surface induce cantilever deflexions in the z direction, which are recorded in function of the x , y position. This optical detection is carried out by a laser beam focused on the back side of the cantilever and reflected through a mirror to a four-diode photo-sensor. This diode delivers a voltage proportional to the lighted area, we can thus follow the vertical and lateral movements of the beam, respectively associated to the vertical deflexions and the lateral twists of the cantilever. This system allows to reach a vertical resolution lower than 1\AA .

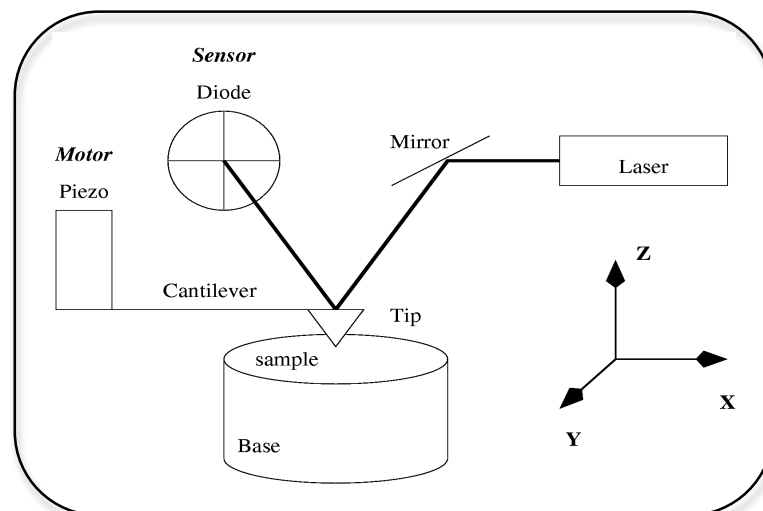


Fig. 6 - Functional scheme of an AFM

The forces acting between the AFM probe and the sample surface have several origins:

- *Capillarity forces*, ten times greater than the Van der Waals forces, they result from the condensation of water molecules and the apparition of a meniscus between probe and sample. When AFM probe works in air at room temperature, capillarity forces appear for a tip-sample distance of few nanometres.
- *Van der Waals forces*, very low, result from a dipole-to-dipole interaction, when the probe-sample distance is a few nanometres.
- *Inter-atomic repulsive forces*, also very low, result from the tip-sample interaction of the electron clouds, when the probe-sample distance is lower than 1 nm.

These forces can have any direction, according the interaction between the sample topology and the tip.

B2. Preliminary analysis of the AFM probe

The geometrical characteristics of an AFM probe are:

a) *Piezo-electric tube*

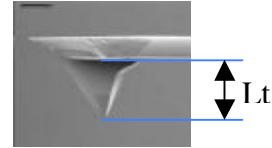
- Total elongation: $L_p=3\text{mm}$

b) *Cantilever*

- Length: $L_c=100\text{mm} \pm 5\text{mm}$
- Width: $w_c= 40\text{mm} \pm 3\text{mm}$
- Thickness: $t_c= 1\text{mm} \pm 0,3\text{mm}$

c) *Tip*

- Height: $L_t=15\text{mm}$
- Basic radius: 10-50 nm



The AFM probe assembly and the associate characteristics are shown in Fig. 5. Taking into account the real dimensions given above and assuming that the interaction between AFM tip and surface is led by the **Lennard-Jones potential**:

$$U_{LJ} = \frac{B}{z^{12}} - \frac{A}{z^6},$$

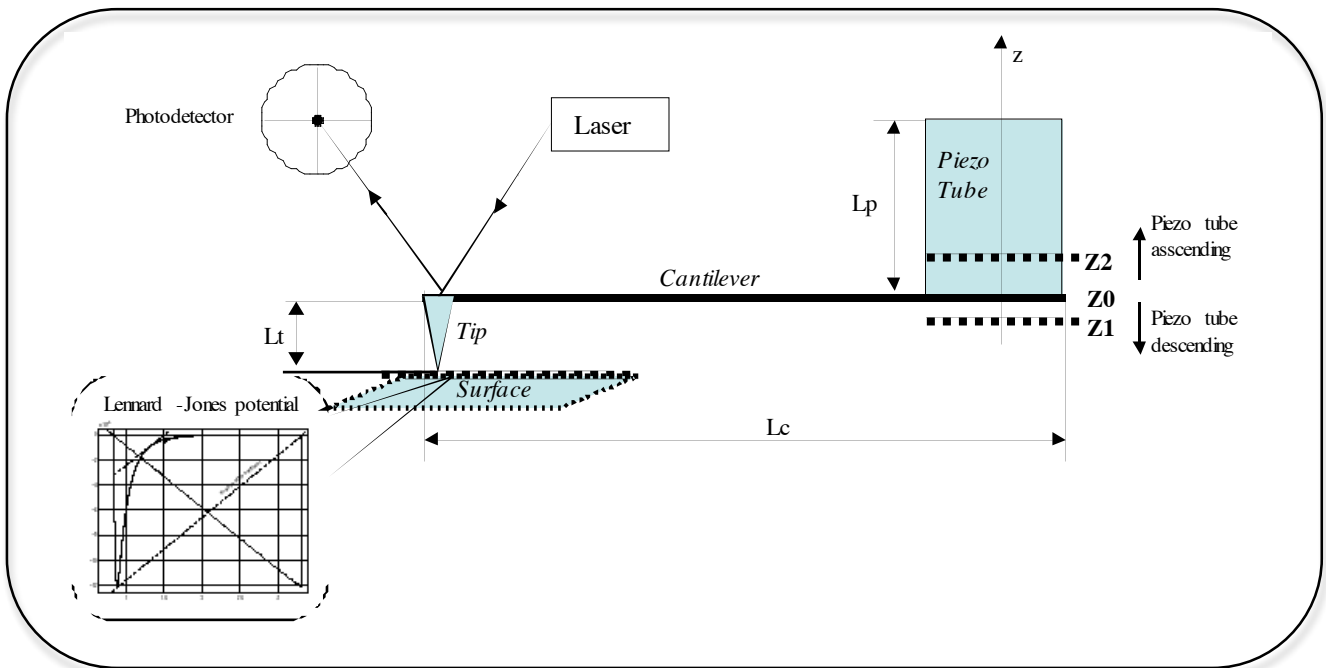


Fig. 5 - Characteristics of the AFM probe

QUESTIONS

B2.1. Write the resultant of the forces acting on the AFM tip considering it at equilibrium.

B2.2. Represent geometrically the cantilever deflection when the piezo-tube is approaching the surface from Z_0 to Z_1 with respect to the real values of the involved displacements. Explain and illustrate the evolution of the laser beam movements in the four-diode photo-detector.

B2.3. The same question for the case when the piezo-tube is retracting from the sample surface (piezo-tube ascending from Z_1 to Z_2).

B3. Physical-mechanical analysis

The *probe of the AFM*, composed by a piezoelectric actuator driven in position, a cantilever and a tip, is assimilated to the *minimal model of mass-spring* illustrated below (Fig. 6) where an inertia m is linked to a stiffness spring, k .

QUESTIONS

B3.1. Identify the 3 components of the AFM on this scheme by placing it side by side with the probe scheme.

B3.2. Write the functional equations of the system and deduce the *forces-positions* transfer function, $f(z_m)$, for a η viscosity environment.

B3.3. Assuming that this minimal model is simulated and that you can adjust all the parameters, describe the influence of m , k , V (*speed of probe*) values in the behaviour of this model.

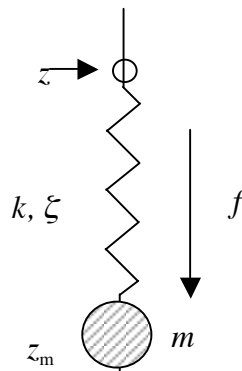


Fig. 6 - Mass-spring minimal model

C – PRACTICAL WORK

Study of an approach-retract with the 2D nanomanipulator.

Aim of the PW:

Understanding the approach-retract phenomenon in contact mode.

An approach-retract curve in contact mode consists in recording the cantilever deflexions in function of the piezo position. Basically, it consists in firstly approaching and secondly retracting the probe from the sample at a constant speed (vertical moves in a given x , y point). The measure of the force, which acts on the cantilever in function of the distance, allows obtaining an approach-retract curve, which relates the nature of the tip-surface interaction.

For each model (ideal case and real case) give a graphical representation of

- the force in function of the z-displacement, $F = f(z_p)$
- the tip position in function of the piezo-tube position, $z_p = f(z_t)$.

C1. Approach-retract effect on 2D virtual nanoscene

The AFM system composed mainly by the piezo tube linked to the tip through the cantilever could be considered as one-dimensional (following Oz axis) phenomenon at least during the approach-retract interaction. The piezo tube is position-controlled and the cantilever could be simulated as a spring with zero-length chargeless that drive the tip following the Oz direction. The model equivalent to this phenomenon is illustrated in Fig. 11.

The 1D manipulation of the virtual model can be done using the HD key (Fig. 12) and through a Virtual Reality kind of manipulation. The visual rendering is structural (geometrical elements of the scene).

QUESTIONS

C2.1. Give a **graphical representation** of the approach-retract phenomenon $F = f(z_T)$, and/or the tip position $z_p = f(z_T)$, and/or any other qualitative representations of your feelings that you may find useful for your physical explanations of the phenomenon in function of the piezo-tube position z_T . On these graphs, take lot of draft comments about what you feel, in order to remember these feelings and analyse the evolution of what you perceive.

C2.2. What is the evolution of approach-retract phenomena when you change the spring constant of the AFM probe? Using your draft observations, make a global analysis about the relation between what you fell and the physics of the hysteretic approach-withdraw phenomenon. Realize measurements with the simulation interface in order to illustrate your explanations with graphical representation (with *Matlab* for example).

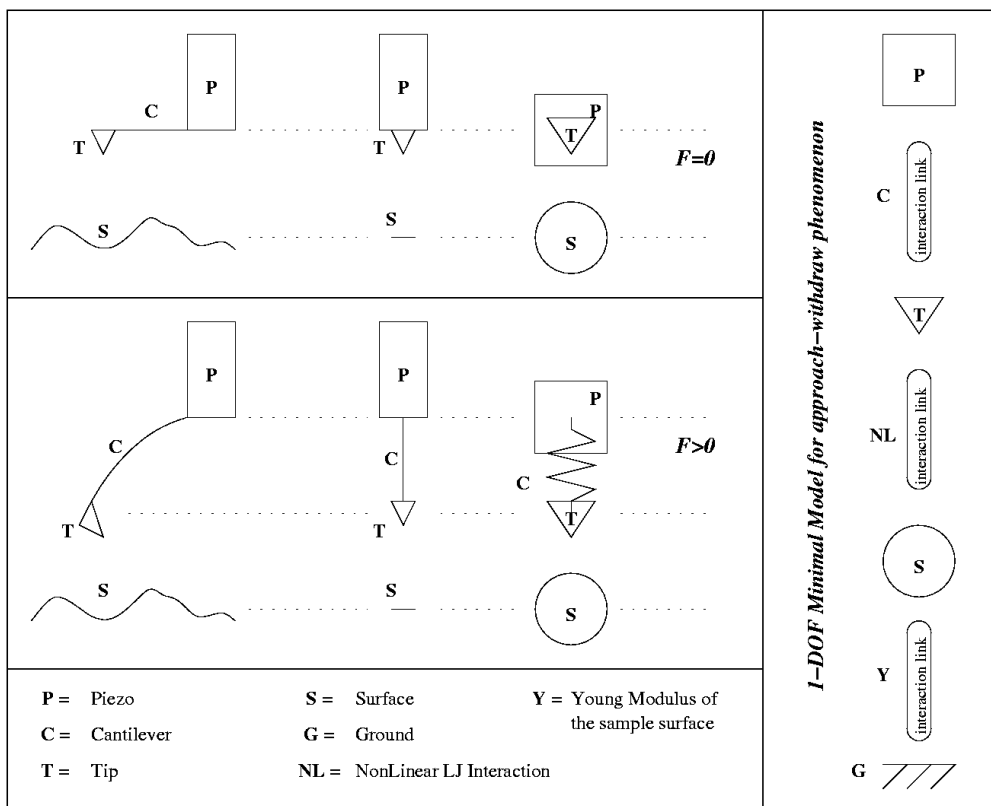


Fig. 11 - Minimal model representing the AFM probe and the surface

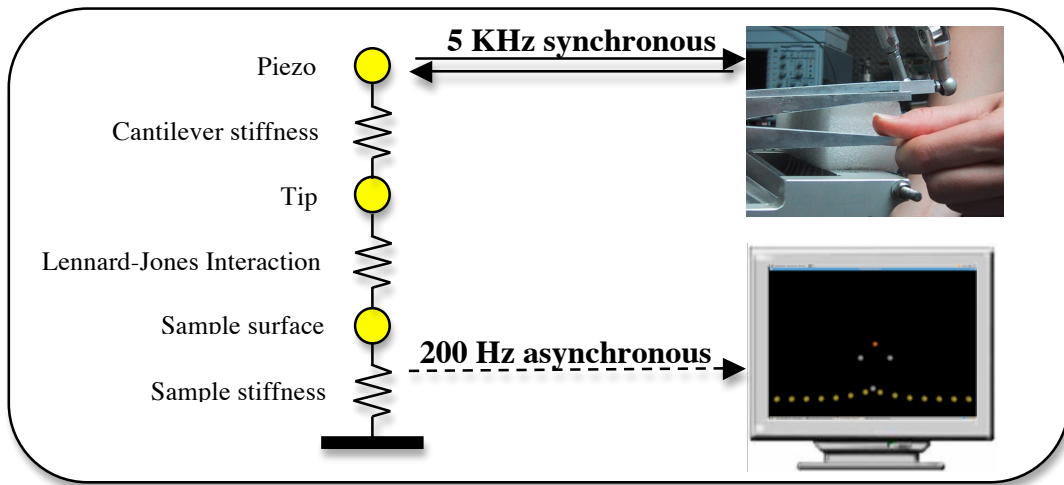
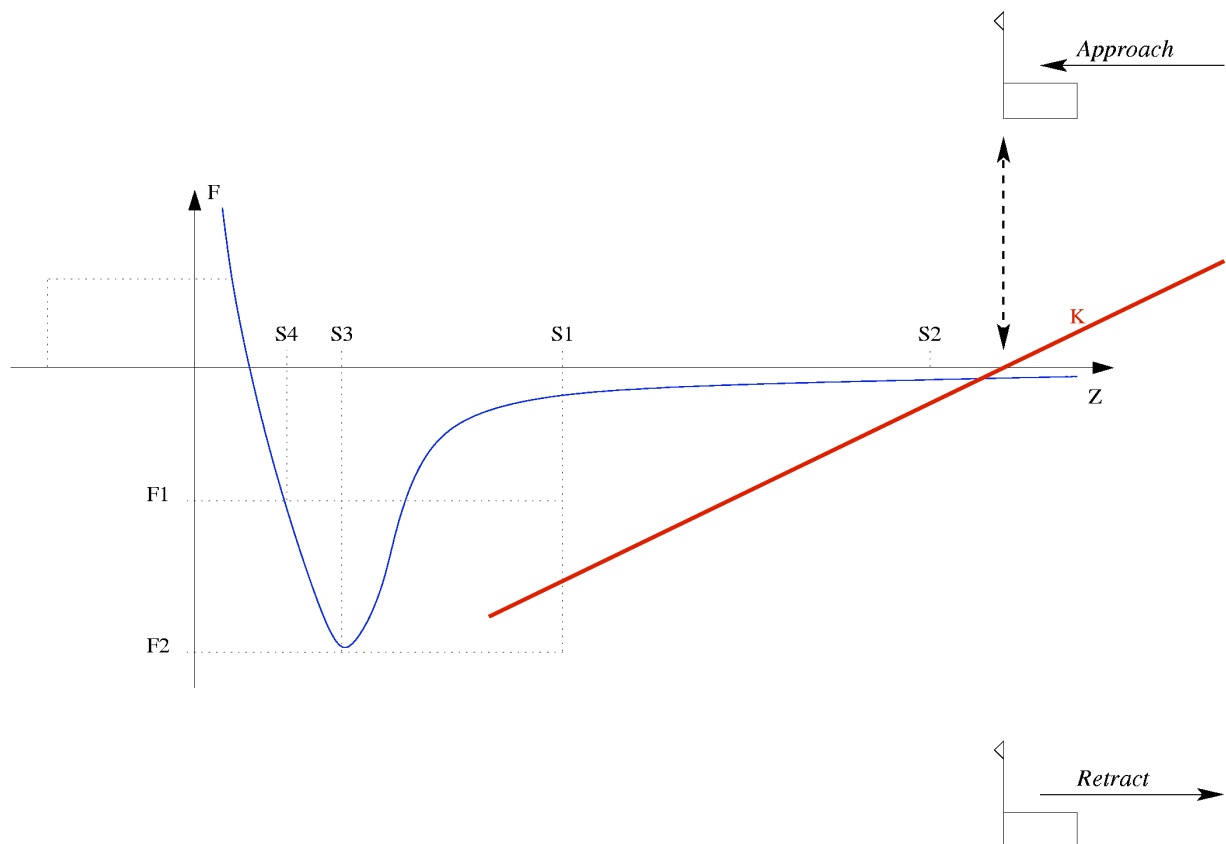


Fig. 12 - Approach-retract manipulation on a virtual surface

C2. Phenomenon analysis by individual descriptions

Aim: We will explain the physical hysteretic phenomenon of approach-retract through graphical and descriptive methods.

Plot here some chosen positions for the tip and the piezo during the approach phase



Plot here some chosen positions for the tip and the piezo during the retract phase

- Tip-Surface Interaction (Van der Waals Curve)
- Tip-Piezo Interaction (Cantilever)
- - - Approach-retract hysteresis curve (to plot)

Fig.13 - Equivalence between non-linear interaction and observed approach-retract curve

QUESTIONS

C2.1. Write the force equations, which describes the non-linear interaction between tip and surface.

C2.2. On the graph in Fig. 13, identify the origin of the K-slope curve, as also the origin of the non-linear curve, from a physical point of view.

C2.3. Using a graphical method, roughly plot the approach-retract curve, using several functional points.

C2.4. What happens when the K value changes?

C2.5. (*Bonus*) Describe a method for simulating graphically the position of the tip and the hysteretic phenomenon thanks to potential curves. As in question C3.3, roughly plot the resulting potential curve, using several functional points.

C2.6. (*Bonus*) The simulation proposes to explore a finite sample. What is the main consequence? Is there a real phenomenon that can be associated to this consequence?

INTRODUCTION

Important: The answers for this first part will not influence your mark result. There are no good answers and you must answer without being influenced by other. The aim is to evaluate yourself on your personal understanding of physical phenomena through a multisensory simulation, and to help you to extract conclusions for your report writing. You should give back results of this part at the end of the session.

1. Have you done the *advanced microscopy* course ? Is it finished ? YES NO

How many hours of course and TD have you taken ?

Have you realized the practical work about the STM YES NO

Have you realized the practical work about the real AFM YES NO

2. ✍ Generally practical works are made in order to practice points learned during the course. Before starting, **write yours questions** about AFM principle. Try to find questions about fuzzy points linked to AFM exploration : kinds of forces, variation in force intensity, kinds of region in the exploration area...
3. 🖐 After the introduction of the simulation platform, you should **explore the simulation** with the force feedback device, without parameter modifications.
- The teacher will propose different configurations of manipulation (vision, sound, haptic). In each case, try to understand the behavior of each simulated object, and note your feeling about these experiments. Try to complete the questionnaire attached.
4. ✍ After this exploration, you maybe have found new fuzzy points about AFM principle. Try to **write new questions**.
5. ✍ Try to **write hypothesis** about each questions you have formulated.
6. 🖐 **Explore the simulation** in order to answer to your questions. Now you can change properties of the simulated scene.
7. ✍ After this introduction, what is your opinion about this exercice. Is it more an illustration of the theory part or a good complement of the real practical work ? Explain clearly your opinion.
8. ✍ According to you, what is the main advantage of this simulation experiment. Try to list different points which differentiate a real AFM manipulation and this simulation.

QUESTIONNAIRE

Important: The (Y/N/U) answers will not influence your mark result. There are no *good* answers. The aim is to evaluate yourself on your personal understanding of physical phenomena through a multisensory simulation, and to help you to extract conclusions for your report. However, you still have to feel the questionnaire completely and give it back inside your report.

Questions	Force	Sound	Visual	Y	N	Undef
1. Do you detect a fast variation in force intensity during the approach phase?	-	-	-			
	-	X	-			
	X	-	-			
	X	X	-			
	-	-	X			
	-	X	X			
	X	-	X			
2. Do you detect a fast variation in force intensity during the retract phase?	-	-	-			
	-	X	-			
		-	-			
	X	X	-			
	-	-	X			
	-	X	X			
	X	-	X			
3. Do you feel several kinds of forces during the approach phase? (both attractive and repulsive, or only one kind)	-	-	-			
	-	X	-			
	X	-	-			
	X	X	-			
	-	-	X			
	-	X	X			
	X	-	X			
4. Do you feel several kinds of forces during the retract phase? (both attractive and repulsive, or only one kind)	-	-	-			
	-	X	-			
	X	-	-			
	X	X	-			
	-	-	X			
	-	X	X			
	X	-	X			
5. Is there any difference in the maximum of force intensity that you perceive during the approach and during the retract phases in	-	-	-			
	-	X	-			
	X	-	-			
	X	X	-			
	-	-	X			
-	X	X				

the repulsive regime?	X	-	X		
	X	X	X		
6. Is there any difference in the maximum of force intensity between the approach and the retract phases in the attractive regime?	-	-	-		
	-	X	-		
	X	-	-		
	X	X	-		
	-	-	X		
	-	X	X		
	X	-	X		
	X	X	X		
7. Does the snap-on occur at the same position of the piezo-tube than the snap-off?	-	-	-		
	-	X	-		
	X	-	-		
	X	X	-		
	-	-	X		
	-	X	X		
	X	-	X		
	X	X	X		
8. Could you maintain the AFM probe several seconds in the region closed to the tip snap-off effect? (just before the probe release up out of the surface)	-	-	-		
	-	X	-		
	X	-	-		
	X	X	-		
	-	-	X		
	-	X	X		
	X	-	X		
	X	X	X		
9. Classify the sensory feedbacks according to their help for understanding the approach-retract phenomenon (1=best to 7=worse)	-	X	-		
	X	-	-		
	X	X	-		
	-	-	X		
	-	X	X		
	X	-	X		
	X	X	X		
	X	X	X		