SP2 - SENSING

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1 Role and objectives of SP2

The role of this sub-project is to develop, implement and operationalize many technological tools that will be used to obtain experimental data necessary to understanding the interaction phenomena, which occur between elements of micrometer size, within the different scenarios that take place in practice during the micromanipulation tasks. These forces must be measured experimentally in order to validate the theoretical models developed in the sub-project 1 (SP1).

Given the difficulties in measuring the interaction efforts, who are of various kinds (friction, surface tension, force field, pull-off, electrostatic force) and that are acting in different environments, we decided to develop sensors operating according to classical principles of physics, but also originals ones which are very powerful on the scale envisaged. Each sensor has its advantages and disadvantages. The idea is to provide maximum measurement solutions for a given problem. It is also needed to ensure the best calibration of these force sensors.

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2 Microforce sensor generalities

The force is an intensive phenomenon. Rather to measure the force itself, the principle is to measure the effect of the force on a sensing device. This device consists of a sensitive body, which has a moving part of mass M, and which is interacting with the soil through a elastic liaison with a materialistic nature or not. This interaction qualified of *spring*, keeping in mind that it is only a mathematical concept (for exemple a non materialistic *magnetic spring* or an *elastic blade*), has a mechanical stiffness K.

To achieve a good microforces sensor able of measuring a range of a few tens of nN to a few hundreds of μN, it is necessary to have a device with a stiffness less than 1 N/m. Then have a powerful sensor giving an accurate measurement of the displacement x of the sensitive body. The force F is simply calculated using the formula:

$$F = K\,x \tag{1}$$

Finally, it is essential that the force sensor integrates the best displacement sensor. It also has a mechanical stiffness K as stable and as small as possible. It avoid cases where K depends on the movement of the sensitive body, conditions of temperature, humidity, etc... The calibration of the sensor consist in determining an accurate value of K .

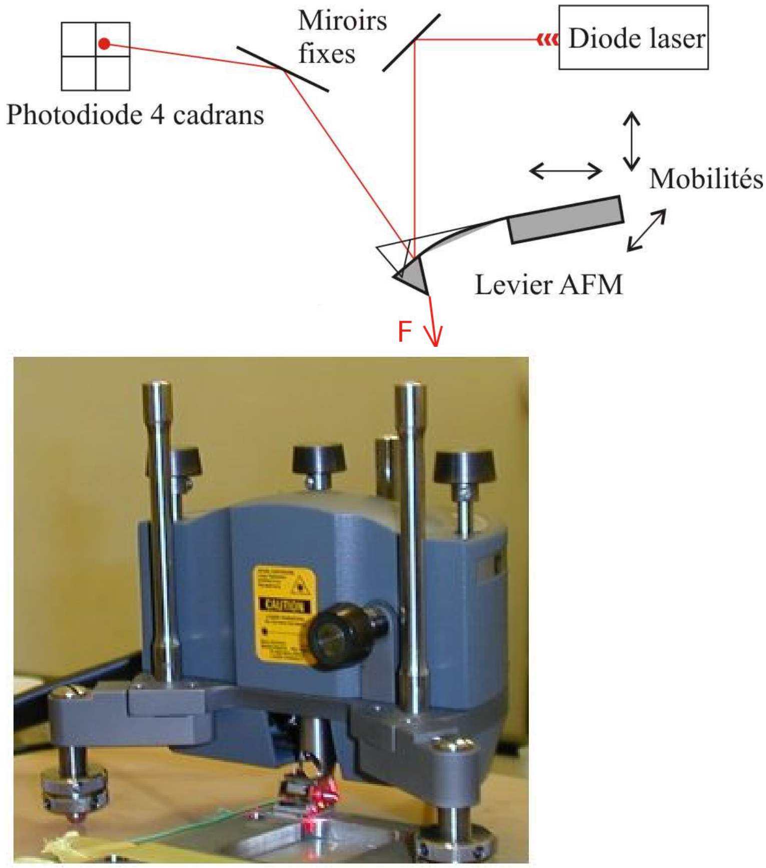

Figure 1: atomic force microscope used for Nanorol.

3 The sensors of the Nanorol platform

There is three sensors currently operational on the Nanorol platform. It is a modified atomic force microscope (AFM), a passive levitation sensor and a commercial sensor. Two other sensors are under study and development, using a magnetic flotation, the second a piezoresistive principle.

3.1 Modified AFM sensor [1] [2]

This is a classic AFM not adapted to measure surface topography but rather a measure of pull-off forces, surface tension, etc... (fig. 1)

Features :

- stiffness of cantilever used between 0.03 N/m and 14 N/m
- a cantilever of stiffness 0.2 N/m allows a measure of 0 to 600 nN with a resolution of 10 nN
- cantilever stiffness calibration by excitation of eigen modes, or thermal noise measurement

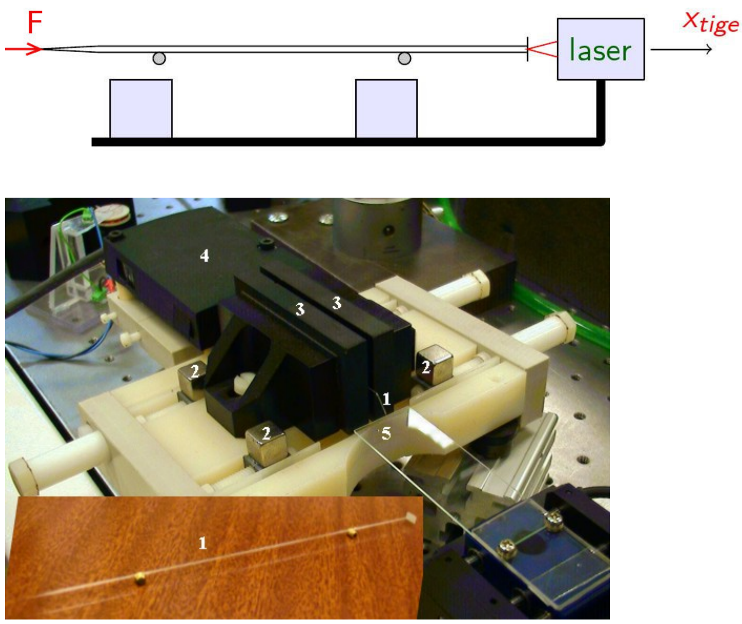

Figure 2: 1 glass capillary, 2 permanent magnets, 3 diamagnetic graphite plate, 4 laser sensor, 5 positioning device.

- measure of a two direction force using the 4 framework photodiode

Known limitations:

- coupling movement of the tip of the cantilever generating unexpected behavior in the process of withdrawal and approach between the tip and the substrate, mainly during the phases of contact
- calibration of the deflection measurement of the lever by the photodiode uncertain

3.2 Passive levitation sensor [3] [4]

This sensor operates on the principle of passive levitation. The sensitive body consists of a glass capillary maintained in levitation passively through a set of permanent magnets and diamagnetic graphite (fig. 2). The stiffness is provided by the magnetic forces. It is as if the capillary, which is considered rigid, is connected to a magnetic spring acting in the horizontal direction. The measurement is performed in this direction for one component of the effort.

Features :

- stiffness between 0.02 and 0.04 N/m depending on the setting of permanent magnets
- force measurement from 0 to 200 μN, with a resolution of 50 nN

- filtering of the measurement by a Kalman filter (elimination of the dynamic component $M\ddot{x}$ due to the aceleration of the capillary).
- measure one component of an horizontal force
- calibration of stiffness by exciting the eigen mode in the direction of measurement

Known limitations:

- bandwidth less than a few hertz
- extreme sensitivity to vibration and surrounding air currents, especially in the range of LF

The development and refinement of this sensor are funded by ANR Psirob Stilmicroforce.

3.3 Femto Tools sensor

This is a silicon sensor micro-machined by the society Femto Tools. The displacements of the sensitive body are measured with a capacitive sensor integrated into the structure (fig. 3).

Features:

- stiffness of 1000 N/m
- measurement from 0 to 2 mN with a resolution of 1 μN
- measure one component of an horizontal force

Known limitations:

- range of force exceeding the range that of the sensors described above §3.1 and §3.2
- most suitable for measurement of surface tension or to apply important load

3.4 Sensors under study and development

Two sensors are under study and development. It is a 3-axis sensor based on a principle of magnetic flotation and a piezoresistive micro-machined cantilever.

3.4.1 floating magnetic sensor [5] [6]

The sensor consists of a floating platform under the influence of magnetic forces generated by permanent magnets (fig. 4). The weight of the platform is offset by the buoyancy of the floats fixed on the platform. This sensor is designed to run on horizontal stresses and couples oriented vertically only. When the platform is sollicitated, a shift is then measured by three laser sensors arranged in the horizontal direction. An object to be characterized has to be prepared

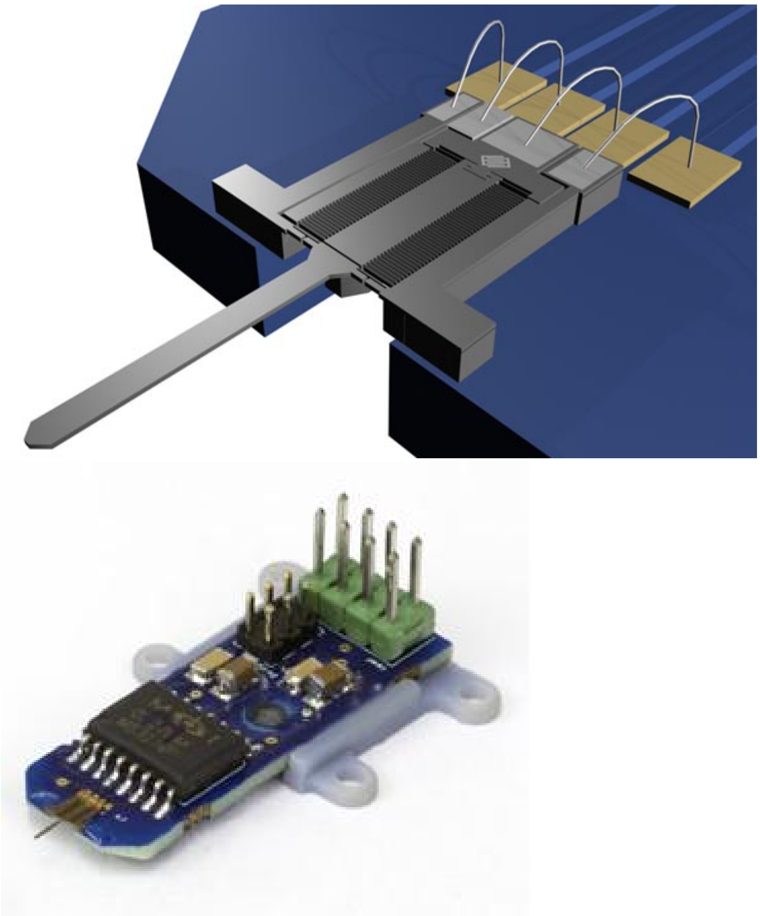

Figure 3: Femto Tools sensor.

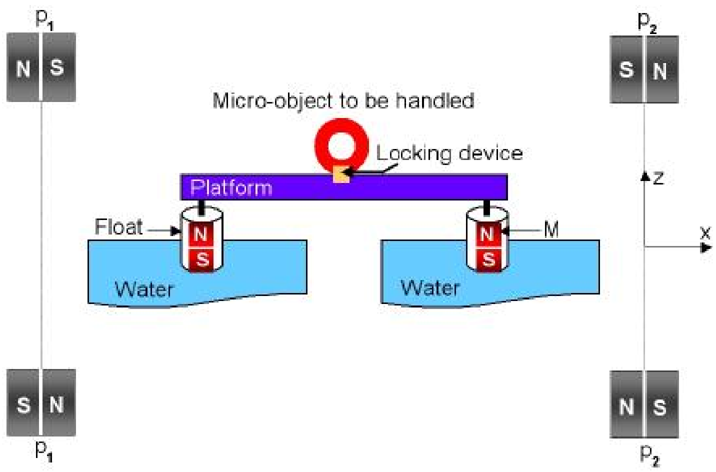

Figure 4: principle of the floating magnetic sensor.

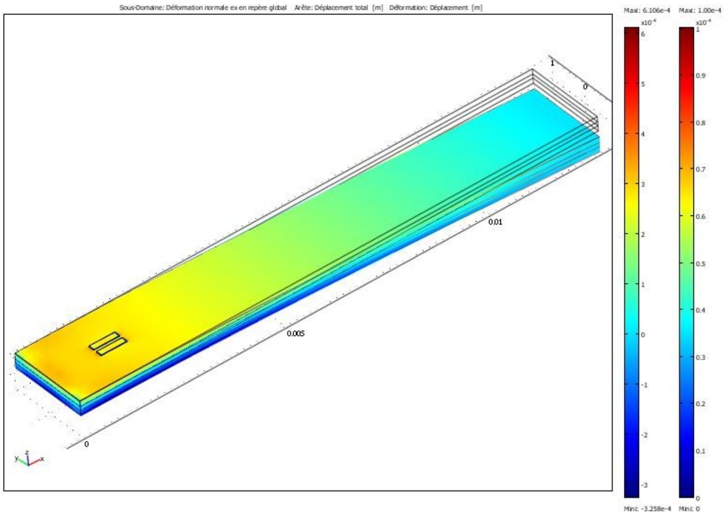

Figure 5: principle of a piezo resistive cantilever.

and then fixed in the center of the platform. The operator works on this object with an effector from outside the platform.

The magnetic forces are equivalent to a spring of stiffness K acting in the horizontal direction but also in rotation around the vertical axis. The absence of dry friction makes the sensor extremely sensitive to external stresses. The components of the force and torque are calculated from the equation:

$$\left| \begin{array}{c} F_x \\ F_y \\ C_\psi \end{array} \right| = \left(\begin{array}{ccc} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_\psi \end{array} \right) \left| \begin{array}{c} x \\ y \\ \psi \end{array} \right| \quad (2)$$

The stiffness implemented are about 0.02 N/m and N/rad. The originality of this sensor is that it is equipped with a device providing a measure of efforts without movement of the floating platform. It implements a feedback loop that drives a set of coils used to generate electromagnetic forces who oppose efforts to external efforts applied. It has be shown that injected currents in the coils are the image of these efforts. It is also expected to operate in different modes such as: maintaining a constant effort, release under limited effort, positioning, etc...

The development of this sensor is funded by ANR Psirob Stilmicroforce.

3.4.2 Piezo resistive sensor [7]

Based on a piezo resistive principle, the developped sensor uses microcantilevers (fig. 5). In this case, the displacement measurement is performed with the variation of the electrical resistance of the cantilever. There is no external displacement sensor needed.

The structure actualy developped is composed of several coupled cantilevers. This work consists in modelling, designing the structure of the sensor, adaptating the range of measurement with a good resolution and reaching a bandwidth in accordance with the dynamic of the measurement.

This sensor will be useful in order to apply large preloads on objects or for force friction measurements .

4 Calibration of sensors and uncertainties of the measurements

Given that the scale provided there is not standard, the calibration of a micro-forces sensor is delicate. The most reliable method is to measure eigen frequencies F_p of the devices. All the devices being governed by differential equations of second order, it is usually possible to simplify the behavior by considering a theoretical mass/spring system with a single degree of freedom. In these conditions, and for a low damping coefficient, the stiffness K of the device is calculated with the equation:

$$K = 4\,\pi^2\,M\,f_p^2 \tag{3}$$

For the AFM, the calibration of cantilevers is achieved in two ways, either by exciting the cantilever using the piezoresistive tube of the AFM, but it is a much more reliable to measure the thermal noise naturally present, using a laser interferometer pointing to the extremity of the cantilever. The model of encastred beam is necessary to calculate the stiffness from the frequencies of the eigen modes, for a given geometry.

The calibration of the passive levitation device is based on the same principle: exitation of the oscillation in the direction of measurement and then measurement of the natural frequency. An electromagnetic device used to generate the capillary oscillations has been coupled to an automatic identification of the transfer function of the 1D model. The identification is used to evaluate the stiffness of the magnetic spring but also the damping coefficient of the oscillations.

The calibration of the sensor Femto Tools is conducted by the manufacturer.

A second calibration method consist in using a sensor as a reference (passive levitation for example) and to calibrate other sensors from this reference.

5 Example of measurements on the platform

5.1 Pull-off strength for a sphere/plan contact

The AFM is used to measure the pull-off strength of the contacts between a sphere and a plan. It uses cantilevers equipped with a glass microball glued at the extremity. The study gives measurement of the influence of a prestrength and environment conditions on the intensity of the pull-off strength.

5.2 Frictional force of a micro-object on its substrate

Measurements have been carried out using the levitation sensor and gave the value of the effort that is needed to push a grain of sodium chloride of 400 μ

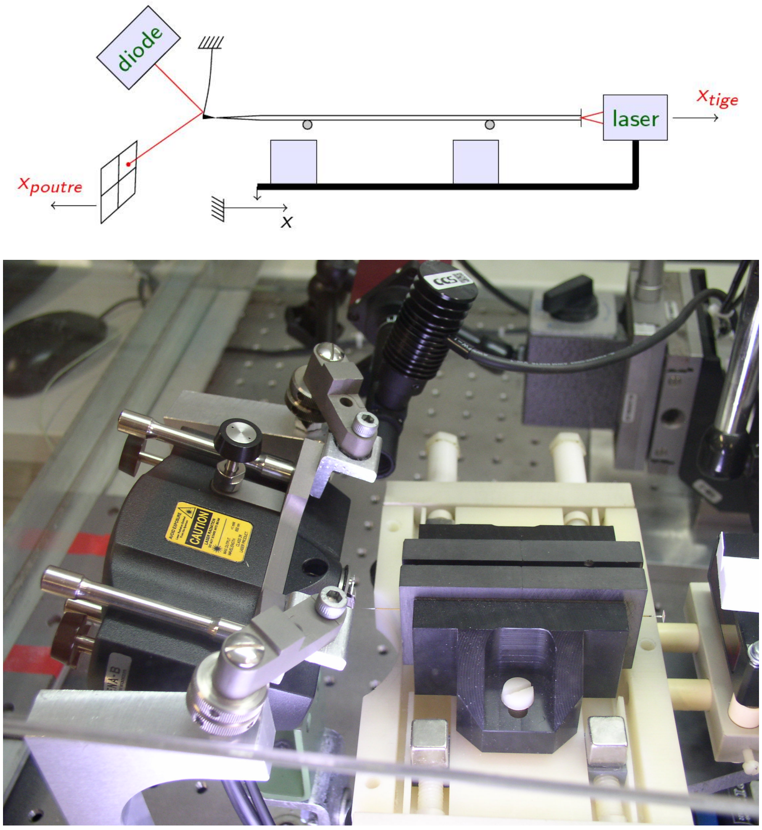

Figure 6: confrontation in action / reaction of levitation and the AFM.

length on a mirror polished glass. This effort is in the micronewton range and is very sensible to the humidity degree of the environment.

5.3 Comparison between AFM sensor and passive levitation

The goal was to show that the calibrations of the AFM and levitation sensors are valid. To perform these tests, the sensors have been placed face to face (see figure 6).

The gradual approach of the tip of the capillary against several AFM cantilevers shows a good correlation of the measured effort (see figure 7).

5.4 Measuring the elasticity of an oocyte [8]

The passive levitation sensor has been implemented in some biomedical experiments. The aim was to determine the elasticity of the pelucide membrane of a human egg, in order to identify mechanical criteria usefull to determine the maturity of the eggs before fertilization. It turned out that during the measurements, surface tension acting on the capillary around its entrance point in the oocyte culture fluid, have had an adverse effect on quality of measurements.

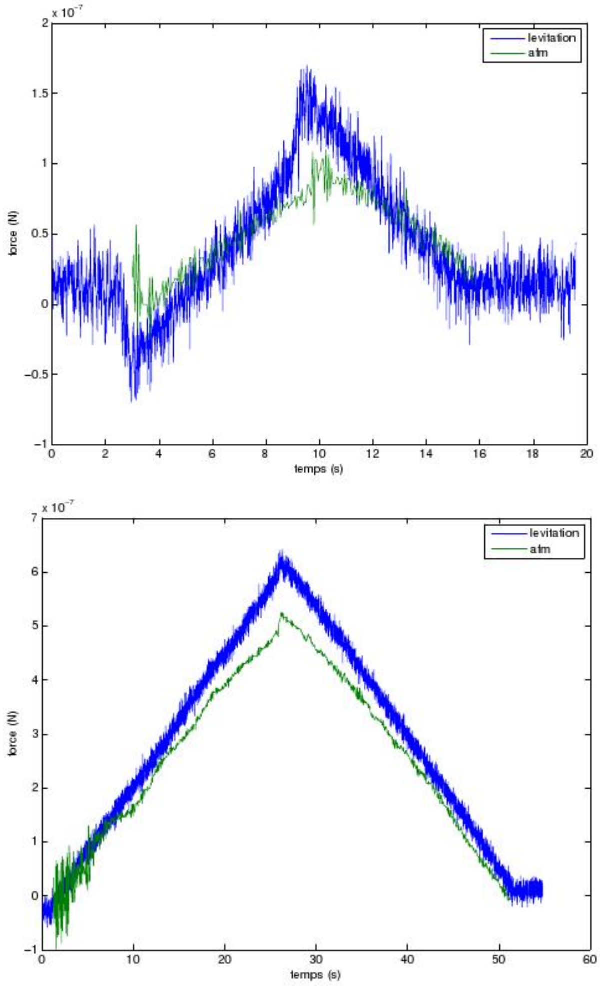

Figure 7: comparison of measurements of the AFM and the levitation sensors for two different cantilevers.

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