The "macroscope": a didactical version of the Scanning Force Microscope

Giacomo Torzo[†], **Giorgio Delfitto**

[†]*CNR, INFM e Dipartimento di Fisica, Università di Padova*

Barbara Pecori

Dipartimento di Fisica, Università di Bologna

Pietro Scatturin

Dipartimento di Psicologia dello Sviluppo e della Socializzazione,Università di Padova

Motivation

Our world is full of images. Some of them (like the image of a coin) are part of a general background knowledge which has been kept growing since our birth in a way that is substantially the same as that of our ancestors and, by appearing altoghether “natural”, do not rise any curiosity about the mechanisms generating the image .

On the other hand the modern technologies, investigating microscopic structure of matter (e.g. in physics or biology), produce today images of different kind, associated to “objects” quite far from our perceptive capability (viruses, atoms…), whose production mechanism is totally mysterious for the common reader.

The lack of information on the production processes of such images leads often the non-experts to “wrong” interpretations, by assigning to the objects characteristics that are meaningful only at a macroscopic leve.

These considerations brought us to design a device that could be used, even with students with poor physics background, to help understanding the basic processes through which images are normally built from electric signals acquired by sensors

The leading idea is to design a device working at macroscopic level with techniques similar to those used investigating the microscopic world.

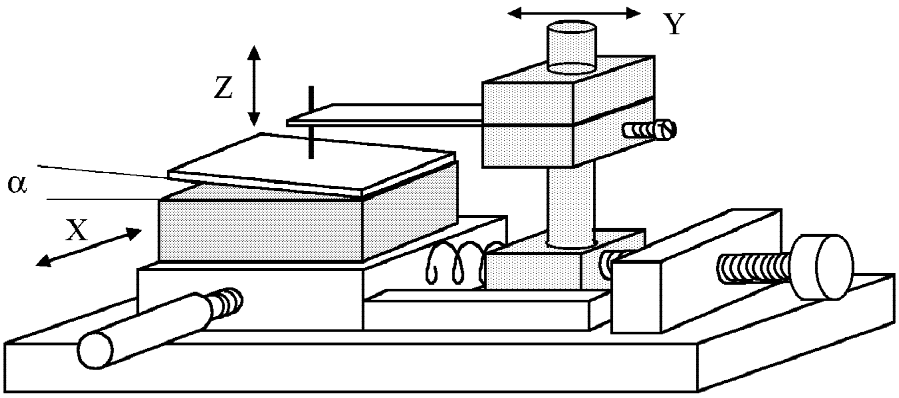
It might appear useless to produce an image of objects that can be seen by eye, but we believe it useful to offer the students the possibility of comparing the “natural” image with the “reconstructed” one, allowing them to follow step-by-step the image-generating process, thus reaching a better understanding of the different nature of the two images.

The “Macroscope”

Our device (named "macroscope" following the suggestion of prof. Cesare Ascoli) is based on the technology of “stylus profilometers”.

We connected a 2-channel interface to a vertical displacement sensor made of a tip soldered to the end of a cantilever whose deflection was measured by a pair of strain gauges, and to a horizontal displacement sensor obtained by linking a potentiometer to the knob of a sliding micrometer.
The interface records two sets of values: the vertical displacement (V_z) and the horizontal (V_x) one.
On the computer screen we trace the plot $V_z=f(V_x)$ reproducing the sample profile along a line parallel to x.

A series of scans (each one made for different positions along y-axis) contains information on the whole sample surface, but if we place them all together in the plot V_z they would result unreadable due to the overlap.
We therefore used a "trick" in order to make the sample topography visible, and to produce a “pseudo-3D” image.
The trick consists in mounting the sample onto a tilted plane so that every displacement along the y-axis produces a vertical shift $\Delta z = \Delta y \tan\alpha$



In this way each displacement Δy produces a fixed shift $\Delta V_z=V(\Delta y \tan\alpha)$, of the signal that would be measured if the sample were on the horizontal plane x,y.

How are electronic images produced?

Electronic images may be of different types, but quite often they are "bit-mapped", i.e. they are a matrix of dots of different color (or grey-scale) that may be printed or displayed on a computer screen. Each dot ("pixel") is a numeric value in the matrix stored in the computer memory.

Topographic images are special images, that give a quantitative representation of the surface of an object, where the color of each point "measures" the distance z of that point from a geometric plane parallel to the average surface of the object ($z=z_0$).

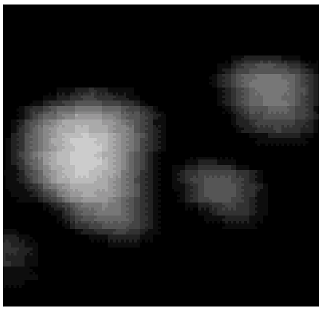
E.g. in the grey-scale LUT ("look-up-table"= correspondence between colors and numeric values in the matrix) the brightness may be proportional to the distance from the reference plane (darker=lower and lighter=higher).

SEM orTEM images are not topographich images, even if they carry informations on the sample nature.

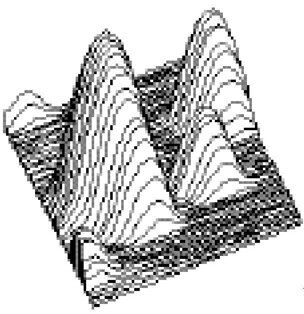
The topographic matrix maps a square region of the surface, each pixel representing the average value of the surface height within a square whose side L depends on the image resolution. The surface is sampled in a square lattice of points equally spaced in the x and y directions along the reference plane.

If we pick up only one raw of the matrix and we plot this set of numbers versus their position along x (with segments joining the consecutive dots) we get an x-line profile (i.e. a vertical cross-section of the topographic image).

By plotting. Putting in the same plot all the x-line profiles corresponding to the various y positions (each one shifted upward of the same quantity δz) we obtain a 3D representation of the surface that is named "wire-frame".



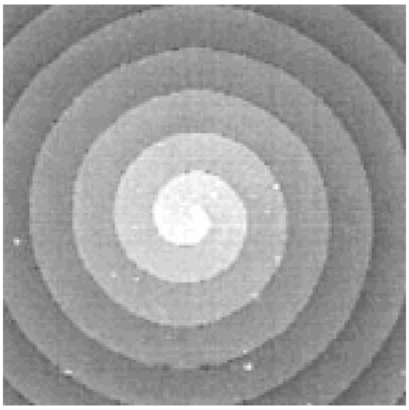
BMP



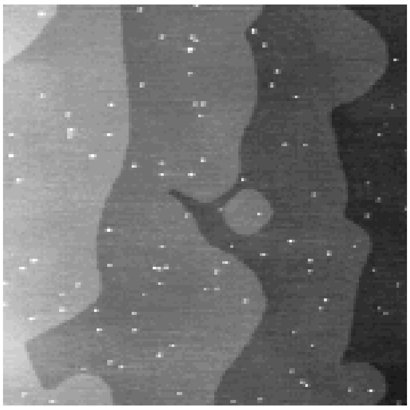
Wire Frame

SFM Images

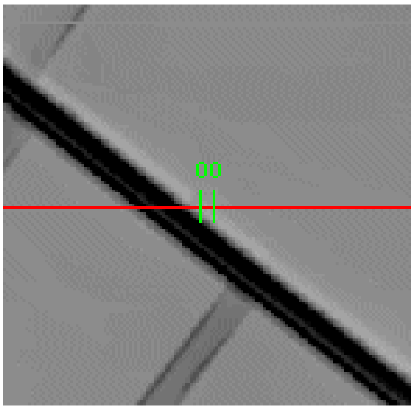
Here are four SFM images obtained with a Park Scientific Instruments microscope (square matrix of 256x256 pixel where lighter dots indicate larger z values)



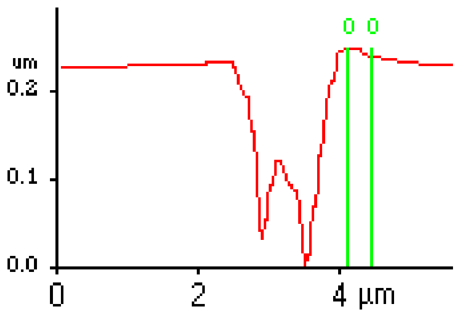
SiC (15x15µm)



InAs/GaAs (3x3µm)



InGaAs/InP(6x6 µm)



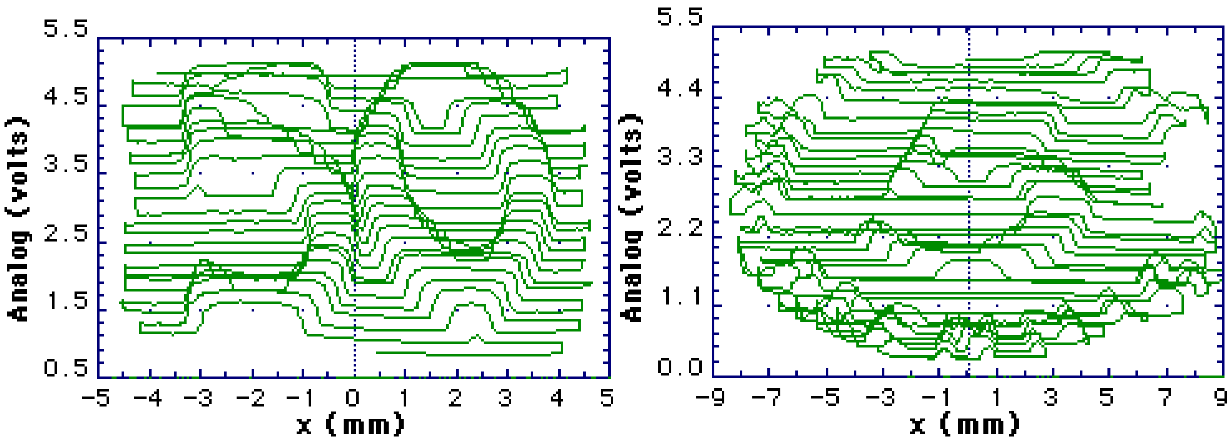
Profile InGaAs/InP

The first image shows a special lattice defect (screw dislocation) in a Silicon Carbide monocrystal: a spirally terrace few microns wide.

In the second image single atomic layer steps are evident in a Gallium Arsenide monocrystal cut along 001 plane, with Indium Arsenide nanostructured layer (white dots).

The third image shows an extended crystal defect in a 450nm thick InGaAs layer grown on InP, and the fourth is an x-line profile taken from the same picture (red-marked in the BMP image).

Images from the macroscope



Profiles of 50 and 5 Pfennig Coins

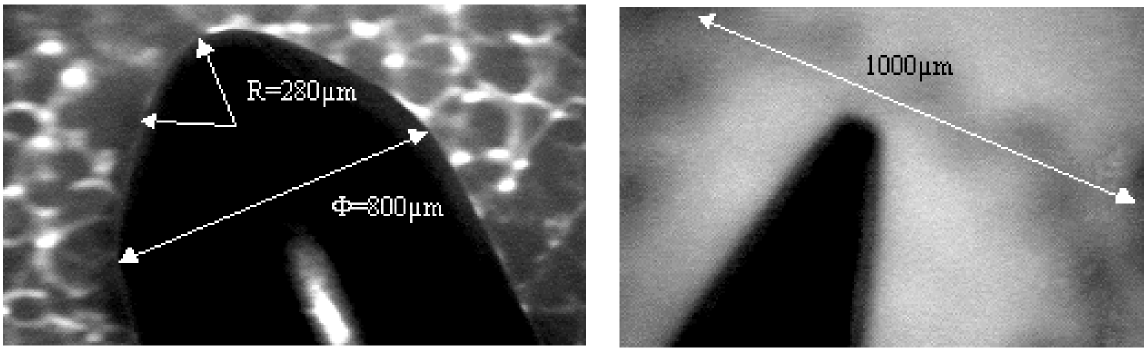
Pfennigs were chosen for their small size and simple design.

Here we used as probe a wool-needle, with a not too sharp tip, to reduce the risk of chokes and lateral deflections of the cantilever when crossing sharp steps on the sample.

The samples

Our device is affected by this problem because it lacks the feedback mechanism allowing to work at constant force (as normally happens in SFM) where the sample holder is suitably displaced along z to keep constant the cantilever deflection, when the tip meets a sample relief.

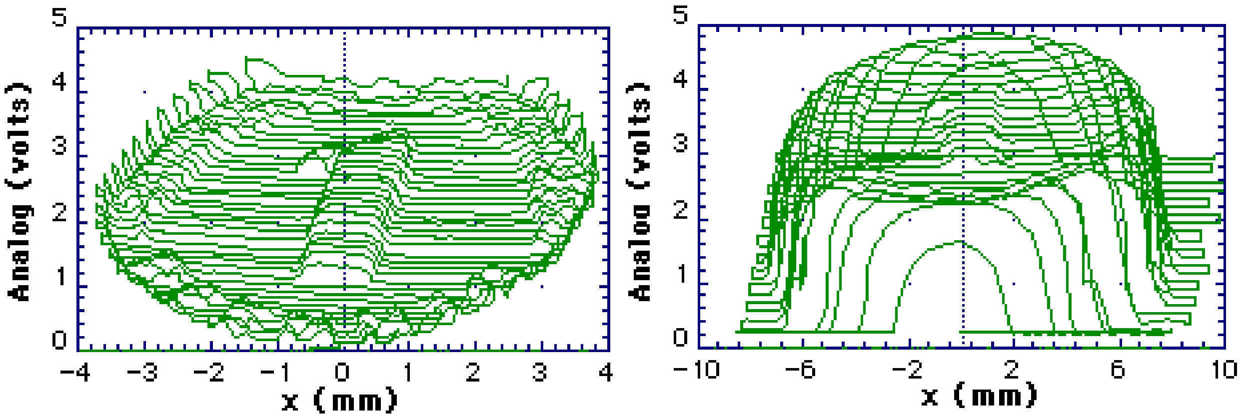
Distortion introduced by finite tip dimensions



Optical micrographs of a wool-needle and of a sewing-needle tips

The smaller is the tip radius of curvature, the better is the lateral resolution.

To show this effect ("tip convolution") we recorded a pair of images of the same sample (1 Pfennig coin) using first a sharper sewing-needle and then a ball-bearing sphere (R=1.5mm).



Profiles of 1 Pfennig obtained with sewing-needle and with 1.5 mm radius sphere

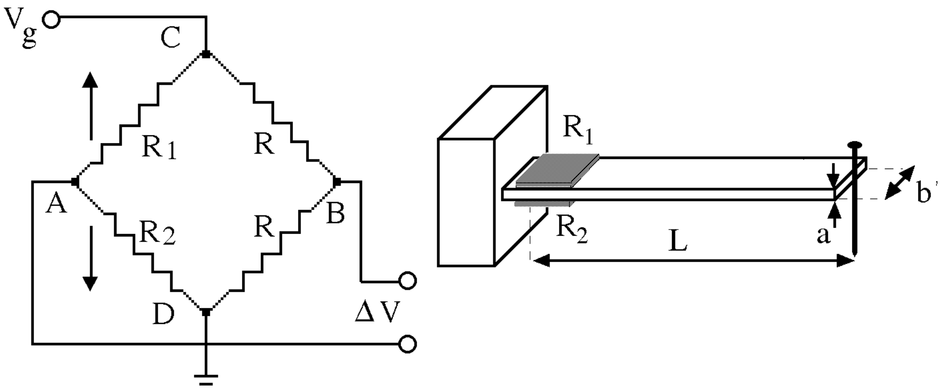
Using a curvature radius larger than the coin thickness we can detect the sample borders (the tip can cross steps slightly smaller than R), but we spoil our lateral resolution.

Using a smaller curvature radius we get better resolution, but the probe-sample interaction becomes important (note that in our device the applied force increases with y): at the scan end the sample results slightly damaged.

Z-detector working principle

The strain gauge is made of a thin film resistance incorporated into a plastic strip to be glued to the object whose strain has to be measured.

Applying to the film a tensile (compressive) strain increases (decreases) its resistance. The change in resistance ΔR is proportional to the relative length change $\varepsilon=\Delta L/L$, with a gauge factor $G=(\Delta R/R)/\varepsilon \approx 2$.



By gluing two identical strain gauges to an elastic cantilever, and by connecting them in a Wheatstone bridge with two fixed resistors R, we obtain a force sensor.

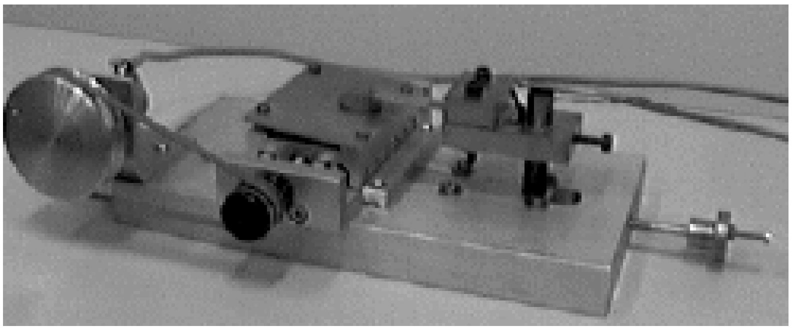
When the tip is pushed upward, with a vertical shift Δz, the cantilever deflection produces the strain $+\varepsilon$ in lower gauge and $-\varepsilon$ in the upper one.

The value of the shift may be written $\Delta z=\varepsilon(2L^2/3a)$, where a is the cantilever thickness and L its length, so that the relative resistance change is $\Delta R/R=G\varepsilon\approx\Delta z(3a/L^2)$.

With $V_g\approx1V$ and $\Delta z\approx0.1mm$ we get a signal $\Delta V= V_g\varepsilon\approx1$ mV, requiring a gain of about 1000 in order to match the input voltage range of the used interface (0-5V).

The X displacement detector

The signal measuring horizontal displacements is provided by a 10-turns potentiometer (Helipot), biased at 5V, driven by a pulley linked to the micrometer axis through a rubber band .



With the typical Helipot linearity (about 10^{-4}), a slide displacement of 2 mm/turn and a signal resolution of 5mV we get a theoretical resolution of 1µm, much better than that allowed by the tip convolution and mechanical tolerances.

Axes calibration

To calibrate the x-axis we measure the change in the Vx value for a known shift Δx and the conversion factor is $K_x=\Delta x / \Delta V_x$ (mm/V).

For the y-axis we measure the change in the V_z signal produced by a known shift Δy along a flat region of the sample surface: the conversion factor is $K_y=\Delta y/\Delta V_z$ (mm/V).

For the z-axis we have $K_z=K_y \tan\alpha$, where α is the tilt angle between the sample surface plane and the x-y scan plane.

Comparison with SFM

The first obvious difference between macroscope and SFM microscopes is the order of magnitude both of the resolution and of the maximum sampled area.

Lateral resolution in SFM is much better (≈100nm) not only due to thinner probes, but also because the x,y displacements are much more accurate thanks to the piezo scanner replacing mechanical micropositioner. Also vertical resolution is much better: with SFM the accuracy may be less than 0.1nm.

The second difference is in the process of image recording: in SFM we get a matrix $z_i(x_i,y_i)$, while the macroscope produces a sequence of vectors $z_i(x_i)$, containing approximately the same values x_i whereas the correspondent z_i values are shifted of the amount $\Delta z=\Delta y \tan\alpha$ at each scan.

The third difference consists in the detected signal: in the macroscope we record the cantilever deflection instead of the vertical displacement that keeps the cantilever deflection constant.

This technique (named constant height mode) is rarely used in SFM, where a servo-system varies the cantilever-sample distance (piezo-scanner computer driven) in a feedback loop (constant force mode).

The lack of servo-system in the macroscope sets an upper limit to the maximum height H of steps, on the sample surface, that may be detected with a tip of given curvature radius R: typically $H<R$.

As a consequence the recorded image is distorted proportionally to the “aspect-ratio” H/B , where B is the base of the sampled relief. The imaged relief has rounded borders with curvature radius R and oversized base (B’= B+2R).

Therefore best images are obtained using a tip with the minimum R larger than the maximum H.

The macroscope in physics teaching

The macroscope is an useful example of the “translation process” that is essential in any representation of the real world.

Schematically we may resume the main steps in the translation performed by the macroscope:

Object Profile (1) -> Tip Position (2) -> Force Applied to Cantilever (3) -> Cantilever Deflection (4) -> Sensor Strain (5) -> Resistance Change (6) ->Electric Signal (7) -> Computer Handling of the Signal (8) -> Visible Image of the Profile (9)

To understand the logic of this process one does not need to know all the technical details: it is still possible to detect the various steps and to evaluate their effect on the final result.

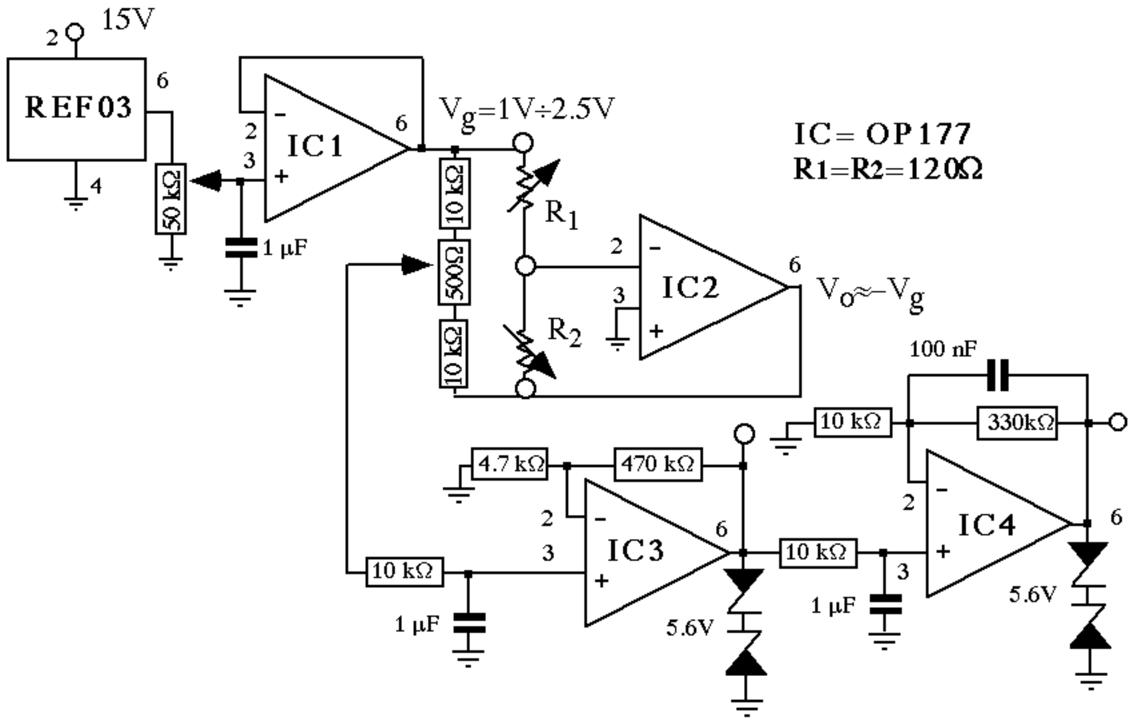
What we can know about the coin with the macroscope (its profile within the limits of the device sensitivity) differs from what we can know by looking at the coin, i.e. exploiting the light signal translated into a colored 3D image through a complex sequence terminating in our brain.

The interaction between observer and observed, characteristic of any measurement., is made clear by the comparison of the images produced by different tips (different coupling between profile and cantilever deflection), enlightening the accuracy limits of the information that can be obtained from the interaction with the investigated sample.

The technical details of the macroscope may be exploited by the teacher to illustrate an interesting set of “tricks” available to physics researchers. (the tilt to get a pseudo-3D image, the bridge configuration to increase sensitivity and stability, the relation between cantilever deflection and measured strain…), offering also the opportunity for a reflection on the links betweenl physics and technology.

The macroscope is a “scaled-up” version of one of the most powerful modern instruments for investigating the surface physics. The comparison with commercial SFM and with the SFM-produced images allows the students to recognize and fully appreciate problems and results of advanced research in this field.

Electronics for V_z signal detection



The bridge is biased at constant voltage V_f (2–5 V) through a buffer (IC1): one arm is made of the two strain gauges (120Ω) and the other of two fixed resistors and a balancing potentiometer.

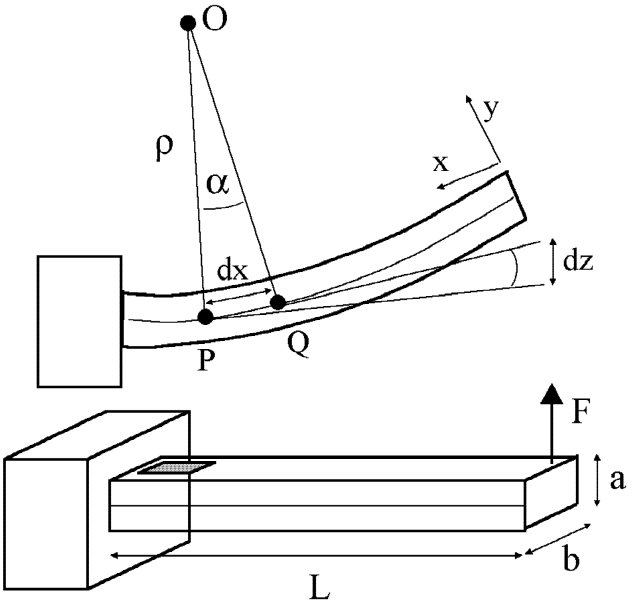
The strain gauges midpoint is kept at virtual ground by the operational amplifier IC4 acting as inverter. The bridge is therefore biased by two signals: V_f and $V_O=-(R_2/R_1)V_f$, where $R_2=R+G\varepsilon$ and $R_1=R-G\varepsilon$ are the gauges resistances, and $G\varepsilon=\Delta R/R$ their relative resistance changes.

The output signal $V_x=(1/2)(V_f+V_O)\approx 2\varepsilon\, V_f$, taken at the sliding contact of the potentiometer, is amplified by IC3 and IC4.

Calculus of the strain produced by the cantilever deflection.

Strain in elastic bodies is described by the relation $\varepsilon = 1/E(F/S)$ relating $\varepsilon = \Delta L/L$ to applied force F, section S and Young modulus E.

In a cantilever, seen as a beam of fibers, the length of an arc dx from points P and Q of the median fiber may be written asthe product of the curvature radius ρ times the angle α =POQ: $dx = \rho\alpha$.



If y is the distance of the generic fiber from the median, the strain is given by $\varepsilon = \pm y/\rho$, with a corresponding force $dF = EdS(y/\rho)$,where $dS = bdy$ is the fiber cross section. The cantilever deflection therefore generates the torque:

$\Gamma = \int y\, dF = \int y^2 (E/\rho)\, dS = (E/\rho) j$, where $j = \int y^2\, dS = \int_0^{a/2} y^2\, b\, dy = a^3 b/12$.

The tangents to P and Q include the angle α, so that the differential deflection may be written $dz = x dx/\rho$, where x is the distance of P from the cantilever end (tip position), to which the force is applied. Substituting ρ, we get $dz = (\Gamma/Ej) x\, dx$.

The equilibrium condition between applied torque Fx and elastic torque Γ gives $dz = (F / Ej)\, x^2\, dx$.. The total deflection Δz is obtained by integration over the full length of the cantilever: $\Delta z = (F /Ej)\, L^3/3 = (F/E)(4L^3/ba^3)$.

The strain ε changes along x, growing with the curvature $1/\rho$. It is maximum close to $x \approx L$, where the strain gauges are placed. There it is $\varepsilon = \pm(a/2)/\rho = \pm(a/2)(\Gamma/Ej)$, and the torque is $\Gamma = FL$. From $\Delta z = (F/Ej)L^3/3$ we obtain $(FL/Ej) = \Delta z/(3/L^2)$ and finally the relation between deflection Δz andstrain $\varepsilon = \pm(a/2)(FL/Ej) = \Delta z(3a/2L^2)$.

With a=0.3mm, b=10 mm, L=30mm, the force applied by the tip to the sample surface, with a deflection of1 mm results 0.25 N≈25 grams, sufficient to slightly scratch a metal surface with a sharp needle.