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Atomic force microscope detector drift compensation by correlation of similar traces acquired at different setpoints

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The atomic force microscope measures surface topography by maintaining a certain cantilever deflection or vibration amplitude as the cantilever is scanned over a sample surface. The desired cantilever deflection or amplitude is referred to as the setpoint, and is maintained by moving the sample toward or away from the cantilever. The signal from the cantilever deflection detector has a real component, due to cantilever deflection, and a drift component due to various sources of drift. We present a method of eliminating the drift component by sensing and correcting it in real time. Our method involves automatically changing the setpoint so as to maintain a certain set difference in the relative feature richness of two traces taken with slightly offset setpoints. We show how the system maintains a setpoint only 70 mV above minimum, perturb it with a gentle blow of air that causes 200 mV of detector drift, and observe its recovery within 13+ −6 s. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1475352]

I. INTRODUCTION

Certain atomic force microscope (AFM)[1,2] samples are best imaged at very low forces.[3] One solution is the use of small cantilevers[4,5] which allow very gentle scanning of fragile, biologically active protein films.[3] Another is to carefully control the interactions of the AFM cantilever with the sample by adjusting solution chemistry.[6]

A complementary method is described here. This method will improve performance for both large and small cantilevers. It works not only for contact mode imaging,[2] but also for tapping modes of various amplitudes.[2]

In theory, the AFM's feedback loop maintains a constant interaction force between tip and sample. In practice the interaction force changes over periods of time on the order of minutes, despite the closed feedback loop which controls cantilever deflection. This happens due to drift effects in the cantilever deflection detector itself,[1,7,8] in particular thermal drift of the support structure,[8] changing index of refraction of the media involved (air or fluid), laser pointing noise[9] and thermal bending[5,10] of the cantilever (Fig. 1).

At present, the AFM operator needs to compensate these drift effects manually by adjusting the force setpoint, sometimes several times a minute for a very delicate sample. These effects can be minimized by matching material thermal coefficients,[11] or detected and compensated using additional probes as a reference.[12]

Here we describe an automated and very sensitive method that compensates detector drift and thereby minimizes the force exerted on the sample by the AFM tip.

II. PRINCIPLE

This method is based on a correlation between two traces that have been acquired at the same area of the sample, but with slightly different setpoints. To understand this method, it is useful to consider how a scan trace changes with the setpoint on a sample that shows some features.

At a certain "low" setpoint, the tip does not touch the sample, and feedback does not occur. The scanned trace is featureless.

If the setpoint is slightly increased, the top of the most prominent features becomes visible.

As the setpoint is increased further, the tip tracks the surface more closely. An ideal imaging setpoint is the setpoint for which the tip follows every surface feature to within limits set by pixelization and tip geometry. It is evident that if the setpoint is increased beyond this ideal setpoint, no further changes can be expected, until either the sample is becoming deformed or the tip is destroyed.

For a delicate sample or high scanning speeds, this destructive setpoint can be very close to the ideal imaging setpoint.

Looking at this dependence of resolved topography, or feature richness, on the force applied by the tip, it can be seen that a trace that is barely touching the sample is much more sensitive to detector drift than a trace that is recorded near the ideal imaging setpoint. Therefore, an evaluation of the feature richness of a trace taken at less than the ideal setpoint can be a good indicator for detector drift. Different mathematical tools such as spectral analysis methods can be used to evaluate the feature richness of the resolved topography in such a low setpoint trace. It seems most useful to compare the resolved topography of the sample measured with a less than ideal setpoint to one taken near the ideal imaging setpoint. Let us consider one trace across the image. Fortunately, the AFM scans each line in an image with both a forward and a backward trace. Therefore, we can compare the feature richness between these two traces at different imaging setpoints to determine the ideal imaging setpoint (Fig. 2).

An additional advantage of lowering the retrace setpoint

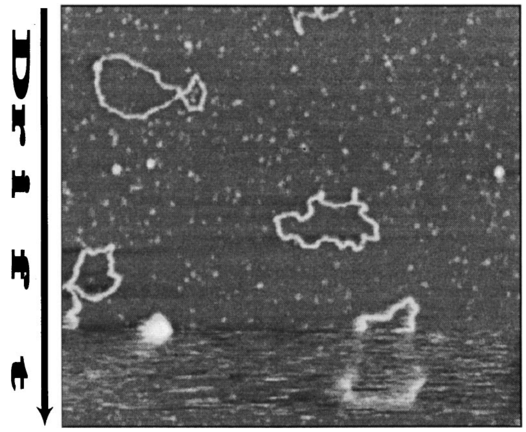

FIG. 1. Low force scan of bluescript DNA on mica demonstrating the effect of interaction force changes due to drift effects. Scanning downward, the scan becomes increasingly blurred as the force drifts lower.

is the decreased tip–sample interaction time—there is no need to stress a delicate sample while no image data is gained. Ideally we want to evaluate the relative feature richness of the trace measured to the actual topography. Because trace and retrace at the same sample location have strong similarities, a value for the relative feature richness of a lower setpoint retrace can be obtained by cross-correlating it with its corresponding trace, and normalize by the trace's autocorrelation:

$$\text{Rel.Feature\_Richness}(\text{retrace}) = \frac{\max[\int \text{retrace}(x)\times\text{trace}(x-\tau)\,dx]}{\int \text{trace}(x)^2\,dx}. \tag{1}$$

The result is a value for the relative feature richness of the low setpoint retrace, that will be low (e.g., 0) for "no features," and high (e.g., 1) for "as many features as the corresponding normal setpoint trace." Trace–retrace pairs at different setpoints, but with a constant setpoint offset, and their respective relative feature richness coefficient are shown in Fig. 3.

It is important to note that only the absolute setpoint suffers from detector drift, but not the setpoint difference between a high setpoint trace and a low setpoint retrace. If the setpoint of the very drift sensitive low setpoint retrace can be stabilized, the setpoint of the higher setpoint trace will be stabilized, as well. To stabilize the low setpoint retrace, a slow (integral) feedback loop keeps its relative feature richness at an initial value by automatically readjusting the AFM's setpoint.

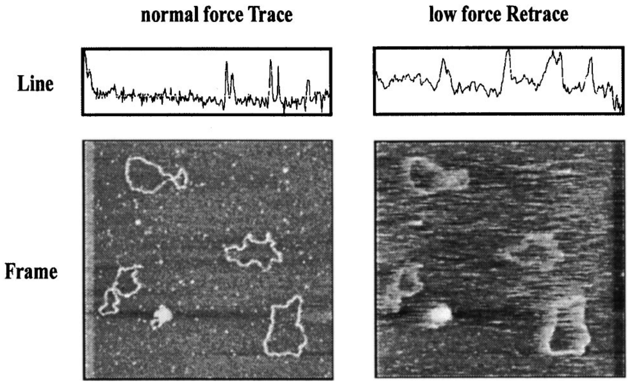

FIG. 2. A single trace and a whole frame scan, and their respective reverse traces at an offset, lower scanning force. The single line scans demonstrate well the lack of smaller features in the low force retrace.

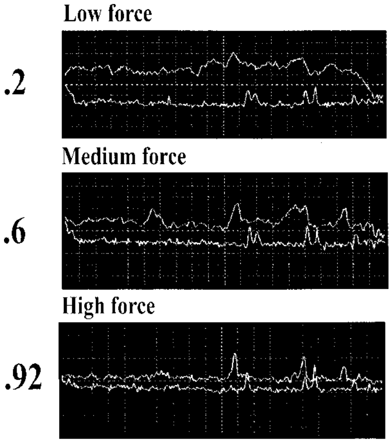

FIG. 3. A single line scan (lower) and its respective, force offset reverse trace (higher) at three different scanning forces, but always with the same force offset between trace and reverse trace. The lower force retrace is more affected by the changing scanning force than the higher force trace. As force increases, both traces become more similar, and the value for the relative feature richness (in generic units) of the reverse trace increases.

III. IMPLEMENTATION

We implemented a compensation system as described above using a Computer (PC under Windows NT 4) with a data acquisition (DAQ) card by National Instruments. The compensation algorithm has been implemented in LabView.

The DAQ board samples the AFM's height (Z-piezo) signal, and a line sync signal. The line sync signal is extracted from the x/y piezo voltages, by external circuitry, generating a signal that is "low" during a trace and "high" during a retrace. The same circuit subtracts an adjustable fraction of this line sync signal from the microscope's setpoint signal in order to offset the retraces' setpoint, as described above. In future versions, these operations could be processed numerically as part of the control program, and a

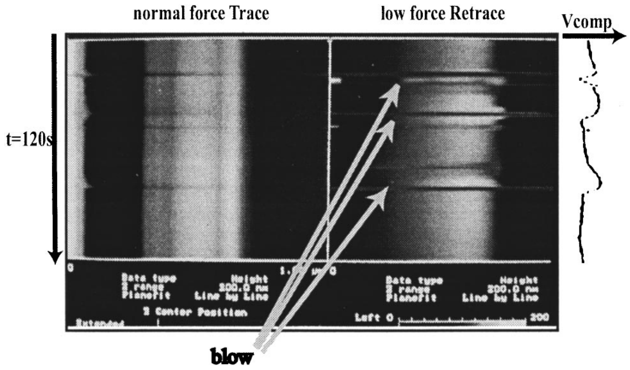

FIG. 4. The drift compensation at work. The slow scan axis is disabled, the vertical becomes time (1 μm horizontal, 200 s vertical). The microscope was exposed to three gentle blows of air. The low force retrace reacts strongly to the perturbation. The trace at a very gentle normal force setting recovers quickly, due to the setpoint compensation voltage (right, 200 mV full scale) generated by the drift compensation system.

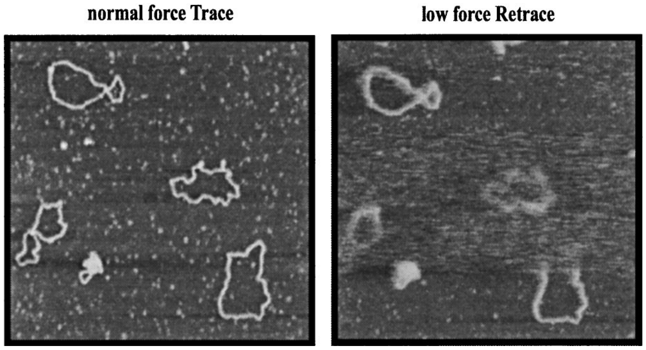

FIG. 5. A trace and its respective low force retrace of a full scan with the drift compensation system activated. The sensitive retrace image shows drift and recovery. The trace image at a very gentle normal scanning force stays unaffected.

more precise and stable sync signal could be extracted directly from the microscope scan generator. After computation of the retrace's relative feature richness, and numerical integration of its deviation, the DAQ generates a setpoint compensation voltage that is added to the AFM's setpoint voltage by external circuitry.

IV. TEST

To test the system, a cantilever was approached to a glass surface with additional features (fingerprint on glass). The setpoint was then adjusted to $\leqslant 70$ mV above the minimum imaging scanning over the surface (scan area 1 μm), the setpoint for the retrace was offset to only show the most prominent features seen in the forward trace. The drift compensation system was then engaged to maintain the current level of correlation between trace and retrace by adjusting the AFM's setpoint, thus stabilizing the AFM's setpoint drift. The slow-scan axis was then disabled: The vertical axis of the resulting image now becomes time (200 s over the whole vertical axis). The system was left alone for several minutes in order to reach steady state. The stabilized trace shows no change throughout this time. Figure 4 shows the AFM being perturbed by three very gentle blows of air from a distance of 1.5 m from the instrument, each of which resulted in a setpoint drift of approximately 200 nm. The left image shows the stabilized forward trace, while the right image shows the response of the lower setpoint retrace to the perturbation. The graph to the right shows the setpoint compensation voltage generated by the drift compensation system. The stabilized image recovers from this sudden perturbation within 13 ± 6 s. Figure 5 shows a scan of DNA on mica, with the stabilized forward trace to the left, and the more drift-sensitive setpoint offset retrace to the right.

We note that with access to the AFM's hardware drivers, the method presented here could be fully integrated into the AFM control software. It has the potential to enable low force scans of fragile samples that would be difficult without it.

ACKNOWLEDGMENT

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