Real time reduction of probe-loss using switching gain controller for high speed atomic force microscopy

Pranav Agarwal, Tathagata De, and Murti V. Salapaka[a)]
Department of Electrical and Computer Engineering, NanoDynamics Systems Laboratory, University of Minnesota–Twin Cities, Minneapolis, Minnesota 55455, USA

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In this article, a switching gain proportional-integral-differential controller is used to reduce probe-loss affected regions in an image, obtained during tapping mode operation. Switching signal is derived from the "reliability index" signal, which demarcates regions where the tip has lost contact with the sample (probe-loss), within couple of cantilever oscillation cycles, thereby facilitating use of higher than optimal controller gain without deteriorating on-sample performance. Efficacy of the approach is demonstrated by imaging calibration sample at tip velocity close to 240 μm/s and plasmid DNA at tip velocity of 60 μm/s indicating significant reduction of probe-loss areas and recovery of lost sample features. © *2009 American Institute of Physics.* [doi:10.1063/1.3233896]

Ever since the invention of scanning tunneling microscope by Binnig *et al.*[1] in 1986, scanning probe microscopes (SPMs) have found widespread use for probing materials and their related properties with spatial resolution at atomic scale and measurement of forces in the range of 1–100 pN. Despite their versatility and usefulness, SPMs are plagued by slow imaging rates typically in the range of 3–6 min/frame and consequently low throughput. A large number of applications viz. fault detection,[2] nanolithography,[3] and visualization of the dynamics of molecular proteins[4] demand a higher imaging rate (greater than 30–40 frames/s is needed).

Tapping mode operation is desirable in most applications since it reduces the lateral forces exerted by the tip on the sample thereby reducing tip-sample wear. In tapping mode, the cantilever is actuated near its first mode resonant frequency and interacts with the sample intermittently. These intermittent contacts with the sample as the cantilever oscillates, transduce sample topography and its properties onto steady state amplitude and phase of the cantilever which are then interpreted to infer sample properties. Given the need for high speed imaging and the advantages of tapping mode operation, the need for tapping mode high speed atomic force microscope (HSAFM) is evident.

There are many factors that need to be carefully accounted for while developing a HSAFM employing tapping mode operation.[5,6] One of the primary challenges for HSAFM is that of probe-loss. Consider the scenario during imaging where the tip encounters a valleylike feature on the sample topography. Suppose also that prior to the arrival of such a feature, the tip is interacting with the sample as it oscillates, with the amplitude being maintained close to the set point amplitude, A_s. On encountering the valley, the tip loses contact with the sample and it is no longer interacting with the sample. Such a scenario leads to probe-loss[7] or parachuting.[8]

[a)]Electronic mail: murtis@umn.edu.

Note that as the cantilever is not interacting with the sample during probe-loss, the amplitude dynamics is decoupled from the sample topography and the positioning dynamics in z-direction. Indeed the amplitude increases as

$$\Delta a(t) = (A_0 - A_s)(1 - e^{-\omega_0 t/2Q}), \tag{1}$$

which is completely determined by operating parameters Q, ω_0, A_0, and A_s where Q, ω_0, A_0, and A_s are the quality factor, resonant frequency, free air amplitude, and set point amplitude of the cantilever, respectively. The positioning dynamics in z-direction is governed by the difference, Δe, from the setpoint amplitude A_s of the current amplitude $a(t)$ given by

$$a(t) = A_s + (A_0 - A_s)(1 - e^{-\omega_0 t/2Q}), \tag{2}$$

which makes $\Delta e(t) = \Delta a(t) = (A_0 - A_s)(1 - e^{-\omega_0 t/2Q})$. If a proportional-integral (PI) controller is employed, the sample position $u(t)$, in z-direction, is given by

$$u(t) = g_{\text{piezo}}(t) * \left[K_I \int_0^t \Delta a(\tau) d\tau + K_p \Delta a(t) \right], \tag{3}$$

where $g_{\text{piezo}}(t)$ is the impulse response of the z-piezo actuator and "$*$" denotes the convolution operator. In typical cases, it follows from Eq. (3) that if $\Delta a(t)$ is large, the sample is pushed toward the cantilever faster. If Δh is the separation between the tip and the sample at the onset of probe-loss then the minimum time, t_d, needed to recover from probe-loss is given by

$$(A_0 - A_s)(1 - e^{-\omega_0 t_d/2Q}) + \left\{ g_{\text{piezo}}(t) * \left[K_I \int_0^t \Delta a(\tau) d\tau + K_p \Delta a(t) \right] \right\}_{t=t_d} = \Delta h, \tag{4}$$

which is obtained by adding Eqs. (1) and (3) since the tip is not interacting with the sample.

A strategy employed by Sulcheck *et al.*[6] for reducing probe-loss is to actively reduce the quality factor Q of the cantilever that lets the amplitude increase and reach its maxi-

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mum value (A_0-A_s) faster that leads to a larger $\Delta a(t)$. However, the drawback of this methodology is that the quality factor remains reduced when there is no probe-loss and thus the on-sample behavior can suffer due to low Q operation. Another strategy for reducing t_d is to increase controller gains, on the positioning piezo, K_I and K_p beyond values that might be optimal for the particular sample. This strategy will lessen probe-loss affected area, however, it will lead to worsened on-sample behavior due to large tip-sample forces and can also induce instabilities due to the uncertain on-sample behavior. The tradeoff arises due to conflicting requirements of imaging parameters viz. Q, K_I, and K_P when the tip is on-sample versus when it is off-sample. Choice of optimal controller gains for imaging a sample depend on g_{piezo} dynamics and sample features. Typically controller gains are chosen as high as possible to enable better tracking of sample topography and maintaining required set point amplitude. However controller gains cannot be chosen arbitrarily high since that leads to unstable behavior of the tip over the sample. This results in large tip-sample forces leading to wear and tear of the tip and the sample. However, controller gains can be significantly higher when the cantilever is not interacting with the sample when compared to on sample scenario, without the adverse effect of instabilities on imaging.

A better alternative is to have separate strategies when the cantilever is on-sample and when it is off-sample. However, such a strategy is possible only if there is a means to infer when the cantilever is interacting with the sample and when it is not, in real time. Kodera *et al.*[8] employ the cantilever amplitude as a means of indicating a loss of interaction with the sample. Probe-loss is inferred if $a(t)$ is larger than a threshold amplitude A_{upper}. For this strategy, it is better that $a(t)$ reaches A_{upper} faster and thus from Eq. (1) it follows that this can be achieved by increasing (A_0-A_s) and/or by lowering Q. Large (A_0-A_s) values imply large forces on the sample when the cantilever regains its interaction with the sample. Such an alternative is not desirable for soft samples and thus large $\Delta a(t)$ is primarily obtained by relying on low Q operation.[8] In general, (A_0-A_s) is also governed by the imaging application and it is desirable to keep this parameter for the user to decide.

It needs to be noted that probe-loss can occur even when the amplitude $a(t)$ is reasonably close to the setpoint A_s and below a given threshold value A_{upper}. This is evident when the cantilever interacts with a sample feature that leads to a complex and prolonged transient phase, where the sample topography is reasonably benign but the cantilever trajectory does not allow interaction with the sample.

Thus, it is desirable to employ a signal that provides an independent measure of probe-loss that is effective for real time applications without overly constraining operation parameters, viz., (A_0-A_s), Q, and ω_0. Such a probe-loss detection technique called the "reliability index" signal was reported previously.[7] Such an independent measure can be employed to (a) actively alter the cantilever dynamics by, for example, lowering quality factor when off-sample and increasing quality factors on-sample thereby reducing the time required by the cantilever to reach its free air amplitude during probe-loss without worsening on-sample resolution, and (b) actively change controller gains of the positioning system

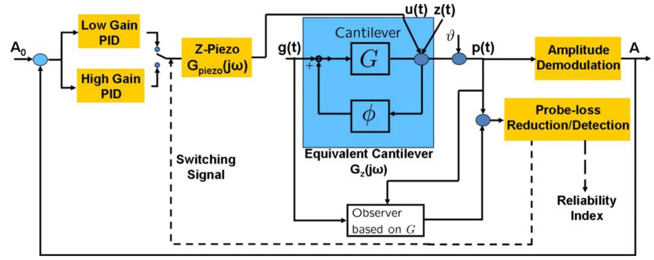

FIG. 1. (Color online) Modeling cantilever-sample interaction in tapping mode operation as a $G-\Phi$ interconnection where $G(j\omega)$ is the second order cantilever beam model, Φ is the nonlinear tip-sample force, $g(t)$ is the dither forcing, $z(t)$ is the sample height profile, ϑ is the measurement noise, and $p(t)$ is the measured cantilever deflection. This interconnection can also be viewed as an equivalent second order system $G_z(j\omega)$, which is dependent on sample height. Observer is built on the free air cantilever model $G(j\omega)$ and takes $g(t)$ and $p(t)$ as inputs and provides $\hat{p}$ as an estimate of $p(t)$. Two PID controllers, one with low gain and the other with high gain are switched depending on the magnitude of the reliability index signal.

with higher than optimal controller gains when the cantilever is off-sample and thereby increasing the rate at which cantilever and sample separation reduces while switching back to smaller controller gains on-sample thereby reducing instabilities and thus being gentle on-sample. An independent measure of probe-loss in real-time facilitates the use of K_I, K_p, and effective Q that are different when on-sample compared to off-sample without constraining A_0, A_s, or Δh.

In this article, we report significant reduction of probe-loss effected areas by implementing a switching gain PI differential (PID) controller which is based on the thresholding of the reliability index. It is shown that reliability index provides a faster thresholding signal as compared to amplitude signal. Real time reduction of probe-loss areas is shown on imaging of calibration sample at tip velocity of 240 μm/s. It is shown that features that are lost during a high imaging rate with constant low gain controller are recovered by the use of switching gain controller even for a high aspect ratio sample. Finally a plasmid DNA on mica, with a height of 1.4 nm, is imaged at 30 Hz scan rate and reconstruction of a lost strand is shown to reveal that the resolution of the technique is better than 2 nm.

Cantilever dynamics in tapping mode can be modeled as a $G-\Phi$ interconnection[9] (see Fig. 1) where $G(j\omega)$ is a second order approximation of the first mode of the cantilever beam and Φ models the nonlinear force exerted by the sample on the tip. It is through Φ that different sample properties such as elasticity, height, and charge get modulated onto interacting cantilever trajectories. $G-\Phi$ interconnection, with a one mode approximation of the cantilever dynamics, can be written as

$$\ddot{p}+\frac{\omega_0}{Q}\dot{p}+\omega_0^2 p=\omega_0^2\left[g(t)+\frac{1}{k}\Phi(p,\dot{p})\right]. \tag{5}$$

In the absence of the sample interaction, $\Phi(p,\dot{p})$, we have

$$\ddot{p}+\frac{\omega_0}{Q}\dot{p}+\omega_0^2 p=\omega_0^2 g(t), \tag{6}$$

where $p(t)$ is the instantaneous cantilever position, ω_0 is the resonant frequency of the first mode, Q is the quality factor, k is the spring constant of the cantilever, $g(t)$ is the dither excitation, and $\Phi(p,\dot{p})$ is the nonlinear static memoryless tip-sample force. The model Eq. (6) will be termed as "sample free" model of the cantilever where the cantilever is away from the sample and experiences no forces from the sample. This model can be identified accurately through thermal[10] or frequency sweep methods. As the cantilever comes close to the sample, damping and tip-sample forces (Φ) effect the cantilever dynamics. The related models are unknown but using averaging theory[11] it can be shown that the cantilever-sample interconnected system can be modeled as an equivalent cantilever with dynamics

$$\ddot{p} + \frac{\omega_0'}{Q'}\dot{p} + (\omega_0')^2 p = (\omega_0')^2 g(t), \tag{7}$$

where ω_0' is the equivalent resonant frequency and Q' is the equivalent quality factor. Thus in the presence of tip-sample interaction, $G-\Phi$ interconnection can be represented by an equivalent second order model $G_z(j\omega)$ (see Fig. 1) that is determined by the parameters ω_0' and Q'.

Accurate identification of the model of the cantilever when it is not experiencing any tip sample interaction enables creation of a reference circuit called an "observer" which takes in as input, cantilever excitation $g(t)$, and cantilever output $p(t)$ and estimates the cantilever output as closely as possible taking into account the known dynamics of the sample free cantilever $G(j\omega)$. A particular implementation of the observer can be represented as

$$\underbrace{\ddot{\hat{p}} + \frac{\omega_0^2}{Q}\dot{\hat{p}} + \omega_0^2\hat{p} = \omega_0^2 g(t)}_{\text{nominal dynamics}} + \underbrace{L(p(t)-\hat{p})}_{\text{correction term}}, \tag{8}$$

where $\hat{p}$ is the estimated cantilever trajectory by the observer and L is the observer gain. The nominal dynamics captures the cantilever response to applied excitation $g(t)$ and the correction term tries to correct for the differences in p and $\hat{p}$ due to tip-sample interaction forces or initial condition mismatch, as fast as possible depending on the gain L. The higher the gain L, the faster is the correction. For $\hat{p}$ to accurately track p, the parameters ω_0 and Q used to build the observer, Eq. (8) need to match the effective resonant frequency and quality factor. Indeed the equivalent cantilever parameters ω_0' and Q' are equal to ω_0 and Q when the cantilever is off-sample and thus the error $p-\hat{p}$ when off-sample is small leading to a low value of the reliability index signal. In this case the observer gain L can be chosen such that $\hat{p}$ tracks p in only a couple of cycles. However, when on-sample, the equivalent cantilever parameters ω_0' and Q' differ from ω_0 and Q and thus the observer dynamics propagates away from the equivalent cantilever dynamics causing a larger error $p-\hat{p}$ and the reliability index is larger. The above strategy thus provides a signal (the reliability index signal) for the detection of the loss of tip-sample interaction within a couple of cycles.

Since a real time indication of when the tip is interacting with the sample and when it is not (probe-loss) is available, a controller gain can be chosen when the tip is interacting with the sample that avoids imaging instabilities and large interaction forces and a high controller gain can be chosen when the tip is not interacting with the sample pushing the piezo faster toward the cantilever while its amplitude is growing and eventually engage with the tip. It must be noted that if such a high gain is chosen throughout the imaging then it will damage the sample or the tip and lead to on-sample ringing. Furthermore, choosing low gain throughout will lead to lost features at high scan rates or large probe-loss areas. However, intelligently switching between the two gains provides the best of both scenarios.

The architecture shown in Fig. 1 is implemented on field programmable gate array (FPGA-Xilinx Virtex 2-pro) where the amplitude based feedback, as in normal tapping mode operation, is implemented but instead of one controller, two PID controllers are implemented whose gains are chosen for optimal on-sample imaging and probe-loss scenario. Which controller is being used at any instance depends on a switching signal, which is calculated in real time based on thresholding on the reliability index signal.

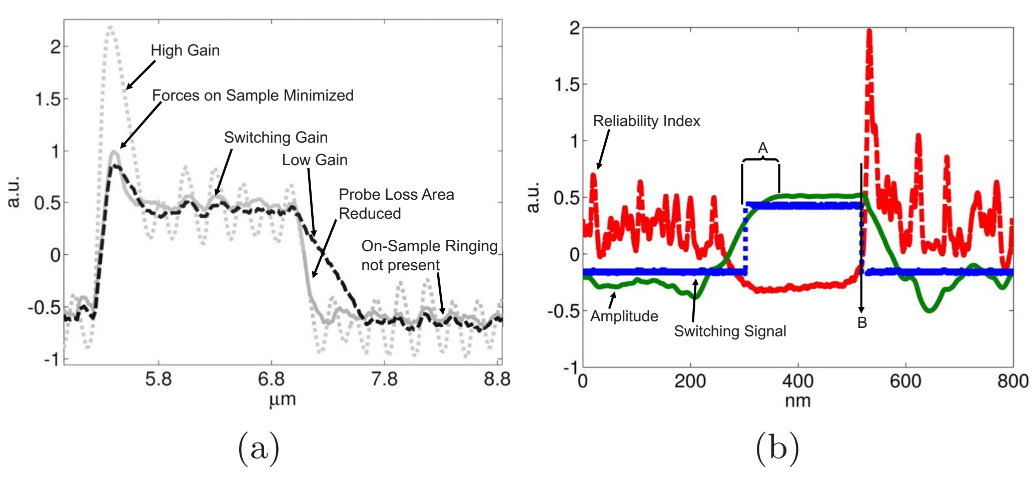

FIG. 2. (Color online) Experimental data (a) show line traces of controller effort while imaging calibration sample at 4 Hz (with a tip velocity of 80 μs). Dotted line shows high gain controller effort; Dash line shows low gain controller effort; Solid line shows switching gain controller effort. (b) Line trace of amplitude (green solid), reliability index (red dash), and switching signal (green dot) while imaging calibration sample at 4 Hz (with a tip velocity of 80 μs) in closed loop operation. Label A in the figure indicates that the switching signal based on the reliability index switches from a low to high state with the amplitude signal trailing the switching signal by $\approx$68 nm in the lateral direction before it reaches its free air amplitude. Therefore, thresholding based on the reliability index signal provides a higher bandwidth probe-loss correction method as compared to thresholding based on the cantilever amplitude. Label B indicates that once the tip re-engages with the sample, the reliability index signal rises faster than the rate at which the cantilever amplitude reduces. The switching signal switches before the cantilever amplitude registers any noticeable change.

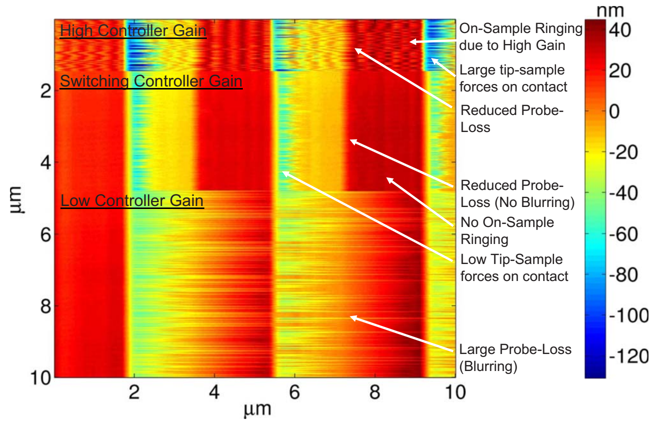

FIG. 3. (Color online) Calibration sample imaged at 8 Hz (with a tip velocity of 160 μs) in tapping mode.

To study the efficiency of the method, experiments were performed on Multimode AFM (Veeco Inc.) with AC240 cantilever (Asylum Research Inc., $f_0=70\,720$ Hz, $Q=210$, and $k=2$ N/m). Sample free model was identified using frequency sweep method wherein excitation frequency ω of $g(t)=A_0 \sin \omega t$ was varied from 0 to 100 kHz and $p(t)$ was recorded. Magnitude and phase information about $G(j\omega)$ was obtained by evaluating the ratios between steady state amplitude and difference between the phase of output and input excitation, respectively. Experiments were performed with this setup where a calibration grating, with 20 nm deep pits and a 3.5 μm pitch, is imaged at 4, 8, and 12 Hz with a scan size of 10 μm. Figure 2(a) shows that if low gain is used throughout then there is good on-sample performance but a significant probe loss area. If high gain is used throughout then there is negligible probe-loss area but there is considerable on sample ringing and consequently large tip-sample forces. By employing a switching gain controller, the probe-loss regions are limited and comparable to the probe-loss regions when using a high gain controller with the benefit that on-sample behavior matches the on-sample behavior when low gains are employed with ringing effects minimized. Similar characteristics are revealed through an image of a calibration sample at 8 Hz (see Fig. 3) where the use of low gain controller leads to large probe loss areas (blurring) leading to image artifacts, high gain controller leads to on-sample ringing while switching gain controller gives a better image. At 12 Hz (see Fig. 4) using low gain controller leads to loss of features but using switching gain controller recovers the square profile. In Fig. 2(b), the line traces of reliability index, amplitude, and switching signal are shown while imaging a calibration sample at 4 Hz scan speed in closed-loop operation. Region A [see Fig. 2(b)] indicates that switching signal goes from a low to high state with the amplitude signal trailing the switching signal by roughly 68 nm in lateral direction before it reaches the free air amplitude value thereby indicating that thresholding based on reliability index can provide a higher bandwidth operation. Region B indicates that when the tip re-engages with the sample, reliability index signal rises faster than the amplitude signal, and the switching signal goes low before the amplitude signal shows any change thereby controlling the force with which the tip re-engages with the sample. As the tip approaches the sample during probe-loss, the model of the cantilever changes due to damping effects before the cantilever tip regains interaction with the sample and is different from the sample free model $G(j\omega)$ on which the observer is based. Thus the thresholding can be set such that the controller gain is switched to a low value slightly before the tip actually makes contact with the sample thereby reducing the piezovelocity and making a soft contact with the sample.

Plasmid DNA was imaged on mica in air at 12 and 30 Hz. Figure 5 reveals clear reduction of probe-loss areas on the use of switching gain controller. Indeed at 30 Hz (see Fig. 6) (with a tip velocity of 60 μs) using switching gain controller leads to recovery of a lost DNA strand, which is close to 1.4 nm in height, compared to a low gain controller

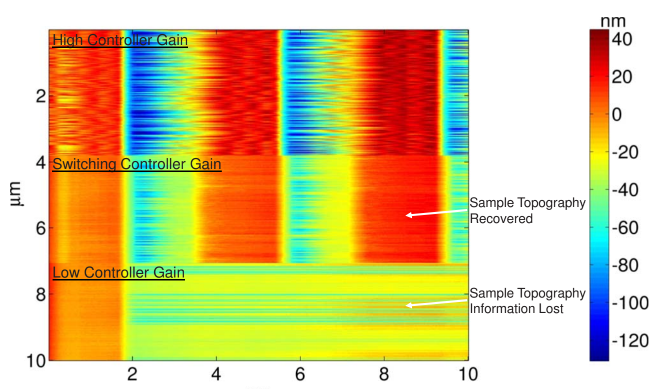

FIG. 4. (Color online) Calibration sample imaged at 12 Hz (with a tip velocity of 240 μs) in tapping mode.

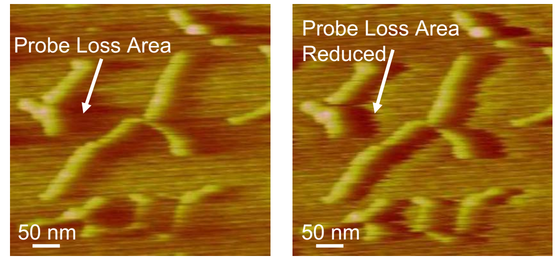

FIG. 5. (Color online) Plasmid DNA on mica imaged in air at a tip velocity of 24 μs (12 Hz) in tapping mode. Left image indicates presence of probe loss areas (dark areas) due to use of low gain controller. Right image indicates reduction of probe loss areas in real time (reduction of dark areas) by using switching gain controller thereby emphasizing that the resolution of the proposed technique is ≈ 2 nm.

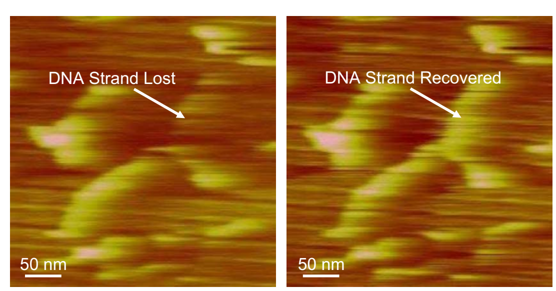

FIG. 6. (Color online) Plasmid DNA on mica imaged in air at a tip velocity of 60 μs (30 Hz) in tapping mode. Left image indicates loss of a DNA strand since it is present in the probe loss area during high speed imaging with low controller gain. Right image indicates recovery of same DNA strand by using switching gain controller at same scanning speed.

operation where the DNA strand is lost. This provides evidence that the proposed technique can be used for improved imaging of biological samples at high scan rates and that it has resolution better than 2 nm.

This paper presents a scheme for real time reduction of probe-loss affected areas during high speed tapping mode imaging based on thresholding of reliability index signal. This technique is implemented on hardware and its efficacy shown on imaging of calibration sample and plasmid DNA at high tip velocities. The method not only helps in reduction of probe-loss areas but also in recovering features that were lost at high imaging speeds with a resolution of better than 2 nm. Reliability index signal can be used for modifying the cantilever dynamics in real time helping to choose different quality factor for different on-sample and off-sample behavior and will form a part of future work.

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