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REVIEW OF SCIENTIFIC INSTRUMENTS **78**, 103706 (2007)

# Feedback based simultaneous correction of imaging artifacts due to geometrical and mechanical cross-talk and tip-sample stick in atomic force microscopy

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This paper presents a feedback scheme that simultaneously corrects, in real time, for the imaging artifacts caused by cantilever and photosensor misalignments as well as misinterpretations in relative lateral position of the tip with respect to the sample due to the tip-sample stick in atomic force microscopy (AFM). The optical beam bounce method, typically used in AFM for imaging, is sensitive to inaccuracies of cantilever geometry and the relative misalignment of the laser source, cantilever, and the laser sensitive diode from the intended design. These inaccuracies, which contribute to the geometrical cross-talk between the normal and the lateral signals, become prominent at the atomic and subnanometer scales, and thereby impede high resolution imaging studies. The feedback scheme accounts for these artifacts and makes imaging insensitive to, in fact, practically independent of these inaccuracies. This scheme counteracts the lateral twisting dynamics of the cantilever, and as a result, it avoids the misinterpretation problem of the relative lateral position of the cantilever tip from the sample and thereby avoids the corresponding imaging artifacts that are typically prominent in contact mode friction force microscopy (FFM). The feedback scheme consists of simultaneously regulating the normal as well as *the lateral* cantilever deflection signal at their respective set points. This not only removes the imaging artifacts due to geometrical misalignments, mechanical cross-talk, and irregular sliding but also the corresponding compensatory control signal gives a more accurate real time measure of the lateral interaction force between the sample and the cantilever as compared to the lateral deflection signal used in FFM. Experimental results show significant improvement, and in some cases, practical elimination of the artifacts. The design and implementation of a split piezoassembly needed for the lateral actuation for the feedback scheme are also presented. 
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## I. INTRODUCTION

The atomic force microscope (AFM),[1] with its remarkable ability to sense interatomic forces, continues to revolutionize nanoscience and nanotechnology. The ability to investigate matter with atomic scale specificity wields an immense potential—especially in areas of biology, material science, and physics. Its impact is already evident from the remarkable feats achieved in the last two decades, wherein it has enabled new studies and has spawned new research areas and technology. For instance, it has enabled new dimension to the area of biological and chemical sensing, where, for example, by coating the cantilever tip with particular types of biomolecules or chemicals, the absorption of reactant molecules, or chemicals onto the cantilever are detected through change in its mass, hence its resonance frequency, or through changes in the surface stress. The possibilities that this method offers to gene scanning and chemical sensing are enormous and are predicted to have an enormous impact on the area of drug discovery. Although impressive science has resulted due to AFM and a host of applications have been enabled by this technology, it is still a long way from realizing its full potential. Significant challenges, in terms of understanding fundamental limitations, development of devices, and enabling of certain applications are yet to be overcome. Recently, there has been a growth in system tools,[2] especially feedback based mechanisms that address some of the challenges, such as studying underlying principles,[3–6] improving the bandwidths of devices[7–11] while maintaining high resolution, and obtaining ultrahigh resolution capabilities.[12] These tools have indeed proven useful in the development of AFM and in extending its capability to various applications and operating modes.

Sample topography imaging remains the most widely used application of the AFM. Although atomic scale images of Si (111) were obtained and reported in 1983 by using a scanning tunneling microscope (STM) in high vacuum and low temperature conditions,[1] it is still difficult to routinely

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obtain them using an AFM. The main advantage of STM sensing mechanism is that the tunneling current is extremely sensitive to height of sample features and thereby it has a high signal to noise ratio (SNR). As a consequence, it is relatively easy to discern the true feature from the artifacts caused by noise. However, in STM, unlike AFM, imaging is limited to conducting surfaces, relatively flatter sample surfaces, and typically requires high vacuum and low temperature conditions (which preclude certain experiments involving samples whose properties alter under these conditions). Though AFM imaging is more versatile, it is not as sensitive as STM. The SNR is not as high and consequently it becomes difficult to routinely obtain subnanometer scale images.[13] This puts extra emphasis on understanding the sources of noise and developing methods that diminish their effects and separating image artifacts due to noise from true features.

The main contributors to artifacts in typical AFM for high resolution (subnanometer) imaging can be mainly categorized as tip-sample convolution, geometrical cross-talk, tip-sample stick, and mechanical cross-talk. These contributors outweigh other sources of artifacts, such as electronic and thermal noise, piezodrift, and creep, which are either negligible compared to them or as in current AFMs, already accounted for.[10,12,14] The artifacts due to large cantilever tips arise due to the averaging effects in the image due to the convolution between the sample feature and the cantilever tip profiles. This problem is well studied,[15–18] where methods to estimate cantilever tip profiles have been devised and then these profiles are used to deconvolve the image data to obtain the underlying sample profile. Even though, the problems due to geometrical and mechanical cross-talk and tip-sample stick misinterpretations have been reported, there are relatively fewer reports that propose methods to address them. In Ref. 19, rotating the sensor diode to counter the effects of the spurious signals is suggested. Another method suggested in Refs. 20 and 21 involves real time electronic correction to obtain independent normal and lateral signals. Both these methods correct only for the geometrical cross-talk caused by the misalignment in the optics. They do not account for the mechanical cross-talk that results from the photosensor being unable to distinguish the cantilever deflections, due to flexure dynamics of the cantilever, from the deflections due to sample features. Most importantly for high resolution images, these methods do not correct for the problem of tip-sample stick since they do not address the issue of the unpredictable irregular and nonsmooth sliding of the cantilever tip on the sample surface caused by the lateral and buckling dynamics of the cantilever. Other solutions, such as in Ref. 20, propose slow quasistatic scanning in order to avoid exciting the lateral dynamics of the cantilever and thereby avoiding the mechanical cross-talk. Even though these solutions do mitigate the mechanical cross-talk by reducing the effects of higher order lateral dynamics, they still do not address the low frequency lateral dynamics as well as the effects of tip-sample stick. Others have created postimaging modules to diminish the imaging artifacts based on models that predict these artifacts. These modules require an extensive and accurate understanding of the dynamics of the

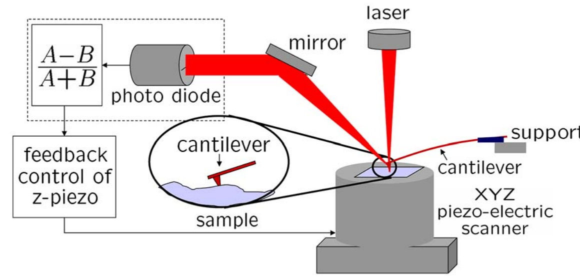


FIG. 1. (Color online) Schematic of the optical beam bounce method used do detect the interaction force between the cantilever tip and sample with the AFM operating in the constant force contact mode. The normal deflection signal is used as a measure of the normal interaction force, and the lateral deflection signal is used as a measure of the lateral interaction force, between the cantilever tip and the sample.

tip-sample interaction, which by itself is a field of current research. These solutions, by their very nature, are sensitive to inaccuracies in models and therefore in turn are sensitive to errors in cross-talk correction. Besides, these methods do not correct for the artifacts or display the corrected images in real time.

In this paper, we propose a solution which simultaneously corrects for all the three problems in real time. We use a control scheme that maintains a constant lateral deflection signal of the photodiode, in addition to maintaining a constant normal deflection signal, and hence a constant absolute deflection of the cantilever. This feedback based control loop not only corrects for the geometrical cross-talk, tip-sample stick, and mechanical cross-talk but it also makes the signals insensitive to these problems and hence is robust to modeling and alignment inaccuracies. This has an additional advantage of providing a more accurate measure of the lateral interaction force between the sample and the probe tip in the form of the lateral control signal.

The organization of rest of the paper is as follows. Section II explains the beam bounce method followed by details of the origin and effects of these problems and thus motivating the idea behind the proposed solution. Section III explains the feedback scheme, proposed hardware modification, and its implementation. The justification of the proposed solution with experimental results to corroborate the claims is provided in Sec. IV. In Sec. V, we analyze and discuss the solution and its salient features. Conclusions and future work are discussed in Sec. VI.

## II. AFM IMAGING AND SOURCES OF ARTIFACTS

### A. Contact mode imaging in AFM

In a typical AFM, a microcantilever is used to obtain the nanometer scale image of the sample topography by using the normal deflection of the cantilever as the sample moves under it (see Fig. 1 for a schematic of the beam bounce method while operating the AFM in constant force contact mode). The cantilever reacts to the interatomic forces between its tip and the sample features and deflects up and down as the sample features move under it. The cantilever deflections are detected by focusing a laser on the back of the cantilever and collecting the reflected laser on a four quadrant photodiode. One of the advantages of this method is its ability to simultaneously record the normal and lateral channels that are indicative of the normal and the lateral interaction forces between the sample surface and the cantilever tip when the cantilever is appropriately aligned with respect to the direction of sample movement. The difference signal between the upper and the lower halves of the diode, known as the *normal deflection signal*, is used as a measure of the tip-sample normal interaction force which is normal to the sample surface. This signal is used as a measure of the sample topography. Similarly, the difference signal between the left and the right halves of the diode, *the lateral signal*, is used as the measure of the tip-sample lateral interaction force which is along the sample surface and perpendicular to the cantilever's longitudinal axis.

When these deflections are directly used for imaging as in constant height operation, the contact forces can vary which typically result in unreliable and distorted images and sometimes tip-sample damage. Therefore in a typical contact mode operation (Fig. 1), the cantilever deflection is regulated at a set point (i.e., the tip-sample normal force is kept constant) while scanning the sample. This is achieved by moving the vertical positioning system ($z$-piezo), to which either the sample or the cantilever and optical assembly are attached up or down to compensate for the undulations in the sample surface by using a feedback controller. The input to the vertical positioner, i.e., the compensating control signal, with appropriate scaling, is traditionally used as a measure of the sample profile. This constant force method avoids force impulses felt by a cantilever (due to encountering a sudden large feature on the sample) that can potentially damage the cantilever or the sample, and also avoids the difficulty in discerning the topography from the nonlinear voltage-deflection relationship that models the cantilever deflection under the influence of the sample with respect to the photodiode measurements.

## B. Sources of artifacts

The most prominent sources of artifacts that affect the resolution capability of the AFM are geometrical cross-talk, tip-sample stick, mechanical cross-talk, and tip-sample convolution. In this paper, we address the first three sources. Geometrical cross-talk is attributed to the relative geometrical misalignment between the laser and the cantilever axes. This misalignment is caused by fabrication inaccuracies and the practically unavoidable incorrect loading of cantilever substrate. Mechanical cross-talk is caused by the lateral and buckling dynamics of the cantilever. The lateral dynamics of the cantilever creates an additional problem of tip-sample stick, which is more prominent at the atomic and subnanometer scales. Additionally, electronic cross-talk affects the system since there are many electronic components in the beam bounce method. However, we distinguish these sources from the prominent sources listed above since their effects are smaller in comparison. For instance, electronic cross-talk mainly depends on the quality of electronic assembly methods of the manufacturer and can be made negligible compared to the prominent sources listed above by careful assembly of the device electronics. A more detailed explanation of the artifacts and their sources is described below.

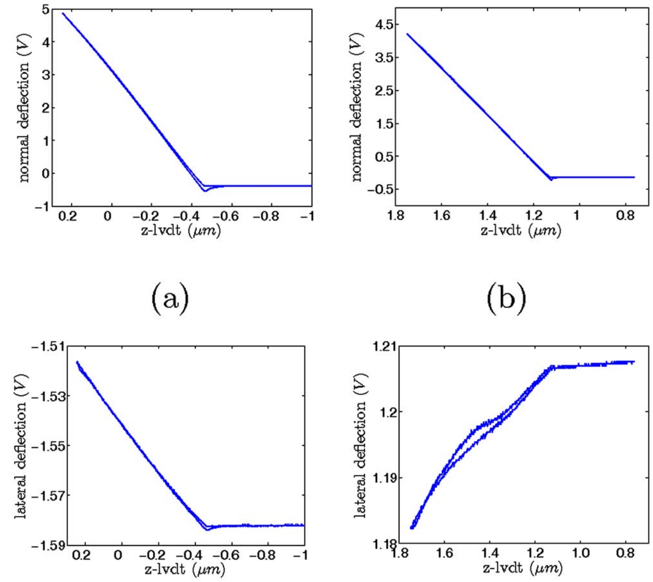


FIG. 2. (Color online) (a) Normal and the lateral signals obtained during a force curve. Lateral channel shows a spurious signal proportional to the normal signal indicating existence of geometrical cross-talk. (b) Normal and the lateral signals obtained during another force curve. The sign of the cantilever misalignment is opposite to that in (a). The spurious signal in the lateral channel with an opposite slope as in the force curve (a) confirms existence of geometrical dependence.

### *1. Geometrical cross-talk*

cross-talk between the normal and the lateral signal is the spurious signal created in one signal due to the deflection in other direction. The lateral and the normal interaction forces between the sample and the cantilever tip are typically assumed to be independent of each other. However, as mentioned above, due to practical limitations in alignment of optics and the flexure nature of the cantilever probes, the cross-talk is inherent, and the lateral and the normal signals, which are used as *measures* of the lateral and the normal interaction forces, respectively, are not independent. The *geometrical* cross-talk, which results from a misaligned photodiode sensor, laser source, or cantilever, gives spurious nonzero readings along the axis which under perfect alignment is orthogonal to the actual cantilever motion and is expected to show zero reading. That is, in the presence of geometrical misalignment, normal deflection of the cantilever creates a signal in the lateral channel and vice versa. This occurs only due to the deviations of the optical assembly from the intended design. Thus geometrical cross-talk, if not accounted for, leads to artifacts in AFM images. The spurious signal in the lateral channel due to the normal deflection of the cantilever in the presence of misalignment is experimentally demonstrated through force curves, shown in Fig. 2. The spurious signal in the normal channel due to the change in the lateral deflection (twisting) of the cantilever in the presence of the geometrical misalignment is experimentally demonstrated by imaging mica in constant force contact mode, shown in Fig. 3.

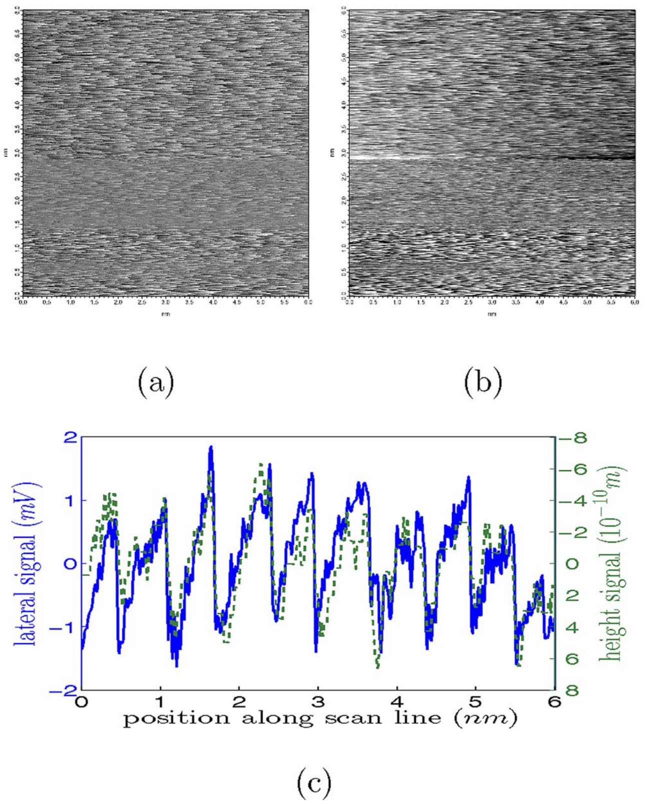


FIG. 3. (Color online) (a) Lateral image of mica, hairy structure (Refs. 22 and 23) indicates lattice scale stick slip. (b) Height image of mica, hairy structure similar to that in the lateral image can be seen. This structure is an artifact with image expected to be more flat. (c) Height (green, dotted) and lateral (blue, solid) image data superimposed from the same scan line obtained from the images (a) and (b). Height signal, which was expected to be more flat, shows a spurious signal proportional to the lateral signal indicating geometrical cross-talk.

A force curve depicts the interaction force between the cantilever tip and the sample, as they are brought closer vertically, as a function of the distance between them. Due to lateral symmetry, we expect no lateral force on the cantilever tip and hence expect neither any lateral twisting of the cantilever nor any change in the lateral signal during a force curve experiment. But contrary to this expectation, typical experiments show varying (nonconstant) lateral signals. This artifact of spurious variation in lateral signal can be misconstrued as lateral twisting of the cantilever. This signal is spurious since the lateral interaction force acting on the cantilever tip does not change once the cantilever touches the sample surface and it experiences only a repulsive normal force perpendicular to the surface. This variation is, in fact, the result of the geometrical cross-talk caused by the combination of gross misalignment in the optics and the change in the normal deflection as discussed in Ref. 19–21.

The effect of misalignment of the axes of the cantilever with respect to the axes of the photodiode can be changed by loading the cantilever substrate into the cantilever holder at different angles and when this is done until the angle of misalignment changes from positive to negative or vice versa, the sign of the effect of the normal deflection on lateral signal reverses sign [see Fig. 2(b)]. This substantiates the claim that the lateral signal during the force curve is indeed a spurious signal where the variation in the normal deflection of the cantilever is spilled over into the lateral signal by the unavoidable geometrical misalignment. Note that increasing this misalignment increases further the magnitude of the signal in the lateral channel. In this context, it should be noted that this geometric cross-talk is the result of both misalignment and a *varying* normal deflection signal caused by the variation in the normal deflection of the cantilever. In other words, if there is no normal deflection, there is no spurious lateral signal even in the presence of optical misalignment and vice versa i.e. if there is no lateral twisting of the cantilever, there is no spurious normal signal even in the presence of optical misalignment.

The other aspect of geometrical cross-talk is the spurious signal in the normal channel. Lateral twisting of the cantilever due to lateral forces on its tip leads to a varying lateral signal, which in the presence of the geometrical inaccuracies results in spurious normal signals. Experiments show signals in the normal channel even in the absence of the normal deflection of the cantilever and these spurious normal signals result in artifacts in the topographic images of the sample surface. The lattice scale image of mica gives a good demonstration of lateral forces corrupting the normal image in the presence of geometrical cross-talk (Fig. 3).

In the current operation of the constant force contact mode, the cantilever deflects laterally (through twisting) when the scanning direction is not parallel to the axis along the cantilever length due to the nonzero component of the lateral force perpendicular to the cantilever length. A combination of this lateral dynamics of the cantilever and the inherent nonsymmetry in the cantilever and optical misalignment creates spurious normal signals, and hence the normal $z$ control signal, which compensates for the change in the normal signal, gives an incorrect measure of the surface topography. These effects are more pronounced in high resolution (subnanometer and atomic scale) imaging as seen in the lattice averaged atomic scale image of mica in Fig. 3. Along with the surface topography, the normal control signal compensates for the lateral interaction force through the geometrical cross-talk, thereby giving a corrupted normal image.

#### *2. Tip-sample stick*

Another source for artifacts, especially in high resolution (subnanometer scale) imaging, is the lateral position misinterpretation due to *tip-sample stick*. Due to the lateral force acting on the cantilever, it twists and occasionally sticks to the sample surface. As a result, the normal deflection signal corresponds to the "stuck" location rather than to the intended location, which leads to misinterpretations in feature locations on the sample. While operating the AFM in the constant normal force contact mode (as described in Sec. II A), when the cantilever twists under the lateral interaction force, it creates spurious signals in the normal channel due to the inherent geometrical cross-talk as well as the image misinterpretation due to the tip-sample stick described above, leading to imaging artifacts.

This effect is seen in the lattice averaged atomic scale imaging of mica. Due to the lateral dynamics of the cantilever and the lateral interaction force between the cantilever tip

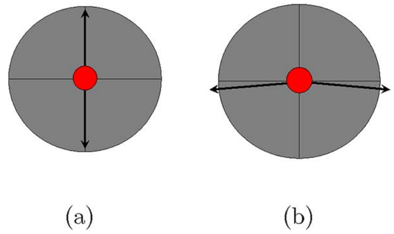


FIG. 4. (Color online) Movement of the reflected laser spot on the quadrant photodiode indicating mechanical cross-talk. (a) The spot moves in the vertical direction when the cantilever buckles or deflects in the vertical direction, thus making it difficult to discern normal deflection and buckling from each other. (b) When the cantilever twists under the influence of lateral interaction force, the spot not only moves in the lateral direction but also in the downward direction away from the center. The angle made by the direction vector depends on the relative electronic gains for the normal and the lateral channel. As a result, cantilever twisting under perfect geometrical alignment creates a spurious signal in the normal channel. This effect is more pronounced when sample features are very small and have significant friction variation

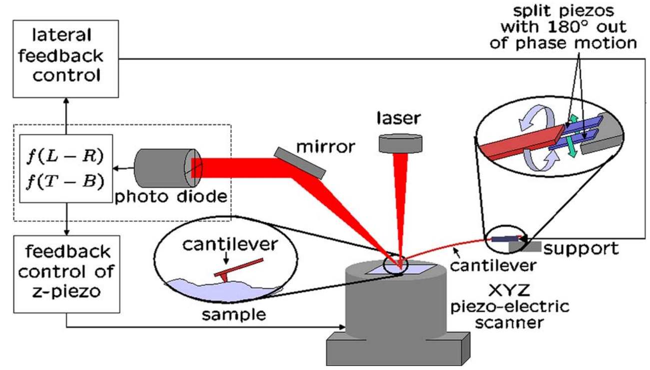


FIG. 5. (Color online) Schematic of lateral compensation working along with constant force contact mode. Two split piezos with 180° out of phase motion are used to demonstrate lateral actuation. Lateral signal from the laser sensitive photodiode is fed to a controller which provides the compensating signal to the lateral actuator through an amplifier.

and mica surface, the cantilever undergoes a stick slip motion[22,23] with a periodicity of 5.2 Å, the lattice constant of mica. This stick slip motion of the cantilever results in a triangular wave form in the lateral channel as seen in the scan line image data in Fig. 3. The linear portion of the triangular wave in the lateral channel corresponds to the situation where the cantilever is stuck to a particular location on the mica surface and the cantilever twist is increasing in approximately linear trend, while the sudden fall in the lateral signal corresponds to the cantilever *slip* when the cantilever suddenly starts sliding since its restoring forces become more than the lateral friction forces. Thus, for an apparent travel range of about a lattice dimension of 5.2 Å, the tip is stuck to a single location and the corresponding height signal during this stick regime represents the height of the stuck location rather than the intended locations along the scan line. Note that this artifact, in fact, is expected to be flat since it represents feature height data of a fixed point. However, due to the geometrical cross-talk, a signal proportional to the lateral signal (which has a linear trend) spills over to the normal signal, and hence we see a linear trend in the normal signal.

#### 3. Mechanical cross-talk

Mechanical cross-talk, as mentioned above, is caused due to the lateral interaction forces between the cantilever tip and the sample surface which excite the buckling and twisting dynamics of the cantilever. Mechanical cross-talk is defined as the spurious signal created in the normal channel due to this buckling and twisting of the cantilever even when there is perfect optical alignment of the axes. Both buckling and normal deflections of the cantilever change the slope of the reflecting surface and hence are indistinguishable to the photodiode sensor [Fig. 4(a)]. Similarly, when the cantilever twists by large angles, the lateral rotation of the reflecting surface of the cantilever not only deflects the laser beam in the lateral direction but also in the normal direction [Fig. 4(b)], which results in a signal in the normal channel which can be construed as normal deflection of the cantilever. Mechanical cross-talk only affects the normal channel and not the lateral channel since normal deflection and buckling do not create any twisting effect on the reflecting surface and hence there is no spurious signal due to this source in the lateral channel under perfect optical alignment.

## III. PROPOSED SOLUTION AND ITS IMPLEMENTATION

### A. Feedback scheme

In this paper, we propose a solution, which *simultaneously* corrects, in real time, both the geometrical and the mechanical cross-talk as well as removes the problem of tip-sample stick. Our solution is to simultaneously maintain the *lateral* and the *normal* deflection signals constant at their corresponding set points through feedback. The basis of this solution lies in the fact that both forms of cross-talk and tip-sample stick result in spurious signals in one channel only if there is a variation of the cantilever deflection in the other direction. In constant force contact mode AFM, the normal direction dynamics of the cantilever are already kept constant using the feedback in the $z$ direction. This prevents any spurious signals from affecting the lateral channel. Likewise, we propose to maintain the lateral dynamics (twisting) of the cantilever constant through feedback controls. This ensures zero spurious signals in the normal channel and hence artifact-free height images.

### B. Actuator design and implementation of feedback scheme

We use a split piezoarrangement to enable the lateral actuation of the cantilever. A schematic of lateral compensation used along with normal $z$ feedback is shown in Fig. 5. This prevents spurious signals in the normal channel due to both forms of cross-talk and tip-sample stick resulting in removal of the artifacts without losing relevant information. This has an additional advantage of providing a more accurate measure of the lateral interaction force (than the lateral deflection signal) between the sample and the probe tip in the form of the lateral control signal which is elaborated later.

In order to enable lateral compensation feedback scheme, the cantilever holder in the AFM (molecular force probe 3D from Asylum Research Inc., Santa Barbara) was

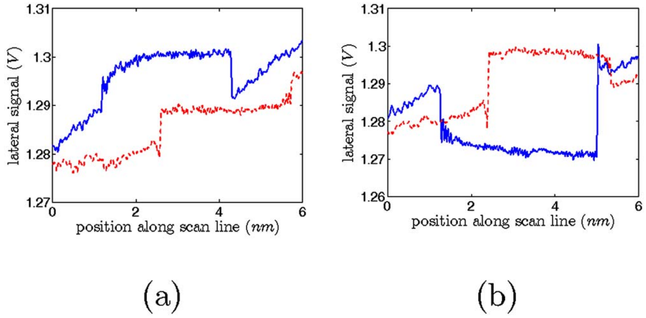


FIG. 6. (Color online) Effective lateral compensation: Both graphs were obtained while imaging mica. The lateral compensator is switched once each during the trace (blue, solid) and retrace (red, dotted). Before switching on the compensator, the lateral signal follows a linear trend, while it is constant when the compensator switched on indicating a successful maintenance of lateral deflection of the cantilever. Different set points were used to demonstrate the effective actuating capabilities of the crude actuator.

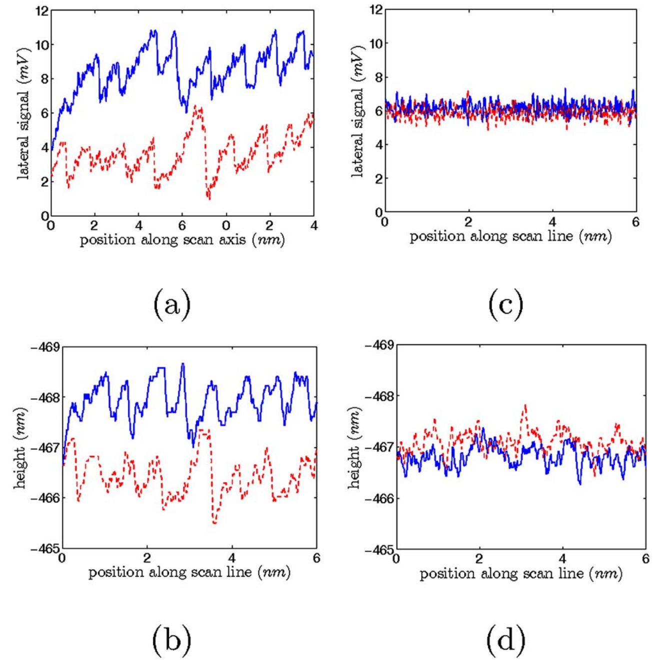


FIG. 7. (Color online) (a) Lateral signal trace (blue, solid) and retrace (red, dotted) indicate the stick slip friction characteristic of mica. The difference between the trace and retrace also indicates friction hysteresis. The corresponding normal signal, which was expected flat, shows a spurious signal proportional to the lateral signal. The trace (blue, solid) and retrace (red, dotted) height signals which are supposed to overlap have a difference of 1.489 nm. (b) Lateral compensation was switched on and the corresponding lateral and normal signals obtained along the scan line. A constant lateral signal indicates successful lateral compensation. Since there is no more lateral twisting, the spurious signal in the normal channel due to the geometrical misalignment is eliminated and the trace and retrace overlap each other. The difference between the height trace and retrace with the lateral compensation on is 0.288 nm which is within the error of $z$ resolution.

modified to incorporate a rudimentary lateral actuator. The existing high frequency dither piezo used to excite the cantilever for intermittent contact mode operation, below the base of the cantilever clamp, is replaced with a set of split piezos, each of which is actuated by voltage inputs that are 180° out of phase. As a consequence, the piezos move 180° out of phase with each other. When one piezo expands, the other contracts creating a rotational effect on the cantilever clamp. This rotation of the cantilever clamp has the effect of laterally rotating the free end of the cantilever reflective surface. The split piezoassembly rotates the whole cantilever along with its substrate, and thereby providing a control over the lateral twisting of the cantilever reflective surface caused by the torque due to the tip-sample lateral interaction force. This modified cantilever holder is used as the lateral actuator to demonstrate implementation of the lateral compensation feedback scheme.

In order to drive these split piezos, a coupled high voltage amplifier was designed which provides with the necessary power requirements to actuate the assembly. A bridge amplifier circuit was designed around two PA78 power operational amplifiers from Apex Microtechnology Corporation,[24] Tucson, USA. This modified cantilever holder assembly is used to perform experiments and confirm the capability of lateral compensation by maintaining the lateral deflection of the cantilever constant. These experiments are discussed below. A proportional-integral controller was designed to compute the control signal depending on the error between the reference set point and the sensor reading (lateral signal from the quadrant photodiode) with the aim of reducing this error to zero. The control signal was then applied to the split piezoassembly through the amplifier. The feedback scheme was implemented on a 100 kHz sampling frequency digital signal processor from Analog devices, ADSP 21160M.

The effective performance of this crude lateral actuator can be seen from Fig. 6. These scan line images were obtained while imaging mica. The lateral compensator is switched on and off once along each of the trace and retrace. When the lateral compensator is off, the lateral signal is linearly increasing, indicating change in the lateral deflection (twisting) of the cantilever due to the lateral interaction force between the cantilever tip and the sample. When the lateral compensator is switched on, it maintains a constant lateral deflection as seen in the Fig. 6.

## IV. EXPERIMENTAL RESULTS

The effectiveness of the feedback scheme that implements lateral compensation, in addition to the normal compensation, for removing the geometrical and mechanical cross-talk as well as the tip-sample stick is demonstrated through the following experiments. In this section, we show that these sources of artifacts themselves are either compensated for or avoided in real time.

### A. Real-time removal of artifacts due to geometrical cross-talk

The plots in Fig. 7 were obtained by performing a constant force contact mode scan on mica that maintained a constant normal deflection. Because of this, there are no spurious signals in the lateral channel in spite of the unavoidable misalignment in cantilever placements and optical assembly. The mica used for imaging is an atomically flat sample. Hence we expect a flat height signal with the trace and retrace overlapping each other within the error of the $z$ resolution. But as seen from Fig. 7(b), the height image along a scan line shows a triangular wave form very similar to the one seen in the lateral channel in Fig. 7(a). This triangular wave form in the height signal ($z$ control signal) is because the $z$ feedback compensated for the normal signal which was corrupted by the geometrical cross-talk and the variations in the lateral deflection of the cantilever. The difference between the trace and retrace is 1.489 nm, obtained by taking the difference between the average height along trace and retrace, as against an ideal value of zero for perfect overlap. The lateral compensator is then switched on and a constant lateral deflection was maintained, as seen in Fig. 7(c). The corresponding height signal along the same scan line [Fig. 7(d)] is flatter than the one in Fig. 7(b). With the lateral compensation on, the difference between the height trace and retrace is 0.288 nm. This value indicates an overlap of the height trace and retrace within the limits of $z$ resolution (the $z$ resolution is in the order of 0.300 nm) and is an improvement of 81% over that obtained when there is no lateral compensation. This effectively demonstrates the removal of cross-talk using lateral compensation.

### B. Real-time removal of artifacts due to tip-sample stick and mechanical cross-talk

The experiment described in Fig. 7 also demonstrates the removal of mechanical cross-talk and spuriousness due to the tip-sample stick. As seen from Fig. 7(a), when the friction compensator is off, the lateral signal follows a triangular wave pattern, indicating a stick slip behavior between the cantilever tip and the sample surface. As explained before in Sec. II B 2, this results in misrepresentation due to tip-sample stick. In order to avoid this, it is necessary that the cantilever tip slides smoothly on the sample surface rather than sticking to any location. When the lateral compensator is switched on, it immediately rotates the cantilever substrate so as to nullify the lateral twisting of the cantilever and maintains the angle of the cantilever at the constant set point. This ensures that the tip becomes laterally rigid and hence cannot stick to any point on the sample surface. Thus the lateral compensator ensures that the cantilever tip slides smoothly without sticking anywhere on the sample surface along the scan line. Hence the corresponding normal signal and therefore the height signal are the measures of the topography of the true location rather than the sticking location. Figure 7(c) shows the friction scan line image data of mica obtained with the lateral compensator on. A zero change in the lateral signal indicates no sticking and thus there are no spurious effects in the normal channel resulting in a correct height signal.

As mentioned before, mechanical cross-talk only affects the normal channel. The effectiveness of the control scheme was demonstrated by maintaining a constant lateral deflection of the cantilever, as seen in Fig. 7(c). When the lateral compensation was not on, the difference between the average trace friction and average retrace friction was 4.83 mV, and when the lateral compensation was switched on, this difference reduced to 0.29 mV, indicating successful compensation of lateral deflection. Since there is no change in the lateral deflection of the cantilever, there is no spurious signal in the normal channel and thus mechanical cross-talk is removed.

## V. ANALYSIS AND DISCUSSIONS

The previous section demonstrates the effectiveness of the feedback scheme, which simultaneously achieved the lateral and normal signal set point regulation objectives, in removing imaging artifacts. The most salient feature of this scheme is its ability to remove all these problems simultaneously in *real time*. All the existing solutions stated in Sec. I can either correct for only part of these problems or they correct for these problems off line. Most of these solutions are *static*, in the sense that the solutions do not change as the experiment proceeds—they give one-time corrective procedure for removal of the artifacts. For example, in the case of solution involving rotation of the photodiode,[19] the rotation to correct for the misalignment is done during the initial setup of the experiment. It is not a dynamic process, where the corrections are made as the experiment proceeds. In the case of feedback scheme proposed in this paper, the removal of the problems happens dynamically as the experiment proceeds. Therefore, lateral compensation has the advantage of addressing the sources that are dynamic in nature, especially the tip-sample stick and the mechanical cross-talk, in real time. The artifacts due to the tip-sample stick and the mechanical cross-talk, unlike those due to geometrical cross-talk, cannot be anticipated before they occur, and therefore cannot be addressed by the static schemes in real time.

A significant advantage of the proposed scheme is that it is insensitive (robust) to the geometrical misalignment. This method depends on maintaining a constant position of the laser spot on the photodiode, thus making this mechanism *independent* of the alignment of the axes on the photodiode sensor with respect to the cantilever axes. That is, the misalignments in cantilever placement and optical assembly do not affect this scheme, and therefore the images, since the location of the laser spot on the diode is independent of the axes chosen and the spot is maintained constant. This provides a significant conceptual and practical advantage over the solution in Refs. 19–21 (and other similar solutions), which is sensitive, as pointed by its authors, to the way the axes of the photodiode are aligned, and therefore its precision depends on how well the rotary stage mechanism aligns these axes with the cantilever axes.

The proposed scheme, for its implementation, requires very few changes to the existing setup of an AFM. The lateral compensation uses the existing lateral channel from the photo diode as a sensor signal and thus requires no new sensing mechanism. The only change required is the addition of a lateral actuator. For the purpose of demonstration, this lateral actuator is implemented by replacing the intermittent contact piezo by two split piezos. This modification was done on the easily replaceable cantilever holder, which makes this scheme easier to implement and economically cheaper, compared to modifying the optical setup (as in Ref. 19). Even better and cheaper actuators could be used in the form of piezoresistive (and piezoelectric) cantilevers, where the actuating mechanism is on the cantilever itself. In

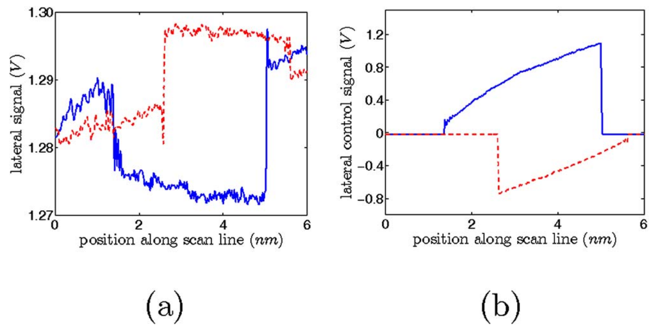


FIG. 8. (Color online) (a) Lateral signal. (b) Lateral control signal. The lateral compensator is switched on and off once each along both the trace (blue, solid) and retrace (red, dotted). When switched on, the lateral compensator maintains a constant lateral signal and hence a constant lateral deflection (twist) of the cantilever. During this scan, the lateral signal has a linear trend which is eliminated when the compensator is switched on. During the on time of the compensator, the lateral control signal provides the measure of the lateral interaction force which can be seen by the linear trend shown by the lateral control signal.

addition to giving better actuation, it will require even lesser modification since cantilevers are already a consumable component of an AFM and require frequent replacements.

Since the lateral compensator ensures smooth sliding of the cantilever tip on the sample surface, the constant lateral signal no longer carries the information of the lateral force acting on the cantilever tip. The lateral force information gets reflected in the lateral control signal which helps maintain this constant lateral deflection. This is demonstrated in Fig. 8.

As seen in Fig. 8, when the lateral compensator is switched on, the lateral control signal starts following the pattern (a linear trend) which otherwise would be shown in the lateral signal when the compensator was off. Thus, while the lateral signal is maintained constant, the lateral control signal captures the lateral interaction force between the cantilever tip and the sample surface. This lateral control signal happens to provide a more accurate measure of the lateral interaction force which can be explained as follows. In the absence of lateral compensation, the lateral signal is used as a measure of the lateral interaction force. But at any given moment, the instantaneous lateral deflection (twisting) of the cantilever is not only due to the instantaneous lateral interaction force but also due the inertial effects of the lateral forces which are related through the nonlinear higher order dynamics of the cantilever. When lateral compensation is used, the lateral twisting motion of the cantilever is held constant and the corresponding lateral control signal dynamically compensates for the overall lateral dynamics of the cantilever. Thus, by avoiding the lateral dynamics of the cantilever, the lateral control signal contains a better estimate of the instantaneous friction force rather than the lateral signal in the absence of the lateral compensation. This argument is analogous to the explanation given for the better imaging capability of the constant force mode as compared to the constant height mode in contact mode imaging. Further, this has the additional advantage of avoiding the nonlinear relation between the lateral deflection of the cantilever and the lateral signal captured by the photodiode. The standard FFM uses the lateral signal as the measure of the lateral force under the assumption that the lateral signal is linear with respect to the lateral deflection of the cantilever, which is not true when twist angles are large. This assumption is not required when the lateral deflection is maintained at a constant level as done in lateral compensation. Thus, lateral compensation provides a more accurate measure of lateral force than the standard lateral signal in FFM.

In this paper, we have discussed the imaging artifacts and a solution to remove them with respect to contact mode operation. As such this feedback scheme becomes directly relevant to contact mode operations in AFM such as in contact mode imaging and friction force microscopy. However, this scheme can be extended to other modes of imaging operations, such as in intermittent contact mode that is typically used for imaging soft biological samples.[25] For instance, the geometrical cross-talk effect of lateral deflections on the normal signal can be diminished by controlling the lateral motions of the cantilever. However, that will require a detailed modeling and analysis of these effects and cross-talk in the context of oscillating cantilevers.

## VI. CONCLUSIONS

From the above experimental results, we have demonstrated the effectiveness of the feedback scheme that implements simultaneously the set point regulation of the lateral and normal deflections of the cantilever. With the lateral deflection signal maintained at a constant set point, the spurious signals in the normal channel due to the unavoidable cross-talk are eliminated. Since the lateral compensator dynamically compensates for the lateral dynamics of the cantilever, the cantilever tip no longer sticks to the surface of the sample. This ensures perfect smooth sliding of the tip on the surface preventing the mechanical cross-talk as well as the spuriousness caused by the tip-sample stick. Thus, by simply modifying the cantilever holder to incorporate a lateral rotating crude actuator for the cantilever, we have demonstrated lateral compensation to remove artifacts in high resolution imaging. In spite of using an elementary lateral actuator, an improvement of 81% was obtained where the scheme significantly diminished the problems of geometrical misalignment, tip-sample stick, and mechanical cross-talk simultaneously, and in real time, as against when it is not used.

This scheme is a robust solution since it is insensitive to relative misalignment of the sensor, laser, and cantilever axes. It is also very cheap to implement since the required changes are within easily replaceable components such as cantilever holder or the cantilever itself. In this paper, although lateral compensation, as a way to correct for cross-talk and tip-sample stick spurious effects in contact mode, is presented, it can be used in any mode where these problems occur. The future work of this research involves lateral compensation using a better actuator. This better actuator could be designed by mounting piezoresistive material directly onto the cantilever so as to remove any possibility of noise entering into the system.

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