Ultra-High Speed Atomic Force Microscopy: video-rate and beyond

Fathi M. Salem
Integrated Circuits and Systems Lab.
Department of Electrical and Computer Engineering
Michigan State University
East Lansing, Michigan, U.S.A
salemf@msu.edu

***Abstract*—Ultra high-speed Atomic Force Microscopy (AFM) is desirable for imaging fast dynamic processes, e.g., protein molecules motion in their aqueous or membrane environments. The paper identifies the limiting factors of present AFMs in achieving ultra high speed imaging. Specifically, the vertical control-loop bandwidth is the key limiting factor due to the low resonance (about 150 kHz) piezo-material cantilever actuator. We then propose a bandwidth solution by using integrated coil-array actuators driven by programmable oscillators and power amplifiers as an alternative to piezo-actuators in the vertical (z-direction) control loop. The slower piezo actuation, however, can still be used in the lateral slower x-y directions to achieve scanning range in the micro-meter range. This integrated circuit and system solution potentially would turn the AFM imaging system into an ultra high speed nano-scale video camera.**

I. INTRODUCTION AND MOTIVATION

T

Atomic Force Microscopy (AFM) systems [1-3] have revolutionized nanoscience and engineering with impact on biology and material sciences [1-5]. These fundamental tools are enabling discoveries in material behavior, bonding, and evaluation as well as cell and cell-membrane diagnosis through imaging and manipulation [1]. Yet, present AFM systems have challenging limitations characterized by specific features that this paper identifies and seeks to eliminate [1-5]. *A compelling challenge* in High speed AFM in aqueous solutions is to be able to visualize (biological) proteins in action-- without disturbing their functioning. In liquid solutions, the cantilever Q-factor is extremely reduced due to hydrodynamic interactions between the cantilever and the liquid thus hindering imaging (see [1-3]).

From the imager viewpoint, this requires capturing frame-images faster than (video-rate) 30 milli-second range using very weak cantilever-sample force interactions [1-3]. As an example, assuming a conservative resolution of 100x100 pixels to capture 150nm x 150nm range, this would require capturing a "pixel" within ($30m/10^4$) sec/pixel=3 micro seconds (/pixel). Thus, this would require the full sensor-control-actuator-cantilever loop path in the z-axis to be within this time range! Sensors and control can be implemented in high-speed opto-electronic modules and thus potentially if integrated can easily achieve fast times in pico or one micro second ranges. Cantilevers have been dramatically reduced in sizes and optimized in performance by focused, specialized industry and research. At present, a developed cantilever with a tip can achieve in the order of 3MHz in air and 1.2 MHz in liquid with a spring constant ~0.2 Nm^{-1} [1, 3]. Such cantilever optimization has been pursued through dedicated materials research to increase the resonance (and hence the bandwidth) or reduce time delays. Thus, in liquid, the response time of the cantilever-tip is in the order of (1/1.2MHz=) 0.88 micro-sec. The truly limiting factor in the loop has been the actuation by piezo-material that at best has resonances in the order of 150 kHz (i.e., time response ~1/150KHz=6.67 micro seconds). As this number alone is greater than the limiting time range of 3 micro seconds, even a 100x100 resolution image of 150nmx150nm range can not be captured at near video rate. Thus, High Speed AFMs can not at present resolve time to capture the true dynamic functioning of critical proteins for various biological studies-- including disease diagnosis (e.g. proteins influential in the opening and closing of salt-specific cell-membrane channels or Alzheimer detection and potential treatment). The objective of this work is to develop and demonstrate a viable and reliable circuits and systems approach to achieve high speed imaging of biomaterial in liquid. This translates to imaging in a time range of 30 msec/frame or faster in order to resolve time and capture/image true dynamics of proteins in their natural aqueous environment.

II. BASICS OF AFM SYSTEMS

Present Atomic Force Microscopy (AFM) systems consist of a cantilever with a sharp tip interacting with the surface of an object of interest, see Fig. 1. There are primarily contact,

This work was supported by NSF grant No.0840047.

intermittent contact (tapping) and non-contact modes of operations. For the purpose of this paper, we focus specifically on non-contact and tapping (intermittent contact) modes as they are the most suitable for potential fast imaging of soft tissue (membranes and bio-proteins) in motion. Typically PZT (peizo-)material is used for actuation in the vertical (z-) direction as well as in the planar (x-y) directions. The z-direction requires high bandwidth (i.e., small time constants) with 2 orders less for the x and even lower for the y-axis (see the metrics and bandwidth requirement in the next section). While some designs actuate the cantilever over nano meter ranges, other designs actuate the sample (holder) over micro meter ranges.

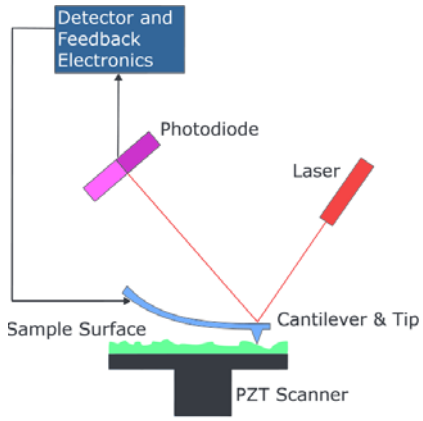

Fig 1. Schematic of AFM system (from [6]).

Fig.2 depicts the force vs. separation distance between (an atom on) the cantilever tip and (an atom on) the surface.

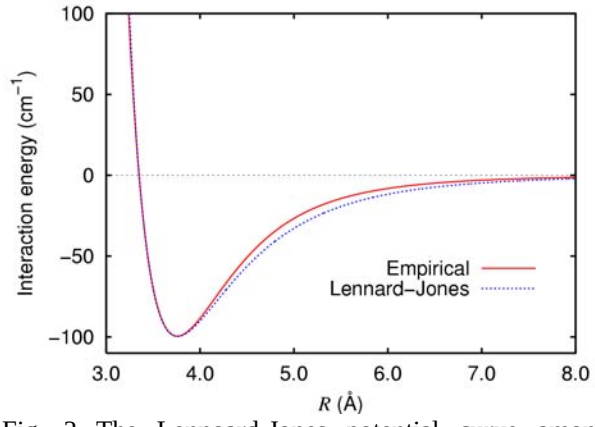

Fig. 2 The Lennoard-Jones potential curve among molecules(from [6]).

It is approximated by the well-known Lennoard-Jones potential model which mathematically given by

$$V(r,l) = 4\varepsilon[(\frac{\sigma}{r})^{12} - (\frac{\sigma}{r})^{6}] \qquad (1)$$

where ε is the depth of the potential well and σ is the finite distance at which the intermolecule potential equals zero, and r is the separation distance between tip and the sample surface [2, 6]. In the bracket, the positive term (i.e., $(\frac{\sigma}{r})^{12}$) represents the repelling potential, while the negative term (i.e., $-(\frac{\sigma}{r})^{6}$) represents the attracting potential due to the van der Waals forces. In Fig. 2, the attracting regime dominates till near 0.4 nm separation, below which the repelling regime dominates.

The dynamic models used for the cantilever-tip module is given as [2]

$$\ddot{p} + \frac{\omega_o}{Q}\dot{p} + \omega_o^2 p = \nabla V(r,l) + u + \eta$$
$$y = p + \nu \qquad (2)$$

where $p, y, \eta,$ and ν denote respectively the deflection of the tip, the measured deflection, process noise, and measurement noise, respectively [2]. Also $\nabla V(r,l), Q, \omega_o, u$ are respectively the vector-force field generated from the scalar potential field $V(r,l)$, the quality factor, the natural frequency, and the control signal. It is noted that eqns (2) is valid for the 3 dimensional physical space, e.g., the x, y, and z- Cartesian coordinates.

III. METRICS AND PERFORMANCE REQUIREMENTS FOR ULTRA HIGH SPEED IMAGING

It is well known that AFM systems are the only nano-scale resolution imaging option in wet-biology [1-4]. However, their speed is limited due to the actuation mechanism, electronics, the cantilever's reduced Q (quality factor) and resonance frequency in liquid. In this section, we identify systemically the major limiting factors in ultra high speed AFM operations and itemize the requirements and metrics of performance to achieve reliable ultra high speed, even beyond real-time video-rate.

A. Bandwidth requirements for high speed imaging:

To articulate the requirements precisely, we describe a typical scanning region and the imaging operation of the AFM system. Let the region to be imaged/probed be of size L by W (in units of nano-meters) and assume imaging will scan N lines. See Fig. 3 which depicts the scanning process where dL is the horizontal (and for simplicity also the vertical) spatial resolution or distance. Then, the tip must traverse a total distance, say D, equals to $LN + (N-1)(L^2 + dL^2)^{0.5}$ to acquire a "frame" of the image. For the total image to be acquired, at least at the video rate, the maximum time for

acquisition is T=1/30=33m sec. Then, the time it takes the tip to move 1 unit (1 n-meter), say T1, is on average T1=T/D.

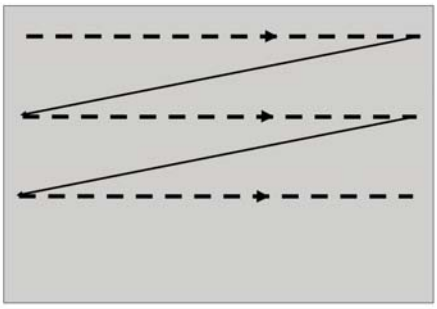

Fig. 3. The scanned region: Length L and width W. dL is he spatial "pixel" size. N is the number of line. N also serves as the resolution

Let the region to be imaged have L=240nm, N=100, then T1=0.6979 micro-sec. For a typical pixel size of 2.4nm (along L and W), the time for the tip to traverse 2.4nm is 2.4*T1=1.675 micro-sec. Thus, this is the (total) time available for the cantilever-tip *(vertical) control* loop to accurately "snap" a pixel sample. That is, it is the total time available for measuring the tip-sample force. In this description, the "pixel" size is 2.4nm x 2.4 nm and the image resolution is 100 x 100 pixels. Thus the feedback bandwidth limit in the vertical (z-) control loop direction is 1/1.675 micro secs=0.5970MHz. It is noted that the z-dynamics are assumed decoupled via either physical scan designs or via control action, from the X-Y direction control dynamics. Thus the upper time bound on the vertical control-loop action is dLxT/D. This performance metrics is used as a guideline for the z-control performance.

B. Control Loop Components:

The AFM control system components in the non-contact or (intermittent-contact) tapping-modes basically are: (i) the mechanical (soft) cantilever with sharp tip, (ii) the (tip) position sensor-detector, (iii) controller/filter electronics, (iv) (force) actuator. The following remarks are now in order:

1) Cantilever-tip design and fabrication are specialized manufacturing enterprises that have produced high quality cantilever-tip designs with high resonances. The control strategies, if directly realizable in integrated analog electronic elements, would cause no bandwidth limit on the control loop. The sensor devices are implemented in analog electro-optics and thus with work underway [1, 3-5] are expected to improve in bandwidth as well.

2) The component usually used for actuation is the high-voltage (in the range of 100-220V), hysteresis-limited, with relatively low resonance (~150K Hz) piezo (PZT) material. Thus it requires a (time-constant) response time of about 1/150K=6.67 micro-sec—far higher than the 1.675 micro sec upper limit. Feedback strategies that amount to counteracting this resonance limit by effectively either cancelling this resonance or operating at higher frequencies would require high gain and power. Due to the presence of thermo-noise and vibrations, as well as the requirement of nano-scale resolution, such methods will be brute force and are not reliably stable in high precision scenarios.

Thus including only the cantilever and the piezo actuator time constants, the total time constant becomes =6.67+0.83=7.5 micro seconds. For the example sample region size and resolution, this leads to a frame-rate=7.5 micro-secx100x100=75m seconds. This is roughly 13 frames/second for a resolution of 100x100 pixels with pixel sizes of 2.4 x 2.4 nano-meters. Thus, the reported frame-rate of 80 m seconds in [3] is the best that can be achieved due to the PTZ piezo-actuator. The existing piezo actuator has reached its speed limit and thus present AFMs can not speed up beyond the 10-13 frames/second for a 100x100 resolution.

This time acquisition constraint provides a compelling reason to propose coil array for vertical actuation. An implemented design approach to minimize thermo-noise in coil actuation devices is to realize any desired coil size by a combination of minimal small coils. Such coils have been fabricated on chips and tested, by innovative use of a commercial AFM systems, to generate forces in the nano- to micro- Newtons forces [7].

Effective control strategies must provide simple solutions synthesizable from (integrated) electronic elements to achieve high speed implementation.

Key issues for high speed coil actuator implementation are delineated in the following:

- How to ensure the generation of atomic forces (in the nano-Newton range) for direct interactions with specimen, or micro-Newton ranges for actuating (a) rigid fulcrum structure(s) supporting the cantilever-tip?
- How to simultaneously achieve density and satisfactory resolution to capture nano-scale details over possibly large ranges (in the order of micro meter squared)?
- How noise sources, 1/f, thermal, shot noises, from the electronic derivers and the thermo-resistivity of the coil(s) can be minimized by the noise of the components and the system? And also in anticipation of the noise from the mechanical or sensing sub-systems.
- For imaging cantilever-array based operations, specially in the dynamic (or tapping) mode operations, how can the oscillations of the integrated coils be synchronized in order to, *synchronously* and *simultaneously*, image the bio- or other material in parallel?

IV. ACTUATION MECANISM FOR HIGH SPEED IMAGING

Vertical coils in 0.5 um technology were designed from the 3 metal layers (using minimum sizes and real-state for the direct elctro-magnetic (EM) force coils, and larger sizes to

accommodate the fulcrum actuation rods). For example, the minimal designed coils occupy 6umx6um.

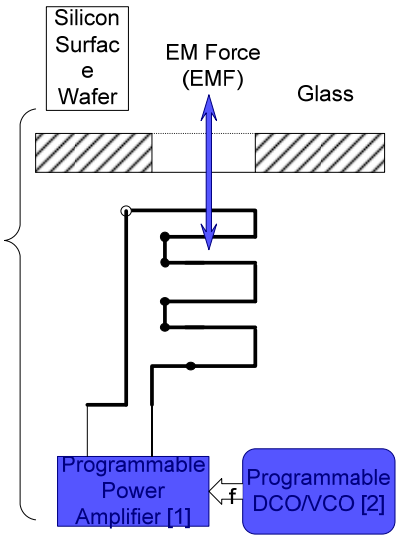

Fig. 4. Diagram of the vertical on chip actuator with driving Power Amp and Oscillator.

A test chip for a sample single coil actuator, with driving oscillator and programmable Amplifier was tested [4]. The photos below depict the uncovered packaged die which was tested with the (Neuroscience) AFM Easy Scan II system. The resulting measurements with no input power (in order to capture background noise, including noise levels that can be subtracted from measurements.) to the 8 (digital-command) power levels are reported in [7]. For this prototype coil, the lowest measured force range is from 27-52 nano-Newtons to the maximum measured force ranges, from 139.5-2607.6 nano-Newtons. These results are close to the ranges desired for the AFM actuator and thus validate the proposed framework. From these designs, one can modify the layout and/or increase/decrease the current amplitude levels to generate increased/decrease force levels.

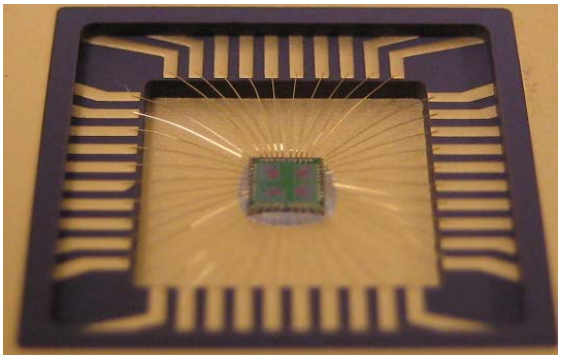

Fig. 5: test chip for the coil elements. Generated forces measured using an AFM system with magnetic tip [7]

A. *An actuator of a single probe-tip*

The array coil actuator can be used in an application that speeds up the single probe actuation. In the configuration of Fig. 6 below, two identical dies with coil arrays are suspended to face one another so that activated coils can be used to steer the tip to a controlled range through a (post-processing, micro-machines) fulcrum structure. Vertical motion can be achieved by activating the coil elements in the vertical direction. Moreover, any line between any (two) coils can form an axis of rotation while other coils, orthogonal to the axis, can rotate the die/fulcrum structure supporting the tip to achieve lateral motion of the tip. The effective result is that the tip can be steered in 3D. The low voltage-power required here is in contrast to using piezo elements requiring high power with voltages in the 110-220 V range. This will render such probing device portable as well.

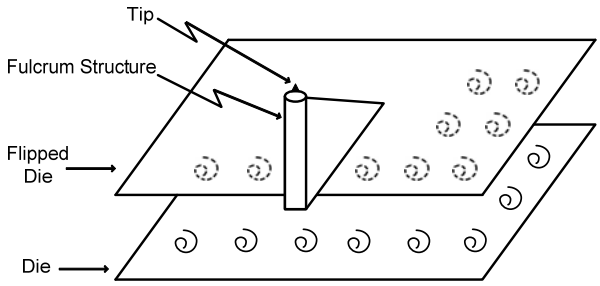

Fig. 6: Two identical array coil surfaces can be packaged to face one another to generate a motoring action between the two surfaces. This action will control the vertical motion as well as rotational motion along any chosen axis between any coils. This provides the tip with "approach" motion as well as with lateral motion over a region for the single tip.

B. *Direct actuation array*

The array itself can be used for direct EM force actuation for magnetic or magnetized material and interaction with magnetized bio-material. This is the focus of other targeted applications for programmable array that can steer biomaterial for our current research activities

REFERENCES

[1] T. Ando et al., "High-speed AFM and nano-visualization of biomolecular processes," Pflugers Arch - Eur J Physiol (2008) 456:211–225.

[2] S. Salapaka and M. Salapaka, "A control Systems Perspective on Nanointerrogation," IEEE Control Systems Magazine, April 2008, pp.65-83.

[3] T. Ando, "Control Techniques in High-speed Atomic Force Microscopy," 2008 American Control Conference (ACC), Seattle, Washington, U.S.A., June 2008, pp. 3194-3200.

[4] S. Morita, H. Yamada, and T. Ando, "Japan AFM roadmap 2006," Nanotechnology, Vol. 18, January 2007, pp. 1-10.

[5] G. Schitter and M. Rost, "Scanning probe microscopy at video-rate," Materialstoday, Microscopy Special issue, Elsevier 2008, pp. 40-48.

[6] http://www.wikipedia.com

[7] F. Abu-Nimeh and F. Salem, "Cmos integrated electro-magnetic force actuator," Circuits and Systems, 2006. MWSCAS '06. 49th IEEE International Midwest Symposium on, vol. 2, pp. 395 – 398, Jul 2006.