

# Fast contact-mode atomic force microscopy on biological specimen by model-based control

G. Schitter, R.W. Stark<sup>‡</sup>, A. Stemmer<sup>†</sup>

*Nanotechnology Group, Swiss Federal Institute of Technology,  
ETH Zentrum CLA, CH-8092 Zurich, Switzerland*

## Abstract:

The dynamic behaviour of the piezoelectric tube scanner limits the imaging rate in atomic force microscopy (AFM). In order to compensate for the lateral dynamics of the scanning piezo a model based open-loop controller is implemented into a commercial AFM system. Additionally, our new control strategy employing a model-based two-degrees-of-freedom controller improves the performance in the vertical direction, which is important for high-speed topographical imaging. The combination of both controllers in lateral and vertical direction compensates the three-dimensional dynamics of the AFM system and reduces artifacts that are induced by the systems dynamic behaviour at high scan rates. We demonstrate this improvement by comparing the performance of the model-based controlled AFM to the uncompensated and standard PI-controlled system when imaging pUC 18 plasmid DNA in air as well as in a liquid environment.

## 1. Introduction

The atomic force microscope (AFM) [1] has become a very powerful tool to image the surface of nanoscale specimens and is used in semiconductor industry as well as in biological research. In order to avoid damage to the probing tip and/or the sample, imaging mostly is done by moving the sample (or tip) in a raster-scanning motion while the imaging force is held constant in a feedback operation (e.g. [1, 2]), which usually is performed by a proportional integral (PI) element (Fig. 1). To this end, an actuator with sub-nanometer resolution allowing for displacement in all three spatial directions is required, such as a tripod scanner [1], a piezoelectric tube scanner [3], or three independent piezoelectric actuators [4], two performing the scanning motion (X and Y directions) and one for the closed-loop of the tip-sample interaction (Z-direction).

A crucial issue in AFM development is to increase the imaging speed. To speed up the response of the probing tip one can use small cantilevers with very high resonance frequencies [5, 6] or reduce the quality factor

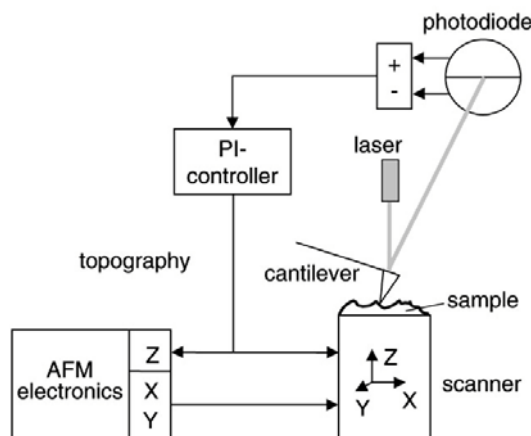


Figure 1: Schematic diagram of a standard PI-controlled AFM. Triangular scanning motion in X- and Y-direction and feedback operation in Z-direction for topographical compensation.

of the probe [7, 8]. However, every scanning probe system is limited in speed by the dynamic behavior of the moving parts. A very common solution to this problem is to increase the

<sup>‡</sup> present address: Ludwig-Maximilians-Universität München  
Dept. Geo- and Environmental Sciences, Section Crystallography  
Theresienstr. 41, 80333 München, Germany

<sup>†</sup> corresponding author: email address: stemmer@nano.mavt.ethz.ch  
phone: +41 1 632 4572, fax: +41 1 632 1278

resonance frequencies of the moving system by building the devices as small, light and stiff as possible (e.g. [6, 9]). Regarding the design of the AFM, little weight and stiffness compromise each other. Building small scanning devices limits the actuation range of the system, restricting imaging to a relatively narrow frame width [4].

For scanning larger samples the vertical bandwidth of the AFM has been increased by introducing additional high-frequency piezo segments to the probing tip [10-12] or to the piezo scanner [13, 14]. Due to the limited range of the fast Z-piezo, both actuators have to be used in a nested feedback loop to compensate the cantilever deflection [15] when scanning. The slow actuator operates the long range movements while the small but fast one performs the compensation of topographical details, which requires a higher control bandwidth at faster scanning. This solution necessitates the adjustment of two PI-loops influencing each other, which requires a lot of tuning experience from the AFM user. Furthermore the dynamic behavior of the AFM in the scanning direction is uncompensated and may be excited at higher scan rates (see e.g. [16]).

A third approach to improve the performance of the AFM is to consider the dynamic behavior of the system by utilizing modern model-based control methods. First efforts in this field have been done by applying open-loop methods [16, 17] or feedback control [18, 19] to speed up the scanning system, or by implementing a model-based feedback controller to increase the bandwidth of the AFM in Z-direction [20, 21].

This paper demonstrates the performance of a model-based controlled AFM system operated in

contact-mode to image biological specimens in air as well as in liquid. The lateral dynamics of the piezoelectric tube scanner is compensated by an open-loop controller [17] while the tip-sample interaction is held constant by a model-based two-degrees-of-freedom (2-DOF) controller. The 2-DOF controller consists of a model-based feedback controller [20] and a feedforward compensation that tracks the sample to the previously recorded scan-line in an open loop manner. Since usually two successive scan-lines are quite similar, the topography of the previous scan line can be taken as an estimate for the actual one and is used for feedforward compensation. Additionally, the model-based feedback controller increases the control-bandwidth of the AFM in the vertical direction.

## 2. Controller Description

To compensate the dynamic behavior of the scanning unit and improve the control performance of the AFM system in the vertical direction, mathematical models of the AFM dynamics in all three spatial directions are required. These models are obtained via system identification [22] which is a control engineering tool to calculate a mathematical model of a dynamical system from a set of measured input and output data. These models describe the system dynamics of the AFM given by the system resonances, low-pass characteristics and transmission zeros between the input of the AFM and the corresponding system output. The inputs are the voltage amplifiers of the piezoelectric tube scanner and the outputs are the positions in the X, Y and Z-directions. Based on these mathematical

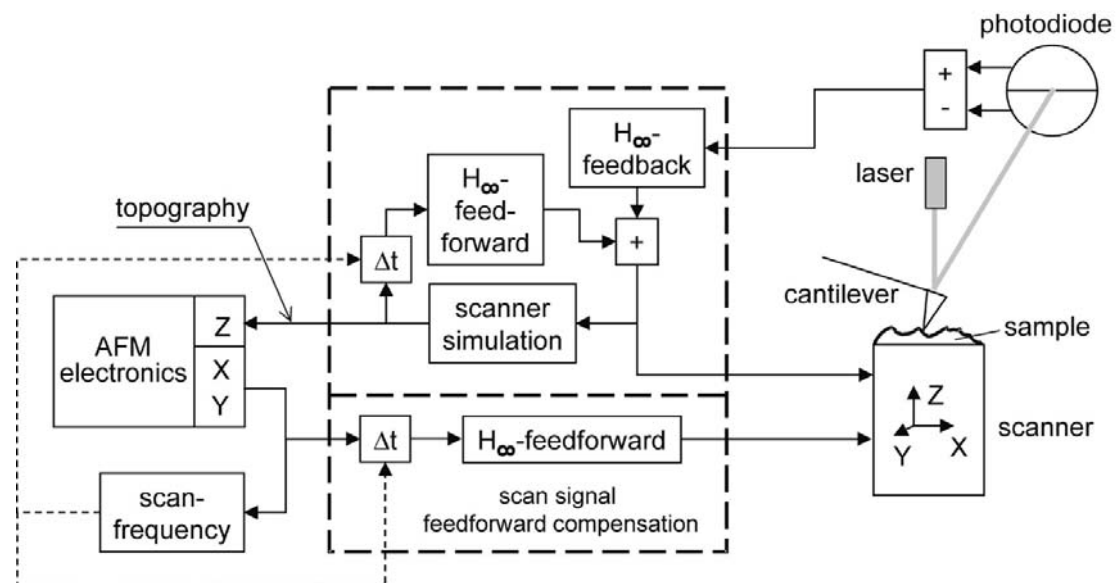


Figure 2: Schematic diagram of the model-based controlled AFM system. Open-loop compensation of the dynamic behavior in the scanning direction; model-based feedback and feedforward control in the Z-direction.

models the new controllers are designed utilizing modern model-based control methods [23]. These controllers consider the dynamic behaviour of the AFM system, improve the performance of the system by compensating the system dynamics, and can be designed to improve the robustness of the controlled system. Robustness is necessary to account e.g. for varying sample masses.

To compensate the dynamic behavior in the scanning directions ( $X$  and  $Y$ ) we calculate model-based open-loop controllers that damp the mechanical resonances of the piezoelectric tube to suppress lateral oscillations (see Fig. 2). A detailed description of the identification and open-loop compensation of the lateral piezo dynamics can be found elsewhere [17].

A new control scheme is introduced to speed up the AFM system in the  $Z$ -direction (Fig. 2). We take advantage of the fact that normally two adjacent scan lines are quite similar. This is certainly true for smooth samples but also holds for rougher surfaces including those with steps along the fast scanning direction since the measured topography is smoothed due to the finite radius and cone angle of the tip. Therefore, the topography of the actual scan line can be taken as estimate of the next one. This estimated topography can be applied in  $Z$ -direction in advance and the feedback circuit only has to compensate small deviations to the actual topography. To this end, we delay the topography signal of the last recorded scan line by one period of the scanning motion and track the sample to this trajectory in a feedforward operation. This compensation improves the performance of the AFM, most notably when topographical steps or ramps perpendicular to the fast scan axis occur. Since the feedforward operation is based on the similarity between two consecutive scan-lines it can be distorted by noise. High-frequency noise is suppressed by a low-pass characteristic of the new controller. However, noise within the control bandwidth cannot be distinguished from topography. Thus, in the presence of noise, e.g. due to building vibrations, the feedforward compensation can be reduced by a simple gain-factor in order to avoid artifacts. Simultaneously to the feedforward compensation a model-based feedback controller [20] operates the AFM at a higher closed-loop bandwidth than the PI-controller does, also to reduce the residual control error. Both controllers can be designed separately and are combined in the implementation step to a 2-DOF controller. The identification of the AFM dynamics in  $Z$ -direction and the design and implementation of the 2-DOF controller is described in detail in ref. [21]. This new controller is calculated for the complete dynamics of the piezoelectric tube scanner, i.e. no further tuning is necessary.

The lateral compensation of the scanner dynamics and the new 2-DOF-controller are implemented on an external digital signal processor according to Fig. 2.

### 3. Sample Preparation

The plasmid DNA was prepared using a slightly modified standard protocol [24].

PUC18 Plasmid DNA from *Escherichia coli* RRI was used as purchased (Sigma Aldrich). The DNA was diluted in 10 mM Tris-HCl, pH 8.0, 1 mM EDTA, 10 mM  $MgCl_2$  to a final concentration of 10 ng/ $\mu$ l. A droplet of 4  $\mu$ l was placed onto a freshly cleaved mica surface. After 120 sec. the mica was carefully rinsed with about 1 ml of ultrapure water and the specimen was blown dry. For imaging in a liquid environment the sample was immersed in a droplet of 2-Propanol.

All experiments were carried out on a commercial AFM System (Multimode, Nanoscope IIIa, Veeco, Santa Barbara, CA). The specimens were imaged in contact mode using oxide sharpened silicon nitride cantilevers (Veeco, Santa Barbara, CA). For imaging in ambient conditions the standard cantilever holder and a lever of type "NP-S, 200 Wide" were used. Imaging in liquid was done in a hanging droplet configuration using the standard liquid cell and a "NP-S, 100 Narrow" cantilever.

### 4. Results and Discussion

For constant force imaging with the standard AFM system the PI-controller was tuned well for each experiment. To demonstrate the performance of our new AFM scanning biological samples at a high speed and to show the improvement we imaged pUC 18 plasmid DNA.

The images shown in Figure 3 compare our model-based controlled AFM system to the standard AFM and were imaged in air at a rate of 30.5 lines per second. At this speed images taken by the standard AFM [3(a) and (c)] are corrupted by position errors due to the lateral oscillations. The coupling between the scanning direction and the vertical direction leads to an apparent corrugation of the sample topography as observed in Fig. 3(a) and an additional control error occurs [Fig. 3(c)]. In case of the model-based controlled AFM [Fig. 3(b) and (d)] the imaging artifacts due to the lateral piezo oscillations vanish. Furthermore, the residual control error given by the cantilever deflection is reduced by the 2-DOF-controller operating the AFM in the vertical direction.

Figure 4 shows the plasmid DNA imaged in 2-propanol at a scan rate of 30.5 Hz by the PI controlled AFM and the model based controlled system, respectively. We assume that due to the better damping of the cantilever's torsional

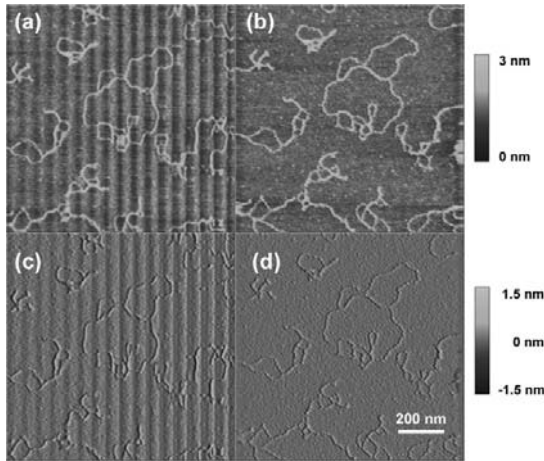


Figure 3: *pUC 18 plasmid DNA imaged in air at 30.5 Hz line scan rate by the standard AFM system [(a) and (c)] and by the model-based controlled AFM [(b) and (d)]. Topography: panel (a) and (b); control error: panel (c) and (d).*

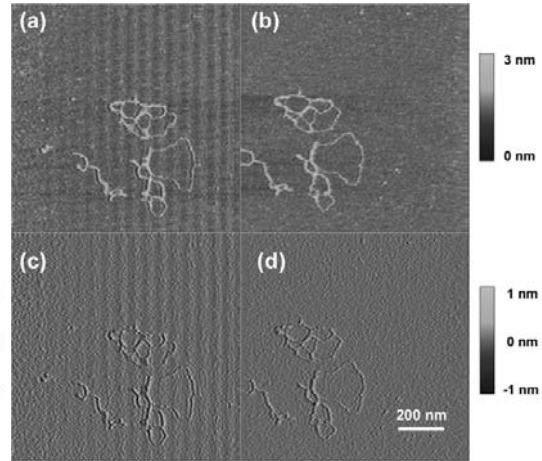


Figure 4: *pUC 18 plasmid DNA imaged in 2-propanol at 30.5 Hz line scan rate by the standard AFM system [(a) and (c)] and by the model-based controlled AFM [(b) and (d)]. Topography: panel (a) and (b); control error: panel (c) and (d).*

dynamics in liquid the artifacts stemming from the coupling between the scanning direction and the Z-direction are not as pronounced as in air, but they are still present when imaging with the standard AFM [Fig 4(a) and (c)]. In case of the model-based controlled AFM system [Fig. 4(b) and (d)] the image quality again is improved and the artifacts and disturbances vanish.

By increasing the scanning rate further, the artifacts and distortions are even more pronounced in case of the standard AFM system, whereas operating the AFM by the new model-based controller still results in images of a good quality. Imaging of DNA was achieved at up to 61 Hz line scan rate in air as well as in the liquid environment (data not shown). Although the AFM modeling and controller design were done for measurements in air, the robustness of the new controller is sufficient to allow for fast imaging in liquid.

## 5. Conclusion

We demonstrate the benefits of a model-based controlled AFM to image fragile specimens such as biological macromolecules at a fast scanning speed. By compensating the lateral dynamics of the scanning unit, topographical artifacts and deformation of the imaged sample caused by the lateral positioning error are minimized.

By operating the AFM in the vertical direction by a model-based two-degrees-of-freedom controller, the control error given by the cantilever deflection is reduced preventing damage to the sample. Operating the AFM by this model-based controller in all spatial directions fast imaging in air as well as in a liquid environment was achieved.

Although the presented results were obtained in contact mode, we expect that a model-based controller also reduces the error and artifacts in tapping mode AFM. The compensation of the lateral scanner dynamics is independent of the measurement mode. In tapping mode imaging a feedforward compensation in the vertical direction is also expected to reduce the residual error.

To further improve the speed in the vertical direction, future implementations might include a multi-input-multi-output (MIMO) controller with multiple actuators in the Z-direction (e.g. [13]). There, a model-based two-degrees-of-freedom controller will provide further reduction of the imaging error due to a higher bandwidth of the vertical positioning system. In addition, such a controller would no longer require to tune two competing PI-loops as present-day multiple actuator systems do.

## References

1. G. Binnig, C.F. Quate, C. Gerber, *Physical Review Letters* 56 (1986) 930.
2. P.K. Hansma, V.B. Elings, O. Marti, C.E. Bracker, *Science* 242 (1988) 209.
3. G. Binnig, D.P.E. Smith, *Review of Scientific Instruments* 57 (1986) 1688.
4. T. Ando, N. Kodera, E. Takai, D. Maruyama, K. Saito, A. Toda, *Proceedings of the National Academy of Sciences of the United States of America* 98 (2001) 12468.
5. M.B. Viani, T.E. Schäffer, G.T. Paloczi, L.I. Pietrasanta, B.L. Smith, J.B. Thompson, M. Richter, M. Rief, H.E. Gaub, K.W. Plaxco, A.N. Cleland, H.G. Hansma, P.K. Hansma, *Review of Scientific Instruments* 70 (1999) 4300.
6. T. Ando, N. Kodera, D. Maruyama, E. Takai, K. Saito, A. Toda, *Japanese Journal of Applied Physics* 41 (2002) 4851.
7. J. Mertz, O. Marti, J. Mlynek, *Applied Physics Letters* 62 (1993) 2344.
8. M. Antognozzi, M.D. Szczelkun, A.D.L. Humphris, M.J. Miles, *Applied Physics Letters* 82 (2003) 2761.
9. D.W. Pohl, *IBM Journal of Research and Development* 30 (1986) 417.
10. S.R. Manalis, S.C. Minne, C.F. Quate, *Applied Physics Letters* 68 (1996) 871.
11. A. Egawa, N. Chiba, K. Homma, K. Chinone, H. Muramatsu, *Journal of Microscopy* 194 (1999) 325.
12. R.V. Lapshin, O.V. Obyedkov, *Review of Scientific Instruments* 64 (1993) 2883.
13. D. Knebel, M. Amrein, K. Voigt, R. Reichelt, *Scanning* 19 (1997) 264.
14. H.J. Mamin, H. Birk, P. Wimmer, D. Rugar, *Journal of Applied Physics* 75 (1994) 161.
15. T. Sulchek, S.C. Minne, J.D. Adams, D.A. Fletcher, A. Atalar, C.F. Quate, *Applied Physics Letters* 75 (1999) 1637.
16. D. Croft, S. Stilson, S. Devasia, *Nanotechnology* 10 (1999) 201.
17. G. Schitter, A. Stemmer, *IEEE Transactions on Control Systems Technology* (2003) in press.
18. N. Tamer, M. Dahleh, in *Proc. of 33rd IEEE Conference on Decision and Control*, Lake Buena Vista, FL, USA, vol. 2, (1994) 1826.
19. A. Daniele, S. Salapaka, M.V. Salapaka, M. Dahleh, in *Proc. of the 1999 American Control Conference*, San Diego, CA, USA, vol. 1, (1999) 253.
20. G. Schitter, P. Menold, H.F. Knapp, F. Allgöwer, A. Stemmer, *Review of Scientific Instruments* 72 (2001) 3320.
21. G. Schitter, A. Stemmer, F. Allgöwer, in *Proc. of the 2003 American Control Conference*, Denver, CO, USA, vol. 5, (2003) 3720.
22. L. Ljung, *System Identification, Theory for the User*, 2nd Ed. PTR Prentice Hall Information and System Sciences Series, ed. Kailath T., Prentice Hall PTR, Upper Saddle River, NJ, 1999.
23. S. Skogestad, I. Postlethwaite, *Multivariable Feedback Control*, John Wiley & Sons, Chichester, 1996.
24. H.G. Hansma, D.E. Laney, M. Bezanilla, R.L. Sinsheimer, P.K. Hansma, *Biophysical Journal* 68 (1995) 1672.