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On recent developments for high-speed atomic force microscopy

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Abstract— **The atomic force microscope (AFM) is limited in imaging speed by the bandwidth and dynamic behavior of the actuators and mechanical parts. For high-speed imaging all AFM components have to be optimized in performance. Here, we present improvements of the force sensor, the scanner, the controller, and the data acquisition system. By combining all these improvements, the next generation AFMs will enable imaging speeds more than two orders of magnitude faster than current commercial AFM systems.**

I. Introduction

THE atomic force microscope (AFM) [1] has become the most important tool to image and operate on the scale of a few nanometers. However, imaging is slow with the AFM and is still limited to quasi-static processes, since current AFM systems take from tens of seconds to several minutes to acquire a single frame. The imaging speed is limited by the dynamic behavior of the main AFM components, i.e. the force sensor [2], the three-dimensional-positioner (scanner) [3], and the feedback-bandwidth to track the cantilever deflection (e.g. [4]). Some work has been done to speed up the response time of the force sensor in tapping mode imaging by using small cantilevers [5][6] or tuning down the quality factor of the oscillating cantilever [7]. A common approach to increase the speed of the scanning system is to build the scanner as small, light and stiff as possible [6][8], but building a small scanner usually limits the actuation range of the positioner, restricting AFM imaging to a relative narrow frame width [6]. The bandwidth in the vertical direction (Z) has been increased by introducing additional fast actuators to the probe [9][10] or the sample [11][12]. The two actuators in Z then have to be operated in a nested feedback loop. The slow actuator operates the long range movements, while the small but fast one compensates the small topographical details, which requires a higher feedback bandwidth. Further improvements in speeding up the AFM have been made by

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utilizing modern control methods. First efforts in this field have been done by implementing open-loop methods [3][13] or feedback controllers [14-16] for the scanning motion, or by utilizing model-based feedback to increase the closed-loop bandwidth in the Z-direction[4][17].

In this paper we discuss some key challenges for the next generation of high-speed AFMs. This communication reviews some of our achievements in the past and presents the most recent developments for fast AFM imaging. By combining all these improvements in one instrument, we expect to achieve imaging speeds more than two orders of magnitude faster than commercial AFM systems.

The manuscript is organized as follows. Section II deals with small cantilevers as improved force sensors for high-speed imaging. In Section III we review control engineering methods to improve the tracking accuracy of the scanning unit and the feedback controller for measuring the sample topography. In Section IV we discuss the mechanical design of the scanner. A synchronized generation of the scanning signals and data recording can be used for high-speed data acquisition (DAQ) [18], as discussed in Section V of the manuscript.

II. Small Cantilevers

For the closed-loop operation in the vertical direction, the speed of the error signal generation is crucial. Using small cantilevers the response time of the tapping force sensor can be reduced [5][19]. Small cantilevers have two main advantages (cf. Fig. 4 in Viani *et al.* [5]). If one designs the downscaled force sensor for the same spring constant *k*, which is necessary for gentle imaging of fragile biological specimen, small cantilevers are a factor of 1000 smaller in mass *m* than commercial cantilevers [19]. The reduction of mass by a factor of 1000 gives an increase in the cantilever resonance frequency f_0

$$f_0 = \sqrt{\frac{k}{m}} \approx 30 \,, \qquad (1)$$

by a factor of about 30. Thus also the thermal noise of the cantilever *kT* is spread out over a factor 30 wider frequency range, which brings the noise per root Hz down by $\sqrt{30} \approx 5$ [19].

III. MODEL-BASED CONTROL

In order to raster-scan the image area at a constant tip-velocity, usually triangular scanning signals are applied to the X- and Y-directions (lateral) of the AFM scanner. When the fundamental frequency of the triangular scanning signal is larger than about one percent of the lateral resonance frequency of the scanner, the scanning signals start to excite the dynamics of the scanning unit [3]. These oscillations of the scanning unit are then superimposed on the desired constant velocity motion, which affects the tracking accuracy of the scanner. The coupling between the scanner's lateral and vertical axes of motion together with the superimposed lateral oscillations cause several imaging artifacts (see Fig. 1(d-f)). By implementing a model-based open-loop controller that pre-shapes the scanning signals [13], the lateral oscillations of the scanner can be suppressed and the imaging artifacts vanish. Figure 1 shows a comparison of a piezoelectric tube scanner (J-scanner, MultiMode-AFM, Veeco, Santa Barabara, USA) at 61 Hz line scan rate uncompensated (images d-f) and with the open-loop controller to suppress the scanner dynamics (images g-i). The improvement in the tracking accuracy and the reduction of the imaging artifacts can be seen clearly.

To improve the performance of the AFM in the vertical direction one can make use of the fact that typically two adjacent scan-lines are similar. Therefore, one can implement a two-degrees-of-freedom (2DOF) controller [17] as shown as block diagram in Figure 2. A model-based $H_\infty-$

Fig. 2. Block diagram of the model-based controlled AFM. The elements in the dashed block represent the controllers for the three positioning axes. The "Signal conditioning" block is to convert the control action to the topography signal and to generate the target trajectory for the feedforward compensation of the last scan line (cf. [17]).

feedback controller operates the piezo at a higher feedback bandwidth, while simultaneously a model-based feedforward compensator tracks the sample to the topography of the last recorded scan line. The feedback controller then only has to compensate the differences between the last and the actual scan line. Figure 3 shows a comparison of the control error between a well-tuned standard PI-feedback and a model-based 2DOF controller when imaging a 530-nm silicon calibration grating at an imaging speed of 10 lines per second. From Fig. 3(b and d) it can be seen clearly that the control error is much smaller in case of the 2DOF controlled AFM when compared to the PI-controlled system (images a and c). By reducing the control error, given by the cantilever deflection, the AFM can be operated closer to the minimal force point, and therefore not only the variations of the
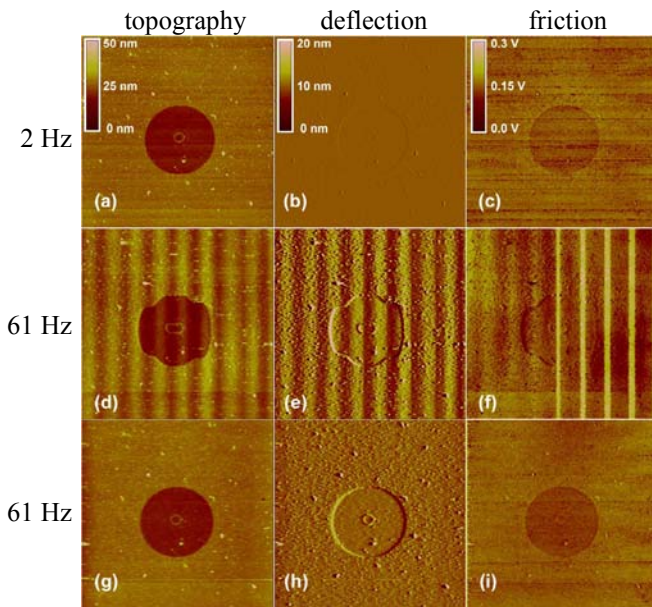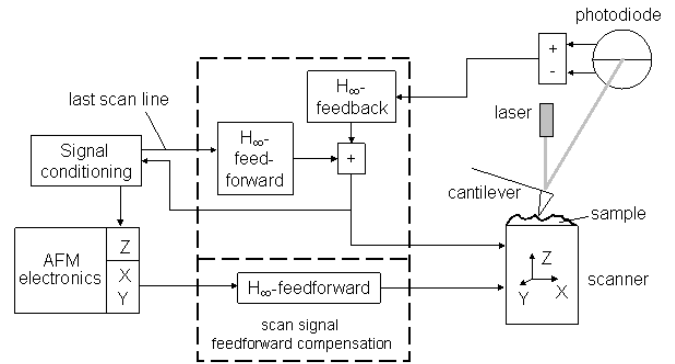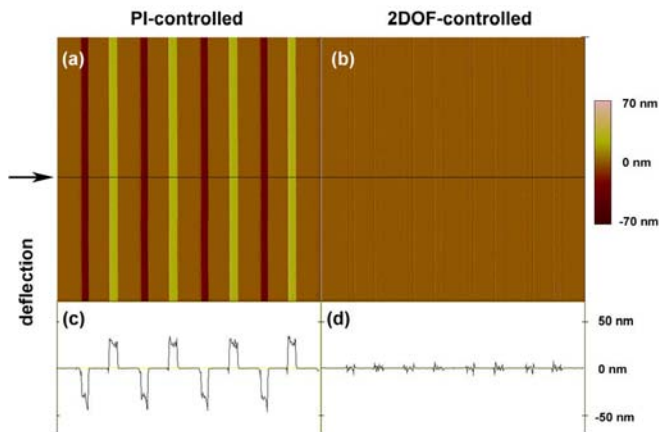

Fig. 1. Tracking accuracy of the uncompensated piezoelectric tube scanner and the open-loop controlled piezo tube. (a-c) reference scan at 2 lines per second uncompensated, (d-f) 61 lines per second uncompensated, (g-i) 61 lines per second open loop controlled [13].
The specimen is a silica-bead projection pattern; image are recorded from right to left and measure 13.5 μm in width.

Fig. 3. Comparison of the control error between a well tuned PI feedback controller and the model-based 2DOF-controller imaged at 10 lines per second. Images are recorded from right to left and measure 15 μm in width. The 2DOF controller reduces the cantilever deflection substantially [17].

imaging force is reduced but also the average imaging force gets minimized, which prevents damage to the probe and/or the sample.

IV. MECHANICAL SCANNER DESIGN

To improve the performance of the scanning unit a new scanner design has been developed. This design is based on stack-piezos with flexure springs (patent pending). This scanner is designed to be compact and rigid [20] to shift the resonance frequencies in all positioning directions as high as possible. The key element herein is, to keep the mechanical paths as short as possible, in order to avoid levered oscillations of the scanning unit. By using stack piezos and flexures for each positioning axis, the crosstalk between the axes of motion can also be minimized. This minimized crosstalk furthermore reduces some imaging artifacts during scanning and leads to more accurate topographical data of the imaged surface.

During the design process this scanner has been optimized by simulating its dynamic behavior with commercial finite element analysis software (ANSYS, Inc, Canonsburg, USA). The predicted first resonances of the new scanning unit are at 27 kHz in the lateral directions and 33 kHz in the vertical directions, which is a factor of about 27 and 4 higher than the J-scanner used for the measurements shown in Figures 1 and 3.
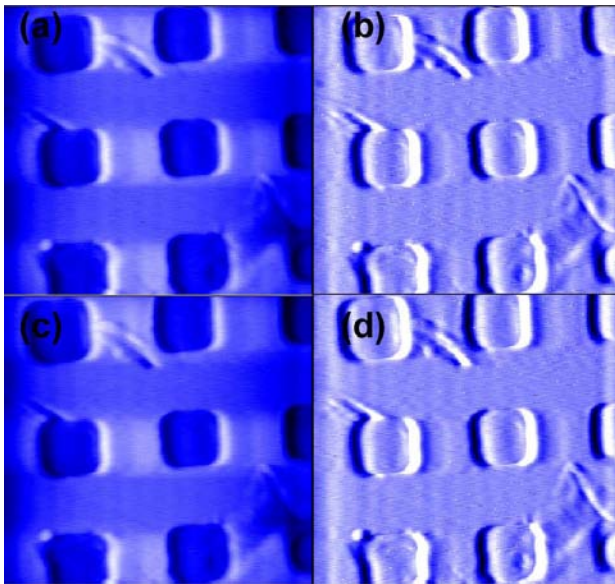

Fig. 4. Two consecutive images taken at a line scan rate of 2048 lines per second at a resolution of 256 x 256 pixels, i.e. 8 images per second. The sample is a silicon calibration grating with a pitch of 3 microns, the height of the topographical steps in the grating is 44 nm. The width of the frames is about 8 μm; topography images: (a) and (c); deflection images: (b) and (d).

Two consecutive images taken with the new scanner at 8 frames per second and at a resolution of 256 pixels by 256 lines are shown in Figure 4. This frame rate corresponds to a line scan rate of more than 2000 lines per second. The images presented are acquired in contact mode with an analogue PI-feedback controller. For generation of the scanning signals and recording the data the DAQ system [18] discussed in Section V was used. The scanning signal in the fast scan axis (X) was modified in order to pre-compensate the hysteresis of the piezo actuators by adding a sinusoidal signal to the triangular scanning signal. In order to align the up and down frames during imaging the piezo hysteresis and creep in this positioning direction were compensated by closed-loop operation of the slow scan axis (Y). For faster control in the vertical direction, at this high bandwidths and imaging rates a more sophisticated feedback controller (such as presented in Section III) would have to be implemented on a field-programmable-gate-array (FPGA), since standard digital signal processors (DSP) are not able to handle the amount of data and to operate the AFM system in real-time at the sampling rate required.

V. DAQ-SYSTEM

One way to reduce the data that has to be handled by the DAQ-system is to make use of the fact that the scanning motion is known in advance. Therefore a synchronization between the generation of the scanning signals and the recording of the topographical data, i.e. the output of the feedback controller in the Z-direction and the cantilever deflection, can be used to record the data triple (X,Y,Z) for displaying the images [18]. Another aspect one has to consider in high-speed imaging is the phase delay due to the system dynamics of the electro-mechanical system of the scanning unit. But since this delay is an intrinsic property of the AFM system it can be predicted easily and the recording of the data can be done to this shifted data triple. By applying this type of synchronization, which has been done to record the images shown in Figure 4, the imaging speed of the AFM is no longer limited by the data acquisition system [18].

VI. CONCLUSION

In this article we propose new designs and concepts for the main components of the atomic force microscope. Small cantilevers can be used for better noise performance and a faster response of the force sensor. Modern control methods are used to suppress the dynamic behavior of the AFM system and to improve the bandwidth of the positioning unit in all three spatial directions. A new scanner design that is based on stack-piezos and flexures improves the performance of the scanning unit substantially. A new fast

data acquisition system that synchronizes the generation of the scanning motion with the data recording removes the limitations due to the AFM electronics. This new AFM system is capable of imaging up to about 2000 lines per second and will be improved further by implementing modern control methods. This will improve the image quality further and minimize the imaging forces, which is important for imaging of biological samples. This system will be able to operate at frame rates that are faster than the Scanning Electron Microscope (SEM) without the restriction to image in vacuum and will be used for imaging of chemical and biological processes in real-time.

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