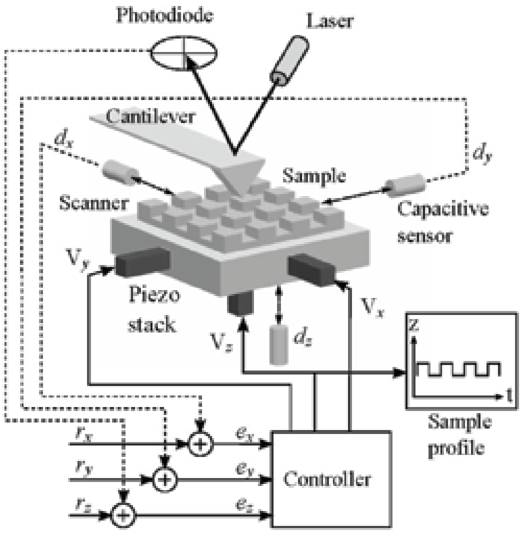
Control Challenges in High-Speed Atomic Force Microscopy

The atomic force microscope (AFM) is one of the most versatile methods of imaging structures at nanometer scale. Its ability to operate in a non-vacuum environment gives the AFM a significant advantage over competing microscopy methods such as the transmission electron microscope (TEM), the scanning tunneling microscope (STM), and the scanning electron microscope (SEM). Consequently, the AFM has brought about significant progress in a multitude of scientific fields ranging from nanotechnology to life sciences and medicine.

Furthermore, being a "mechanical microscope," the AFM can be used to manipulate matter at nanometer scale as well. Thus, it has emerged as the driving technology in nanomanipulation and nanoassembly and has generated much excitement in nanorobotics.

The AFM's ability to image and manipulate matter at the nanometer scale is entirely dependent on the use of feedback loops. Thus, there are numerous opportunities and a significant need to apply advanced feedback control methods, especially for high-speed AFM.



The figure to the left is a schematic representation of a modern AFM, with a nanopositioning stage and multivariable feedback control. Each axis is driven by a piezoelectric stack actuator. Capacitive displacement sensors measure the scanner's position in three dimensions. The sample topography is measured directly by the interferometer in the vertical direction. In early AFMs, the scanners operated in an open loop. Today, most commercial AFMs are instrumented with displacement sensors, allowing for feedback; however, the feedback controllers used are rudimentary.

The Atomic Force Microscope

When used for imaging, the purpose of an AFM is to characterize a sample by bringing a sharp probe very close to the sample surface and then moving it, relative to the sample, in a raster pattern. This movement is achieved using a nanopositioner such as a piezoelectric tube scanner or a piezoelectrically driven flexure-guided stage.

The probe tip is affected by the forces on the surface, some of which are attractive and some repulsive. These forces cause a deflection of the micro-cantilever on which the tip resides. This deflection is detected using a laser beam that is bounced off the cantilever and back onto a photodetector.

The AFM can be used in various operating modes, broadly classified as "static" or "dynamic." In the static mode, the probe is dragged on the sample surface and a constant force is maintained by the z-axis controller, a PI controller in almost all commercial AFMs. In dynamic modes, the micro-cantilever is oscillated sinusoidally at or close to its resonance frequency, and variations in its oscillations due to the interactions with the sample are monitored to infer sample properties.

The Need for High-Speed AFM

Conventional AFMs are slow, operating at scan frequencies of several Hertz. Consequently, it can take the microscope several minutes to develop an image. Distortion in the AFM image can occur if the surface features being interrogated change rapidly compared to the AFM's operating speed. The image distortion occurs because the measurements at the initial and final pixels of an image are taken at significantly different time instants. Thus, a high-speed AFM is needed to minimize image distortions when the surface or the process being studied, manipulated, or controlled has fast dynamics. For example, AFM imaging of living cells currently takes in excess of 1 minute per image frame. This is clearly too slow to investigate biological processes that occur in seconds. Significant challenges are associated with operating an AFM at high speeds, most of which lead back to feedback control problems.

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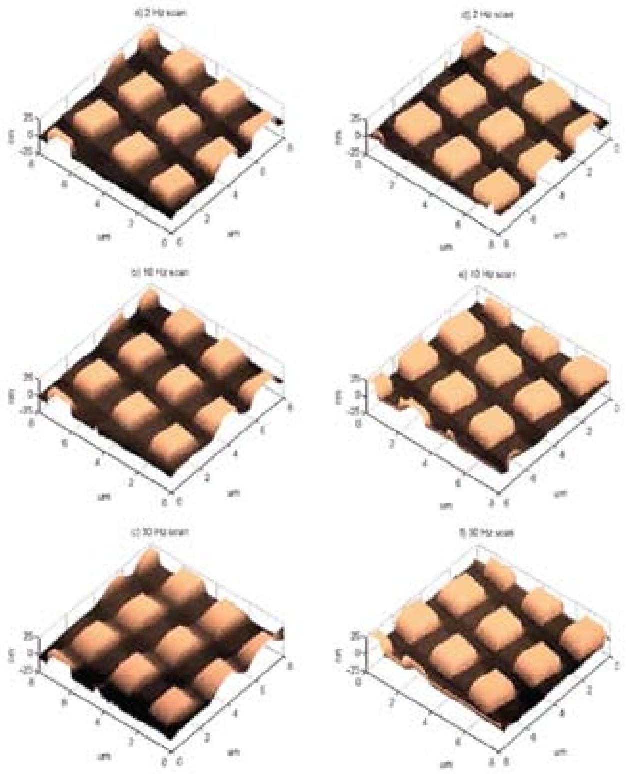
Control Challenges... and Opportunities!

Advanced control is a key technology for high-speed atomic force microscopy, but control designs will need to address several challenges:

- AFM scanners are highly resonant systems. Control design must be informed by properties and parameters of the resonance modes.
- The performance of piezoelectric actuators can degrade over time. Furthermore, they are prone to hysteresis and creep effects. Control designs must be robust to such changes.
- High-bandwidth control is required for positioning accuracy in the AFM scanner. Sensor noise complicates controller realization.
- For high-speed AFM in particular, optimal non-raster-scan methods will be required. Such methods will require further advances in control design.
- The AFM scanner is a multivariable system. Significant cross-couplings exist that cannot be adequately managed with today's PID controllers.
- The vertical axis control loop is especially nonlinear. Conventional linear control methods are inadequate.
- The AFM microcantilever is a highly resonant system, but when operated in a fluid environment, it is prone to significant damping. Feedback can be used to mitigate this problem.

Images of a calibration grating developed on a commercial AFM are shown below. The features are 3 mm apart and have a height of 20 nm. Images (a)-(c) were developed using the AFM's standard control loops at scan frequencies of 2 Hz, 10 Hz, and 30 Hz, respectively; (d)-(f) were developed with an advanced controller that combines positive position feedback to flatten the frequency response of the scanner together with integral action to improve tracking. Both sets of experiments were conducted at the same scan frequencies and under similar conditions.



As illustrated below, significant improvement in tracking can be achieved by using a properly chosen non-raster-scan method. If a scanner is required to follow a cycloid-like trajectory, its lateral and transversal axes must track sinusoidal signals. This is a far less stringent requirement on the controller than tracking triangular signals, as needed in a conventional raster-scanned AFM. An alternative non-raster-scan method is based on the spiral of Archimedes. Control problems associated with closed-loop implementations of both methods are exciting and challenging.