A Computer-Controlled Classroom Model of an Atomic Force Microscope

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* In memoriam

The concept of "seeing by feeling" as a way to circumvent limitations on sight is universal on the macroscopic scale—reading Braille, feeling one's way around a dark room, etc. The development of the atomic force microscope (AFM) in 1986 extended this concept to imaging in the nanoscale. While there are classroom demonstrations that use a tactile probe to map the topography or some other property of a sample,[1-3] the rastering of the probe over the sample is manually controlled, which is both tedious and potentially inaccurate. Other groups have used simulation or tele-operation of an AFM probe.[4,5] In this paper we describe a teaching AFM with complete computer control to map out topographic and magnetic properties of a "crystal" consisting of two-dimensional arrays of spherical marble "atoms." Our AFM is well suited for lessons on the "Big Ideas of Nanoscale" such as tools and instrumentation,[6] as well as a pre-teaching activity for groups with remote access AFM[7] or mobile AFM.[8] The principle of operation of our classroom AFM is the same as that of a real AFM, excepting the nature of the force between sample and probe.

The classroom AFM is shown in Fig. 1. In the first iteration of our design, the scanning device was a salvaged XY plotter for use in tracing curves, and we note that this may be a good option for someone with a very limited budget. However, we later replaced the XY plotter with a new, inexpensive translation table designed for a CO_2 laser engraver (300 x 200 mm table by WaveDynamic), which provided an advantage in terms of robustness, serviceability, and reproducibility of the design. The new translation table, driven by stepper motors, is also much smoother and more precise than the old XY plotter, and is easily mounted on top of an attractive metal enclosure (Item #SC151504NK, AutomationDirect), which both conceals the electronics and forms the sample stage.

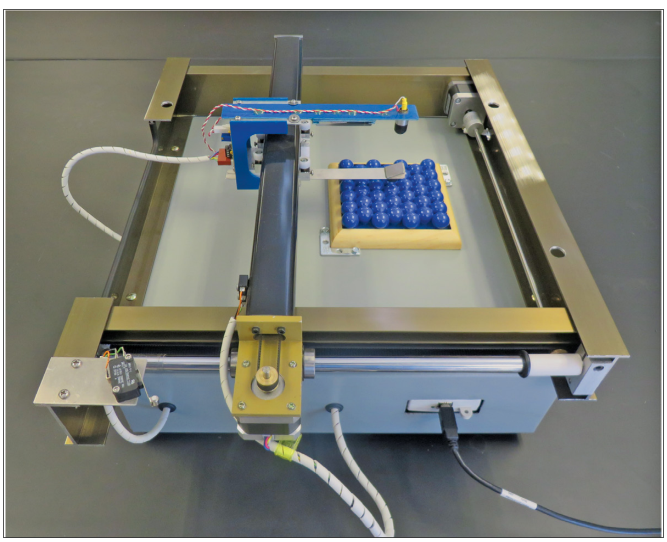

Fig. 1. Photograph of the classroom AFM. The black USB cable in the foreground is attached to the NI USB-6008 controller, seen through a rectangular window cut in the electronics box. All computer communications go through this cable. On the back of the electronics box (not shown), there is a switched & fused connector to 110-VAC power. The marble array is held in place via metal cleats on the microscope stage and can be changed out in seconds, as can the cantilever, shown hovering over the array.

The AFM probe head, shown schematically in Fig. 2, is constructed largely from printed circuit board stock and mounted to the movable part of the translation table. Modern AFMs achieve topography measurements by reflecting a laser beam (in our instrument, a 635-nm diode laser obtained from a laser pointer) off the mirrored surface of the probe cantilever (in our case, a strip of 1/32-in aluminum sheeting), striking a position-sensitive photodiode sensor. Deflections of the cantilever due to probe-surface interactions translate to laser deflection on the photodiodes. Our microscope uses a single photodiode (FDS1010, Thorlabs, Inc.) as a sensor. Position-sensitivity is achieved via insertion of a linearly varying neutral density filter (NDL-10C-2, Thorlabs, Inc.) between the mirror and the photodiode; deflection of the laser then results in a change in the voltage produced by the photodiode. The probe tip is made of either a rounded plastic dowel for measuring topography or a small rare-earth magnet for measuring magnetic force.

The only home-built electronics in our design is an amplifier circuit to increase the voltage signal produced by the

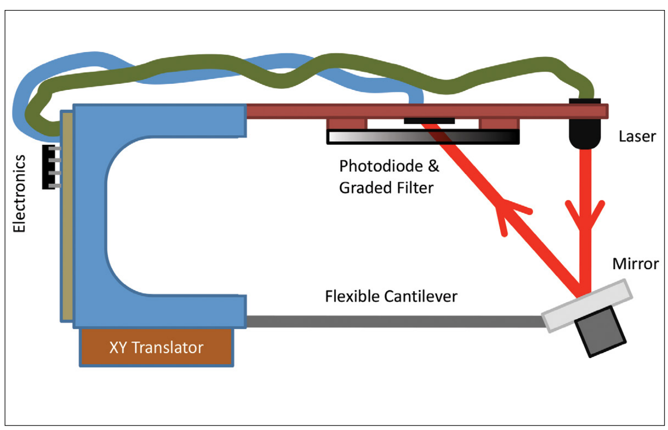

Fig. 2. Schematic drawing of the probe head. The laser beam strikes the mirror and is reflected to the photodiode. Bending of the cantilever due to sample topography or magnetic force causes a change in the angle of the mirror and the reflected laser beam. The light intensity at the photodiode is thus made stronger or weaker, due to the presence of the graded filter.

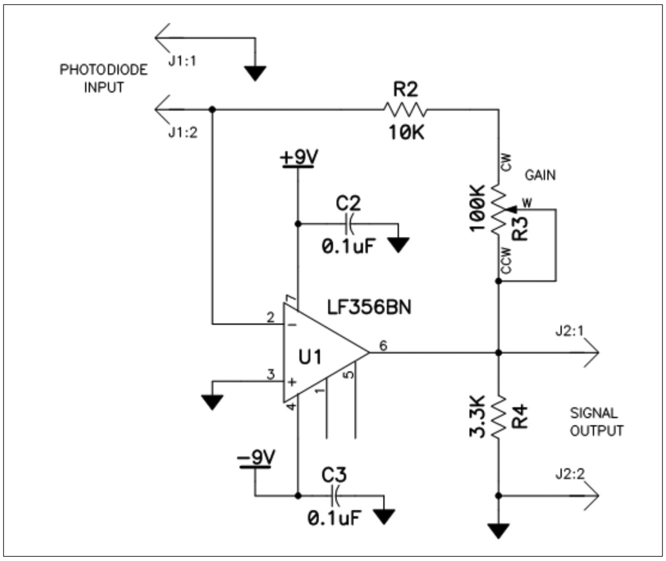

Fig. 3. Schematic of the amplifier circuit that increases the strength of the photodiode signal.

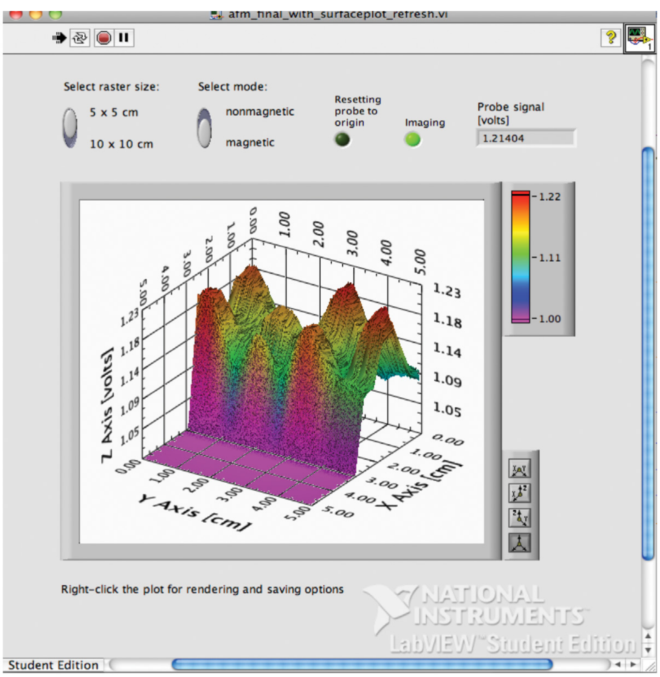

Fig. 4. Graphical user interface for the LabVIEW program that runs the AFM. Users can toggle between standard plot projections and manipulate the plot in a separate window. The "action shot" shown here was captured when the imaging process was about half finished. The flat pink part of the plot indicates the extent of the marble array remaining to be imaged. About four minutes is required to complete the 5 x 5 cm scan shown above, using 4-mm resolution.

photodiode sensor, shown schematically in Fig. 3. This is mounted on the back of the probe head, with a power/data cable leading into the electronics enclosure. The amplifier circuit is powered using a salvaged PC power supply, easily obtained at low or no cost. A 3.3-V source on the same power supply provides the laser power. Both amplifier and laser circuits can be powered on and off by means of a switch on the electronics enclosure.

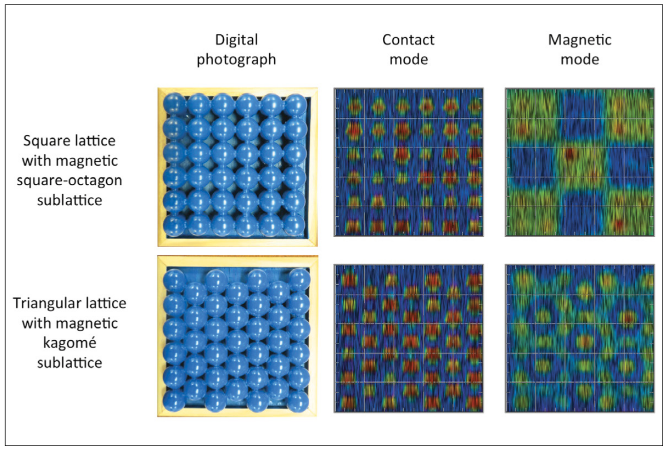

Fig. 5. Marble arrays and 2-D projections of AFM images obtained from the arrays. Top row left to right: photograph of square lattice, AFM image of square lattice in contact/nonmagnetic mode, AFM image of square lattice in magnetic mode. Bottom row left to right: photograph of triangular lattice, AFM image of triangular lattice in contact/nonmagnetic mode, AFM image of triangular lattice in magnetic mode. The red color in the nonmagnetic images represents a large upward deflection of the cantilever, while blue represents a small upward deflection or no deflection. In magnetic mode, yellow and blue represent downward and upward deflections, respectively. Both arrays measure 10 x 10 cm. About 15 minutes is required to complete a single 10 x 10 cm scan, with 4-mm resolution. This resolution corresponds to 17.4 data points per marble for the square lattice and 16.0 data points per marble for the triangular lattice.

The computer interface (NI USB-6008, National Instruments) outputs digital signals to the two stepper motor drivers (DM422, Leadshine) to control the position of the cantilever on the XY table, and measures an analog voltage corresponding to the signal from the probe. The interface is controlled via a program written in LabVIEW 2012, available upon request. The program is both easy to run (via a graphical user interface shown in Fig. 4) and fun to watch, as a 3-D surface plot is built and updated in real time.

"Crystal" samples were constructed by gluing magnetic marbles (Item #3037623, Edmund Scientific) on plywood substrates. The magnetic dipole moments of the marbles are oriented vertically, and it is impossible to tell if a given marble is "spin-up" or "spin-down" by simply looking at the array, or by imaging it in contact/nonmagnetic mode. Imaging these arrays in magnetic mode, however, captures the spirit of a real AFM measurement—the instrument is needed to see patterns of magnetic force that students cannot otherwise see. In one sample, the marbles form a triangular lattice but with a built-in magnetic Kagomé sublattice. In another sample, the marbles form a square lattice, but with a built-in magnetic square-octagon sublattice. The two available modes (contact/nonmagnetic and magnetic) serve to hint at the great diversity of probe-based microscopy techniques in use today.[9] A simple quick-release mechanism allows the magnetic cantilever and the nonmagnetic one to be switched out in a matter of seconds, making it possible to image multiple samples in multiple modes, all within the time constraints of a typical class.

Sample images obtained with the AFM are shown in Fig. 5. The contact/nonmagnetic images clearly reproduce the structure of the marble arrays, demonstrating correct function of the AFM. The magnetic images are more interesting. In the triangular array, lattice sites that are not part of the magnetic Kagomé sublattice have a blue circle around them, indicating a region of repulsive force. In the square array, the magnetic square-octagon sublattice manifests as a "checkerboard" of attractive and repulsive magnetic domains. As with a real AFM, imaging is sensitive to the laser-cantilever-photodiode alignment, ambient light and vibrations, and other factors. We also observe a linear systematic slope that is present for all the images, but tends to diminish when the instrument is warmed up. In spite of these limitations, we find the marble array images are sufficiently reproducible for purposes of classroom instruction.

The design and sophistication of our AFM could be improved in several ways; some of these improvements could be made in the classroom after students have become familiar with the operating principles of the instrument. For instance, we have not attempted to make a numerical correlation between photodiode signal and actual height. This would involve a geometric analysis of deflections and angles, as well as an introduction to optical density theory. Data processing techniques could also be used to remove the background slope and obtain higher quality images. More user options such as scan rate, resolution, and sample size could be added to the LabVIEW program. To take full advantage of these additional user options, we suggest that the cost-effective NI USB-6008 interface be upgraded to a device with an onboard timer. Much faster scan rates could then be achieved. Currently, the maximum scan rate is about 0.3 cm/s because the digital pulse trains that control the stepper motors are frequency-limited by a software timer. "Pointier" cantilever tips could be fabricated to further improve the resolution. This would help distinguish between atoms (marbles) of different size, as in a NaCl crystal. Finally, we suggest that other imaging functionality, such as thermal and acoustic modes, could be added to the classroom AFM.

Acknowledgments

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