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An Educational Model of an Atomic Force Microscope

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ABSTRACT

We have constructed an operational, educational model of an atomic force microscope which employs and highlights the fundamental concepts and principles involved in nanoscale microscopy. The probe, which holds the laser source and the cantilever tip, is mounted on a carriage which moves in the horizontal x-y plane. The translation in the x-direction is obtained using a screw system, while y-direction movement is governed by two sets of rack and pinion gear systems. Off-the-shelf optical rotary encoders provide horizontal position transduction while vertical deflection of the cantilever tip on the sample surface is achieved by a pen-laser-based dual photodetector system. The hardware and electronics required to build the entire device may be purchased for less than $1,000 making it ideal for K-12 teachers trying to demonstrate the fundamentals of nanoscience to their students. This project also includes an instruction manual for building the device which is available on the author's website.

Keywords: nanotechnology, atomic force microscopy, K-12 education, design

I. INTRODUCTION

Scientists and engineers from all disciplines are now exploring the “nanoworld” for possible solutions to the pressing problems and challenges faced by the 21st century, ranging from finding cures for diseases [1,2] to developing new materials [3-5] to making microscale and nanoscale machines [6-8]. Many of these problems have been declared unsolvable on the conventional scale, underlining the present importance and enormous future potential of nanotechnology in several spheres such as nanoelectronics, nanobiomedical applications and aerospace technology. The accessibility of this "nanoworld" relies critically on the magnification of structures that lie beneath the physical optical limit dictated by the range of wavelength of visible light (400 to 700 nanometers).

The atomic force microscope (AFM), a subclass of scanning probe microscopes (SPM), is a product of a maturing magnification technology approaching twenty years of development. The AFM is an essential tool for the magnification of nanoscale objects and according to the ISI Web of Knowledge^{SM} has been an essential tool in over 25,000 publications to date. For a current review of the technology see [9-14]. However, people, especially younger students, unexposed and unaware of the technologies behind high magnification microscopy, are unable to accurately visualize and comprehend the varying degrees of perspective and information contained in the magnified images. Thus, a thorough understanding of the principles of nanoscale magnification is essential for the appreciation of the unique characteristics of the “nanoworld” and is imperative in order to advance to the level of manipulation of nanoparticles; nanotechnology’s ultimate goal.

The AFM was invented by Gerd Karl Binnig, Calvin Quate and Christopher Gerber in 1986 [15]. Prior to the invention of the AFM, the other scanning technologies in use were the SEM (Scanning Electron Microscope), the TEM (Transmission Electron Microscope), the STM (Scanning Tunneling Microscope) and the Topografiner [16], which were developed prior to 1986. Typical ranges of resolution of all of the above instruments range from 0.2-400 nm or, from the range of a fraction of an atomic diameter to the lower range of visible light wavelengths. The AFM incorporates and advances many of the strengths of these systems such as high-power magnification, and negates several drawbacks such as simplified sample preparation,

Compared to the 2D images of the SEM and TEM, the AFM scans true 3-dimensional images with detailed depths and contours of the sample surface with the aid of a highly sensitive z-axis. It can scan samples in vacuum, under hydrated conditions and in dry air. Moreover, the AFM does not require time-intensive sample preparation and can be tuned to minimize sample degradation with repeated scans, which has proven especially useful in biological imaging e.g. [9, 17-19].

Recent advances in atomic force microscopy include the addition of nanomanipulation with the AFM to produce a machine capable of synchronous imaging and manipulation (Figure 1), as well as incorporation of multiple AFM probes on a single integrated chip [14]

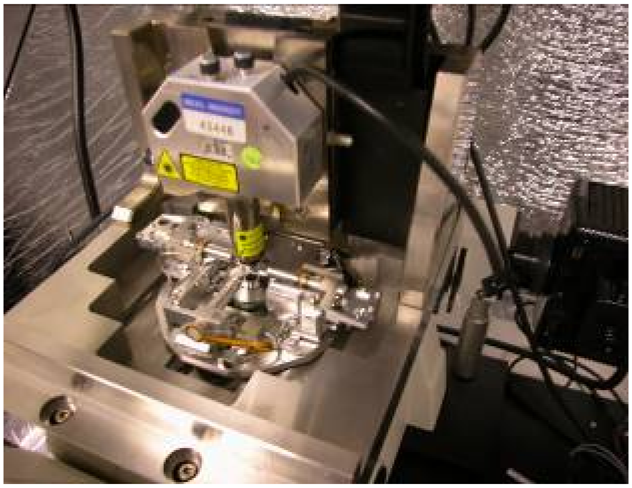

Figure 1. An example of a modern atomic force microscope manufactured by Digital Instruments and being modified in the Layton laboratory at Drexel University to incorporate the Zyvex L100 nanomanipulator.

The AFM consists of a mechanical device called the probe which comprises of a cantilever, a laser-emitting device and photodiodes. The cantilever with a sharp tip, attached to its lower end, has an effective radius from 10-3000 nm. The cantilever scans the sample surface utilizing several distinct modes of scanning such as constant force, constant height, tapping mode and non-contact mode. More details of this may be found from individual AFM manufacturer's literature. A monochromatic light beam (laser) is incident on an optical lever. This optical lever reflects the laser beam from the cantilever to the photodiodes, which measure relative the intensity of the laser signal. A more detailed discussion on the theory of noise limits and cantilever design for atomic force microscopy may be found in Rieth (2003) [20].

In summary the AFM has witnessed significant technical and theoretical advances over the years. To sustain this pace of progress, the coming generation of scientists and engineers need to be made aware of the basic concepts of the AFM. This would provide them a solid foundation on which to base their future advancements, innovations and explorations into new frontiers of atomic scale magnification. Therefore it is incumbent upon us as researchers and post-secondary educators to provide our K-12 educators with a simplified model of nanotechnological machines such as the AFM to bring to their students at least and appreciation for the tools and concepts they will need for the future, and at best a sense of wonder and interest in science and technology that will propel them throughout their careers.

II. PROBLEM STATEMENT

Nanotechnology is a rapidly emerging field which will lay the foundations for numerous scientific breakthroughs and technological advancements in the coming years. Therefore, students, our future workforce, should be exposed to a broad spectrum of educational tools and content from an early age. This would provide them a holistic overview and possibly spark their curiosity in the subject [21]. It will empower them to make informed decisions in their future studies and professional careers in the nanotechnology arena.

But presently, the problem is there are not many such educational tools to effectively introduce basic nanotechnology courses in middle schools and high schools. Even existing AFMs, considered as essential instruments for commencing any primary study in nanotechnology, do not demonstrate the working of the various parts and their interactions with each other e.g. [22]. Therefore, AFMs have a confined scope of usage as educational tools as they fail to highlight the principles and the engineering involved behind their operation. We hope to solve the problem of the lack of educational tools and effectively provide a practical demonstration of the principles involved in atomic force microscopy magnification.

There have been recent attempts to assess the efficacy of developing an engineering design dialog between university engineering students and high school students with a predisposition for engineering [23]. Our group has also established a strong dialogue between Drexel engineering students and local high school and middle school teacher through the National Science Foundation's Research Experience for Teachers.

Thus, the problem we are trying to solve is how to bring the concepts of nanotechnology to K-12 teachers in a hands-on fashion with maximum educational impact and minimal financial expense.

III. METHOD OF SOLUTION

We have constructed an operational model of an AFM (Figure 2). The basic framework, a 1x1x1 ft cube, is fashioned out of aluminum L-beams. It provides support as well as a configuration for the motion of the probe. The carriage for the probe is created by using similar aluminum L-beams.

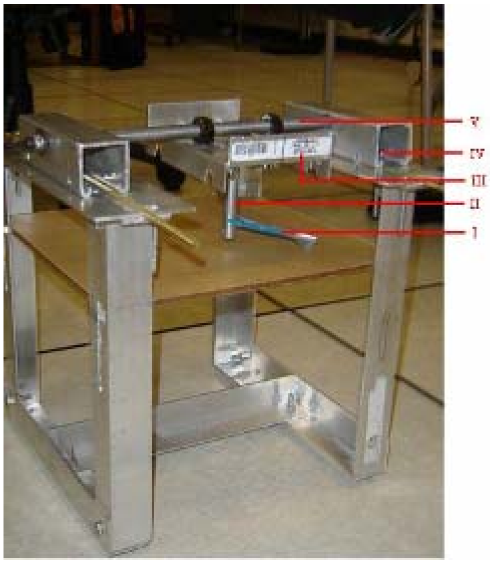

Figure 2. Our constructed model of the AFM. (I) Cantilever (II) Probe (III) Carriage carrying the probe (IV) Rack and pinion concealed under the C-shaped beam (V) Threaded screw.

The cantilever tip, which is a combination of a plastic CD jewel case, a glass mirror and a sharply cut triangular-pyramidal Teflon tip is hinged to the bottom end of the cantilever stem. The top end of the stem is attached to the carriage (Figure 3).

The laser pen and the photodiodes are first calibrated within a small range of angles (approximately -2^0 to 2^0) to ensure accurate reception of laser signals from the pen to the photodiodes via the cantilever glass mirror.

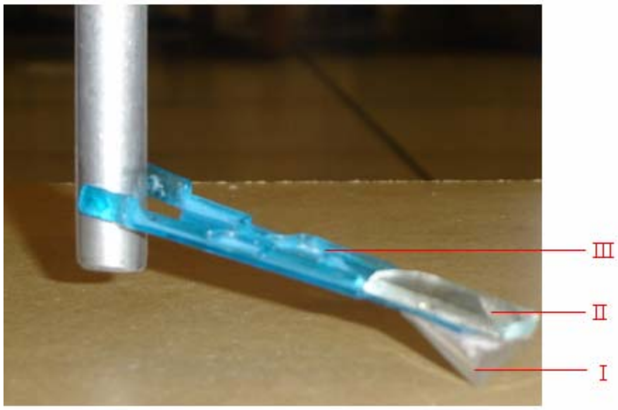

Figure 3. The cantilever attached to the probe. (I) Teflon tip (II) Glass mirror (III) Cantilever made of ordinary CD jewel case.

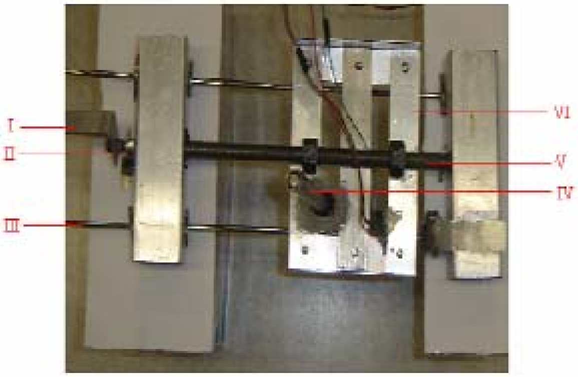

Figure 4. The movement of the probe in the X-direction is achieved by (I) a handle to rotate the (II) screw encoder sending signals to DAQ board. (III) Axles support the (VI) carriage, which carries the (IV) laser pen and (V) threaded screw

The laser pen and the photodiodes are then fixed to the opposite sides of the carriage using an appropriate adhesive. The entire carriage is mounted on a screw-collar system from the top (*Figure 4*). The carriage rests on a pair of axles which direct the motion of the carriage in the y-direction

The screw-collar system is supported by the platform. A rack-and-pinion system is positioned along the platform to provide the mechanism of movement in y-direction (Figure 5).

The translations in the x and y-directions are individually recorded by incremental rotary encoders [24] which are mounted, on the axles of the rack-and-pinion system and on the screw of the screw-collar system. The motion of the cantilever tip along the varying contours of the sample is being measured by the calibrated combination of laser pen, cantilever mirror and photodiodes to track the progress along the z-direction. Eventually, the signals representing the motion along the x, y and z directions are sent to the Data Acquisition Board (DAQ board).

The DAQ board, National Instruments' SC-2345, receives the digital signals relayed by the incremental rotary encoders into its triple-row

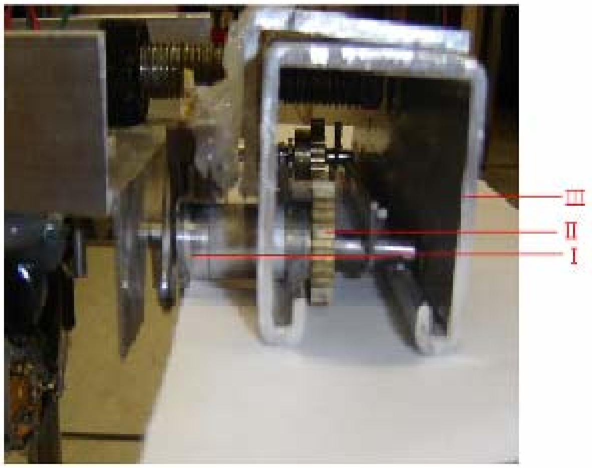

Figure 5. The movement of the probe in the y-direction. (I) Encoder sending signals to the DAQ board (II) Pinion (III) C- Shaped beam.

Screw Terminal Block, designed for digital input. Both encoders are powered by a 5V source in the Screw Terminal Block. The photodiodes are connected to the SCC-CI20 module, a dual-channel module for analog inputs of two distinct currents.

After appropriate conditioning, the DAQ board relays the three signals to the NI PCI-6023E Multifunction I/O Board, which is connected to a PCI slot of a desktop PC. This board in turn inputs these signals into the DAQ assistants of the Virtual Instrument (VI) programmed in LabVIEW®. We have written the VI software code which simultaneously receives processes and converts the three signals into numerical distances. Additionally all of this is documented in a manual which is available on the author’s website.

The x and y distances are calculated based on ratio and proportion formulae after conducting experiments and performing measurements. The number of digital pulses received in rotating the encoder by an angle of $\pi/2$ is noted. After noting the change in angle, the linear distance is calculated using the formula,

$$\Delta s = r \cdot \Delta \theta , \tag{1}$$

where Δs is change in Linear distance, r is encoder radius and $\Delta\theta$ is change in rotation angle.

The *‘distance moved per digital signal received’* is calculated using ratios, which is then used in the code to multiply by the number of digital signals received in real time. This concept is used for both the x and y distance calculations. For the z distance, the formula used is,

$$d = \frac{U - D}{U + D}, \tag{2}$$

where U and D denote the up and down signals received by the two photodiodes, respectively.

This distance is the measure of the deviation of the cantilever tip from the reference point, the point of zero deviation, thereby giving us the z-coordinate. Thus, the distances along all three axes are plotted on a 3-D graph which displays the contours of the sample.

IV. RESULTS AND CONCLUSIONS

The cantilever tip scans the sample surface, tracing and detecting all the irregularities through varying laser signals to the photodiodes. These signals are plotted into a 3-D graph by LabVIEW® after passing through a series of Data Acquisition devices. A pegboard was used as a sample and an arbitrary path was chosen to be traced (Figure 6). The irregularities of the graph, obtained after moving along the path, represent the contours of the scanned sample (Figure 7). A detailed beam dynamics model may be found in [25]. Compared to an actual AFM, our model has a lower resolving power on the order of a few millimeters.

The z-direction signal suffers from background noise due to ambient lighting and imperfect isolation of photodiodes. However, the original aim of constructing the model was to lucidly demonstrate the principles and concepts involved in the nanoscale magnification procedure followed by an AFM as well as to highlight its various working parts and their mutual interactions. Therefore, enclosing the entire model in an optical insulator to reduce the noise effects of ambient lighting would make it an ineffective teaching tool. Thus, we redesigned our drawings and we placed the photodiodes facing downwards, allowing the model's frame to cancel out a significant percentage of the incident stray light.

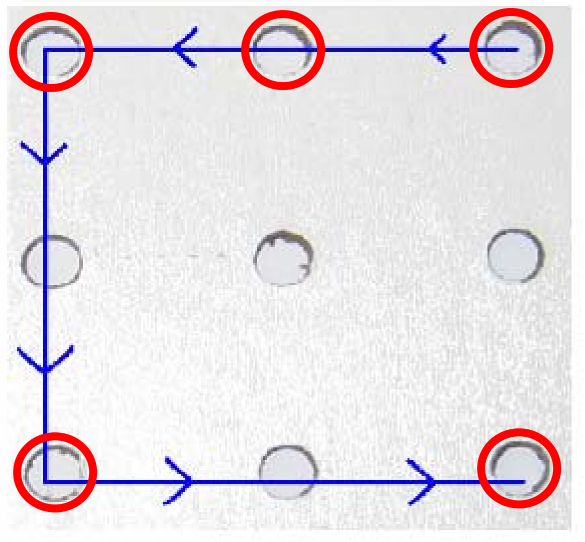

Figure 6. A pegboard was used as our sample. The blue line shows the U-shaped path along which we moved our probe to scan the sample.

As can be seen from Figure 7, the depressions of the pegboard are represented as peaks. This was done for graphical purposes. While five distinct peaks may be seen, two of the depressions were not detected. This was caused by a combination of rapid scanning in the y direction on the bottom portion of the "U" and by rapid scanning in the x direction on the final leg of the "U." Imperfect data such as this is common in actual atomic force microscopy and may help teach students the concepts of taking data and may also give them a motivation to develop improvements to our design.

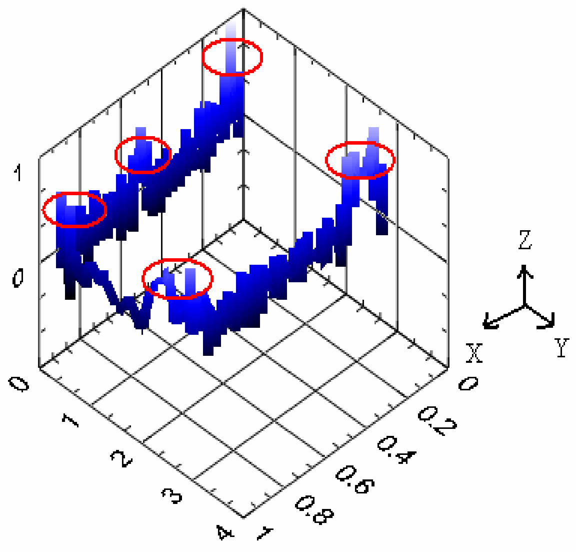

Figure 7. A 3-D plot of the scanned sample. The graph was obtained using LabVIEW®.

V. FUTURE WORK

Future work will incorporate the addition of motors and rewriting the code in JAVA so that the entire device may be controlled via the internet with a microcontroller card such as the TINI microcontroller card from Dallas Semiconductors. This strategy has been used successfully in technology education transfer in other laboratories, e.g. [26, 27] for further access see http://mechatronics.poly.edu/MPCRL/

Additionally, the incorporation of this technology will allow us to do real-time three dimensional imaging. A full instruction manual for constructing your own educational atomic force microscope, please visit http://www.pages.drexel.edu/~bel23.

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