REMOTE OPERATION OF SCANNING PROBE MICROSCOPES
OVER THE INTERNET

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ABSTRACT

As a result of the NSF-funded Interactive Nanovisualization in Science and Engineering Education (IN-VSEE) project, the first interface for remote operation of the revolutionary scanning probe microscope (SPM) over the Internet, termed “SPM Live!”’, has been developed. The feasibility of using the Internet for remote operation of research-grade instrumentation that can be used directly in the classroom or laboratory for carrying out real-time experiments has been demonstrated. “SPM Live!” helps convey the excitement of nanoscience and nanotechnology, promote student-initiated learning, and increase interest in science and engineering careers. “SPM Live!” can also be used to provide teachers with an introduction to the technology and its use in teaching. A live two-way communication has been created from a Web browser to the SPM through a remote architecture for remote control. This involves sending live data from the SPM to a remote operator via the Internet and then providing a way for the user to send commands to the microscope. Although only one remote operator can control the microscope at a time during a remote session, multiple remote observers can view and analyze the data simultaneously and control can be passed from one user to another. Further since the SPM data is inherently three dimensional, a plug-in has been developed to display the data as a three-dimensional model, with support for zoom, par, rotation, etc. The development, implementation, limitations, and directions for future work on this project are discussed in this article.
I. INTRODUCTION

The fields of nanoscience and nanoengineering are critical for the successful development of nanotechnology, which can lead to the next industrial revolution. Consequently, the preparation of a new generation of scientists and engineers for these rapidly emerging fields is essential. It is particularly important to integrate nanoscience and nanotechnology concepts into high school and college curricula, which will require innovative educational approaches to help students understand the structures and properties of matter on a scale below 100 nanometers, i.e., the nanoscale.

The NSF-funded Interactive Nano-Visualization in Science and Engineering Education (IN-VSEE) project anticipated this technological and educational need by bringing research-grade, yet user-friendly, imaging technology and instrumentation, typically located only in elite research centers, into any classroom in an effort to “level the playing field”. The project is based on the unique capabilities of the scanning probe microscope (SPM) to provide nanoscale imaging of material surfaces for science and engineering education, with a focus on education related to the rapidly developing fields of nanoscience and nanotechnology. This project has created a consortium of university and industry scientists, community college and high school science faculty and museum educators with a common vision of creating an interactive Internet site to develop a new educational thrust based on remote operation of the Nobel-prize-winning SPM.
The primary goals of IN-VSEE are to (i) convey the excitement of nanoscience and nanotechnology to promote student-motivated learning and pursuit of science and engineering careers, (ii) teach fundamental interdisciplinary concepts in science and engineering using a visual format to help students learn and integrate information more effectively, (iii) provide students with the capability to routinely explore materials in three dimensions with resolutions at the nanoscale and even down to the atomic scale, and (iv) demonstrate the feasibility of remote operation of research-grade laboratory instrumentation for development into a powerful educational tool. To accomplish the above goals, IN-VSEE has focused on the development of a diverse Web site, novel remote SPM operation, materials-oriented educational modules, an extensive image gallery, and broad outreach and dissemination. Detailed information about all of these resources can be found through IN-VSEE’s Web site at http://invsee.asu.edu.

A unique feature of IN-VSEE is the design and implementation of a live data broadcasting and remote control system for the SPM over the Internet termed “SPM Live!” The system allows one or more users to remotely view and control the SPM. Therefore, the microscope can be shared through the network to increase collaboration between researchers and improve the efficiency of online education. Below we discuss the development, implementation, limitations, and future directions for the remote operation of SPM’s over the Internet.

II. DEVELOPMENT

Scanning probe microscopes, such as scanning tunneling microscopes (STM) and atomic-force microscopes (AFM), do not produce images like optical microscopes (Wickramasinghe, 1989). They use a very sharp tip to probe the surface of a sample being studied. The tip can be positioned very precisely and reports the height and other properties at its current position. The
tip scans across the surface in a raster pattern, producing a two-dimensional array of heights and other measured properties.

TopoMetrix Corp. (currently ThermoMicroscopes Corp.), the first company to broadly license the SPM patents, provides software (Viewer and Control Interface) running on Windows 3.1, which does not support viewing over the network or multiple users. Russell Taylor’s NanoManipulator (nM) (R. Brady (1991) & R. Taylor (1993)) project group at University of North Carolina at Chapel Hill have obtained and has been working with TopoMetrix software and permission to put code hooks into TopoMetrix software such that the microscope data can be delivered to another computer (Unix Workstation) via a socket connection. It also controls the functionality of the microscope. The nM system provides a virtual-environment interface that hides the details of performing complex tasks using the SPM. It takes the two-dimensional array of heights, tessellates with triangles, and uses a graphics computer to draw surfaces in three dimensions. Specular highlights bring out features in the data that are missing in the grayscale image. The nM system also uses a force-feedback device to allow the user to directly control the lateral motion of the SPM tip, using it either to feel or modify the surface. The nM system uses the X-window system on the network. However, it is a single-user system which cannot support multi-user asynchronous access. Although the nM system has simplified the interface of SPM operation, users still need training and must have a basic knowledge of Unix and X-windows.

The development of Internet (platform independent) capability is one of the main goals of the IN-VSEE project. The main components of the IN-VSEE system are the rendering engine, conference server, control server, CGI, and Java Applet Interface. The system architecture shown in Figure 1 is quite complex and involves the microscope itself, local microscope control software running on a PC, and the remote microscope software controller on a Silicon Graphics
(SGI) machine. The latter should not be confused with the ability to remotely control the microscope via the Internet.

The low-level remote control interface for the microscope and the rendering engine is based on the NanoManipulator (nM) system. The nanoManipulator (nM) server was modified to make it suitable for the IN-VSEE application. The connection between the nM (running on the SGI) and the computer running the microscope is via the socket interface. The microscope itself collects the data by probing the surface of the specimen in a raster fashion alternating between left-to-right and vice-versa. Each traversal is known as a scan line. Each scan line can contain from 128 to 512 height measurements (height fields) depending on the scan parameters. Correspondingly, there are as many scan lines as the number of height fields to give a square matrix of data, typically 256x256 or 512x512. The nM system sends data every 4 to 5 scan lines. Again, the exact number depends on other parameters that control the microscope, scan size, and communication speed. The scan size (size of the matrix) is usually set once and is a constant throughout for a specimen. What changes is the scan area or area of the specimen. Since the scan size is known beforehand as well as the scan area before a new cycle of each scan, the microscope only need send the height fields. The intermeasurement distance is a constant for each scan. This results in very few data elements being sent to the nM controller. The rendering engine then constructs a surface and based on the viewing parameters (orthographic or perspective, shading, etc.) displays a three-dimensional image on the screen of the SGI using OpenGL. It then captures the window, converts the pixels in RGB format to JPEG and saves to a mmap, which is a memory-mapped file and is a feature of the UNIX operating system file. It also writes the height fields into the shared memory. It then sets a flag in the shared memory that the new image is ready for distribution.
The SGI machine also acts as a data server for the Web clients and gateway for remote microscope operators. It services requests from clients for both two-dimensional images and three-dimensional raw data. The latter is used by the three-dimensional plug in. In order to keep the rendering engine and control server separate, Inter Process Communication (IPC) shared memory is used to share data between the two servers mentioned above. The shared memory is also used for communication between the data servers. Error codes and commands are exchanged in the same fashion.
III. IMPLEMENTATION

A. Remote Observer

The Web client software runs on any Web browser that supports HTML 4.0 and Java 1.1 and is referred to as the remote observer. Figure 2 shows a view of the remote observer Web page. Version 1.0 of the software used multi-part content (MIME image stream) to send the image to the Web browsers directly (server push). The more advanced Version 2.0 uses the java applet socket connection to retrieve the image. The remote observer applet is alerted by the server that a new image is ready to download and provides the URL for the image. This makes a continuous live view based on a fast network connection. Since Web browsers provide native support for JPEG images, no special browser plug-in is required. The only limitation is the network bandwidth. From our experience, a 14 kbps connection is good enough to see the image of every scan line of a 15 x 15 nanometer CD-ROM surface (500 x 500 pixels, 24 bits color, 200 μ/s). Currently, the Independent JPEG Group’s JPEG packaging is used in order to keep the code portable. The use of hardware JPEG compression of the video capture card or the SGI onboard compression chip can further improve compression rate and image quality.

A live video window and a chat window are integrated with the control interface inside the Web browser. The IN-VSEE system uses video broadcasting to help students and researchers get a live view of the status of the working SPM and to improve communication on conference. The text-based chat window is used for communication between remote observers, the remote operator (see next section) and the expert local operator. It provides a channel for the local operator to communicate to remote users to provide assistance in experiment design, execution, and interpretation.
Basic measurement tools are provided to the remote observer so that the visual experience is extended to the analysis domain. The Java applet provides the capabilities of interactive linear and angular measurements. In addition, the applet provides z-profile capture. When the z-profile mode is active, the user picks two points on the image and a graph of height fields between the two points appears on the screen. While the measurements are truly interactive, the z-profile requires a roundtrip request to the server to (i) map the selected points to the raw data matrix, and (ii) retrieve the height fields between those two points. The applet then draws the graph locally at the client site. These features allow several users to measure different aspects of the specimen without interfering with the operation of the microscope.

Pushing the module button allows access to a number of education modules being developed in the IN-VSEE project. The educational modules provide interactive, discovery-based learning activities to introduce students to the SPM as a research instrument as well as to interpret the data collected. For example, students can view a video of a process and then answer questions about what they have observed. They can also explore a concept they have experienced in a module or discussed in class, or they can discover the concept on their own using Java applet-based activities. Each module presents important fundamental and applied concepts of natural and man-made materials that cut across the traditional disciplines of mathematics, physics, engineering, chemistry, and biology. The modules demonstrate how a material's atomic structure, properties, processing and performance are related at the nano-level and how that relationship leads to its properties and performance at the macro-level. This visualization pipeline provides examples of man-made vs. natural materials ranging from the macroscopic to the nanometer scale. One aim of the modules is to provide an effective bridge between the classroom and the laboratory. Each module has the ultimate goal of drawing the
student into the use of the SPM as a data-collection tool and providing an understanding of the appropriate use of this tool. Collectively, the modules provide a roadmap for students on how to design and conduct experiments, with each module leading to a remote experience.

Pushing the gallery button provides access to the IN-VSEE image gallery, where a Web-style search engine can search the gallery database. An extensive image gallery has been created to serve as a materials visualization resource that can be used for a variety of educational purposes, including classroom presentations, homework, special projects, and honors credit. The IN-VSEE image gallery contains a unique bank of images that illustrate the interdisciplinary nature of modern science and engineering and the value of integrating research into education. The images represent a diverse cross-section of disciplines and span a wide range of size and scale. Images of various materials are provided in several forms: digital photographs showing objects from the macroscopic world, schematics that illustrate the essence of a concept being taught, animations to stimulate the student’s imagination, and micrographs obtained from SPMs as well as from electron and optical microscopes. Text segments also accompany each image that describe the material as well as unique features displayed in the image. Users can perform basic image analysis using the z-profile, x-y distance, and angle-measurement tools.

B. Remote Operator

The SPM can also be controlled via the Internet, which is referred to as the remote operator. The IN-VSEE system provides a simple and straightforward interface (rubberbanding Java applet) for remote control. Students and inexperienced users do not need an advanced level of training before using the microscope. With the original Version 1.0, the remote operator could only control the scanning area of the specimen. The current Version 2.0 provides additional capabilities such as scan rate, various gain parameters, image rendering type
(orthographic vs. perspective), etc. Figure 2 shows a view of the remote-operator Web page. The access to the remote operator Web page is via strict password protection. The commands issued from the remote-operator Web page are relayed to the nM server via the shared-memory protocol. These are then passed on to the computer controlling the microscope which makes the necessary adjustments. Once the necessary action is taken, an acknowledgment is relayed back to the remote operator. The remote operator is not allowed to submit additional changes until this acknowledgment is received. Although only one user can control the microscope at a time during a remote session, multiple users can view and analyze the data simultaneously and control can be passed from one user to another.
The microscope data is inherently three-dimensional. Therefore, in addition to delivering the data to Web clients as two-dimensional images (much the same way as a scientist would do in a local environment), the data is also delivered such that three-dimensional images can be created at the client site. The three-dimensional plug-in works as a local analysis tool. It uses
the client pull method to retrieve the live data (height-value matrix). It makes more advanced analysis, such as simulation of surface modifications, possible. Figure 3 shows the plugin operation for a mica surface coated with polystyrene spheres. This is available for the Intel X86 (Windows 95/NT) and UNIX operating systems that have support for OpenGL. Therefore, remote observers can utilize the full potential of topographic images from the microscope. The user can choose any view by using the mouse or a trackball. A three-dimensional object in the plug-in can be panned, zoomed, rotated, and shaded. This capability is possible for Web clients that have at least 233 MHZ or equivalent X86 processor with 32 MB RAM

D. Remote Use and Evaluation

Since this is part of an experimental research project, certain schools and community colleges have been chosen to participate. When a presentation is to be conducted remotely, the specimen is sent ahead of time or one of the samples in the IN-VSEE laboratory is selected. The scheduling of remote experiments can be done through the Internet.

The remote SPM has been used in a variety of settings that include lecture presentations and laboratory activities. It has been field tested in various laboratory sessions, classrooms, conferences, and teacher-training workshops. For example, it has been used by two local community colleges, Chandler-Gilbert Community College and Scottsdale Community College, which are more than 14 routers away from Arizona State University. Remote SPM experiments were used successfully in a laboratory session by the former and in a lecture presentation by the latter, with typically up to 25 students per session. “SPM Live!” was also well received at the 1999 National Imaging Technology in Education Conference held in Tucson, AZ, as well as at Gordon Research Conferences, National American Chemical Society Meetings, International Conferences on College Teaching and Learning, and the 1999 Sigma Xi Forum in Minneapolis,
MN. It also generated excitement at an American Society for Microbiology Education Conference held at Emory University in Atlanta, GA. Recently, Sidwell Friends High School from Washington, D.C. used the remote SPM as a primer for independent projects in biology. IN-VSEE’s resources are currently being adapted and adopted on a larger scale in an NSF-funded project involving Cornell University, the University of Wisconsin, Arizona Western College, and Mesa and Glendale Community Colleges. As shown in Figure 5, this new project is intended to serve as a national model that demonstrates how integration of technology and research instrumentation can be cost-effectively leveraged in an asynchronous manner to positively impact undergraduate SMET curricula to help inspire today’s students to become tomorrow’s scientists and engineers and cultivate the first generation of knowledge and distributed experimentation network users.

The general response from evaluation surveys has been very positive, even with unavoidable occasional network delays. Groups of teachers and students were used to evaluate the potential use of remote SPM for their classrooms and laboratory sessions. The evaluation of the IN-VSEE system is not the focus of this paper, but is well documented and will be published elsewhere. For example, at a workshop demonstrating the potential of SPM for teaching, the following results (mean scores from 7 point bipolar scales scored from +3 to -3 through mid-point of zero) were gathered. There were four groups consisting of 13, 14, 12 and 26 participants. The average attitude toward participation was 2.3, the average potential of this technology for teaching was 2.1, and the average knowledge gain was 2.4. The results to date suggest that the teachers and students who participated are interested in incorporating the remote SPM into their classroom, but it is the students who appear to be most enthusiastic about embracing the technology.
IV. LIMITATIONS

There are still some limitations of the current IN-VSEE system. The foremost is the unpredictability of the data delivery over the Internet. Slow networks can make remote usage and visualization very cumbersome. While this is not a problem of the IN-VSEE system per se, more efficient means of delivering the data, including better compression, need to be developed. The JPEG image format has been adopted because all Web browsers support it.

The security of the IN-VSEE system has not been a prime concern. This was an intentional oversight since the system works in an academic environment. However, this must be addressed in a commercial system or where national and other security is a concern. Just as with any software system that claims to operate under multiple platforms and multiple browsers, there are occasional problems. This is primarily due to some versions of the browsers and/or Java libraries not compliant with the respective standards. The system has also not been stress tested with hundreds of users, although it has been tested with about 25 clients simultaneously using the system, and the performance was acceptable. There are currently three levels of security, advanced, medium and low for users of the operator page. In future, these will be time expired. The handoff is not a problem but has to be done in a systematic manner.

Another potential limitation is the management of remote use as the number of users increases. An important feature of the IN-VSEE system is that the images and data stored at the server site is not per client, since the data is shared among clients. The cost is two socket connections per server and state variables amounting to less than 100 bytes per client, which are recovered when the client completes the experiment and the connection is broken. Since it is a live session, the data is continuously updated. System performance then a function of (i) how many clients can be handled simultaneously by a server and (ii) the bandwidth. The IN-VSEE
server is configured for 64 connections. Typically, the sessions involve less than 25 students per classroom. However, the bandwidths at both server and client end are important. IN-VSEE has two ways to connect to the Internet. One is the vBNS or the NSF sponsored internet 2 connection and the other is the regular T1/T3 connection. Reasonable performance is achieved with a 56.6 K connection. Simple actions, such as turning the video camera off on the observer page, can reduce traffic at the client site.

V. FUTURE DIRECTIONS

From our survey of published literature, this is the first time bi-directional communication has been used via the Internet to control an instrument remotely as well as the first time an SPM microscope has been made available on the Internet. The IN-VSEE system is designed to combine experimental, visualization, and analysis resources in an easy-to-use, multi-client environment. Future work will be focused in the following areas:

• Field test and incorporate user recommendations to improve the system. For example, the operator page now also works on Macintosh computers.

• Improve the analysis tools for the remote observer, and add controls for additional parameters for the remote operator. In the near future, the remote operator will be allowed to control instrument parameters depending upon the operator’s level of expertise in running the microscope.

• Improve the efficiency of the data delivery system using wavelet compression schemes.

• Enable remote manipulation of the specimen. This can allow different samples on a silicon wafer to be selected remotely. The probe in the SPM can also be used to modify the sample surface. Hence, instead of recording or scanning, the probe becomes an extension of the
user’s hand. The probe can be used to cut specimens or arrange atoms in a particular order. Such manipulations are hampered by network latency, since such a system requires a quick round trip from the issuance of the command to the arrival of visual result at the remote location. The Quality Of Service (QOS) will be examined at in collaboration with the very high Bandwidth Network System (vBNS) grant recently awarded to our institution.

• Extend remote operation to other instruments.

Although the focus of the IN-VSEE system is to bring live data from the SPM over the Internet, the concepts and the lessons learned can be applied to other instruments. The motivation is twofold. First, as the instruments get more and more refined and the prices go up, there are going to be fewer and fewer labs and organizations that will have them. Accessing such instruments remotely, including their control, then becomes an important factor. This is true for cutting-edge collaborative research as well as distance learning. A number of other research-grade instrumentations at Arizona State University, including optical microscopes and an ion beam analyzer, are being modified to operate over the Internet, as shown in Figure 6. Secondly, the Internet has become the medium of choice for almost all network-based activity. The IN-VSEE project combines these two themes, and we hope this work encourages others to undertake similar projects. There is already an effort led by Oakridge National Research Laboratory to come up with a common API for all types of microscope interfaces so that different manufacturers can design their software to work over the Internet in a plug-and-play type design.

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**FIGURE CAPTIONS**

Figure 1.

Shown are the elements of the software architecture that makes possible the remote operation of the IN-VSEE scanning probe microscope. Each box represents a separate computer and text within them represents the software packages that perform its functions. Data from the microscope is communicated to a “Rendering Engine” within the Silicon Graphics O2™ computer server at IN-VSEE. A segment of “Shared Memory” within this computer server facilitates the exchange of information between the “Rendering Engine”, “INVSEE Control Server” and “INVSEE Conference Server” and “CGI” functionalities. The latter three functionalities communicate with the internet browser’s (Netscape Communicator 4.7x) “Browser Frame” and the “Java Applet Interface” on the user’s computer (observer and operator pages are shown in Figures 2 and 3, respectively). Interactive, offline, three-dimensional rendering of the microscope data (shown in Figure 4) is performed by a 3D-plugin package downloaded from the IN-VSEE site. This data is obtained from the “INVSEE Control Server”.

Figure 2.

This observer page is accessible to users around the world via the Internet. The image of the sample surface from the microscope, in this case bacteria growing near a surface terrace on mica, can be seen on the upper-left portion of this page. Online, real-time analysis of features on the sample surface can be performed using the “z-profile”, “x-y distance”, and “angle” buttons located directly below the image. Information on the location of the probe and the size of the area being scanned can be found on the upper-right portion of this page. Users can see the microscope and the SPM tips scanning the surface, through a webcam, on the middle-right portion of the page. Communication between users is facilitated by the chat area just below the webcam image. The microscope image can be saved onto the user’s local computer by utilizing the “capture” button. Other features, such as IN-VSEE’s Visualization Gallery and collection of
Authorized users can control the remote SPM through this operator page. The current image of the sample transmitted by the microscope can be seen on the upper-left portion of this page. The grid in the middle allows users to select the area to be scanned by drawing a box and pushing the “submit” button. Information on the location of the probe and the size of the area being scanned can be found on the upper-right portion of this page. Either a three-dimensional perspective or two-dimensional display of the sample’s surface topography can be selected with the “perspective” and “orthographic” buttons, respectively. The lower-left corner shows a feature currently under development. Remote users can collaborate and communicate with each other using the chat area on the lower middle. Instrumental feedback parameters for controlling the microscope are shown on the bottom right. Control of the IN-VSEE webcam can be accessed through the “Camera Controls” button.

A three-dimensional rendering of a mica surface coated with polystyrene spheres is shown. A program that can retrieve and perform interactive three-dimensional rendering of the topographical data from IN-VSEE’s remote SPM is shown. It is downloadable through the IN-VSEE website. The data can be rendered under various modes through the “shading” function. Different perspectives and viewing distances as well as simulated lighting over the surface can be changed by manipulating the image.
Users from different geographical areas and time zones around the world can participate in remote SPM sessions. The operator controls the microscope scanning of the sample, while observers can see the same image and communicate with the operator or other observers. Successful trials have been conducted between users in the continental USA as well as sessions between the US and Rome, Italy, Toronto, Canada, and Tokyo and Osaka, Japan. Breaking such geographical barriers can help realize the exciting concept of a “laboratory without walls”.

Figure 5.
Figure 6.

IN-VSEE’s remote SPM is one of many analytical instruments that are currently being developed to remotely operate over the Internet via a centralized Visualization Facility at ASU. In the future we intend to make other instruments available over the Internet so that researchers from around the world can access a suite of useful instruments conveniently from their local computers.