

Remote Control and Visualization of Scanning Probe Microscopes via the Web

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Abstract

Current efforts in bringing instruments on-line via the World Wide Web (WWW) have done much to enhance distance learning and research. We have achieved success in bringing the Scanning Probe Microscope (SPM) data live on the Web. This work is being pursued under the aegis of the IN-VSEE⁷ project. The project is targeted at bringing SPM data live to community colleges, high schools and other research labs/classrooms. We have further advanced the capabilities by providing remote operation of the SPM via the Web. The remote operator can control many functions of the microscope with reasonable security and ease. The latter marks a milestone in that we have used the Web for truly interactive bi-directional communication involving feedback and control of an instrument. The architecture also incorporates an interactive *chat* channel among the observers and the operator(s). Further, since the SPM data is inherently 3-Dimensional, a plug-in has been developed to display the live data as a 3-Dimensional model, with support for zoom, pan, rotation, etc. We report our efforts to accomplish the above and future directions for the work in progress.

Keywords: World Wide Web, Scanning Probe Microscope, SPM, remote control, visualization, live data, IN-VSEE

⁷ Interactive Nano-Visualization in Science and Engineering Education.

1 Background of Tele-Microscopy

We look at the current state of the art of technology and products that support Tele-microscopy. Tele-microscopy does not have a precise definition. Generally, it means delivering data from a microscope to a remote observer via one of the many media channels. While many different types of microscopes exist, we will focus on one class, i.e., the Scanning Probe Microscope (SPM).

1.1 Scanning Probe Microscope

Scanning Probe Microscopes (SPM), such as scanning tunneling microscopes (STM) and atomic-force microscopes (AFM) do not produce 2D images like optical microscopes. (H. K. Wickramasinghe (1989)) They use a very sharp tip to probe the surface of a sample being studied. The tip can be positioned very precisely (within the radius of an atom), and reports the height and other properties at its current position. The tip scans across the surface in a raster pattern, producing a 2D array of heights and other measured properties.

TopoMetrix Corp. (currently ThermoMicroscopes Corp.), the first SPM 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.

1.2 NanoManipulator of UNC

Russell Taylor's NanoManipulator (nM) (R. Brady (1991) & R. Taylor (1993)) project group at University of North Carolina at Chapel Hill has been working with TopoMetrix Corp. for some time. They have obtained 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 NanoManipulator system provides a virtual environment interface that hides the details of performing complex tasks using an SPM. It takes the 2D array of heights, tessellates with triangles, and uses a graphics computer to draw it as a surface in 3D. 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.

1.3 Limitation of the UNC Project

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. Even nM has simplified the interface of SPM operation. Users of nM still need training and they must have the basic knowledge of Unix and X windows.

1.4 Other Projects and Products involving Tele-Microscopy

Following are some Tele-Microscopy related projects and products we know. They are categorized based on the medium they use.

1.4.1 Video Camera Systems

In 1996, Bio-Tech Imaging Inc. developed the Automated Remote Research Microscope (ARRM) (Bio-Tech Imaging (1996)) which is an automated system for reading and analyzing images of microscope using a color video camera system.

In 1997, Bildanalyssystem AB achieved transfer of live video and images from the remote microscope over a digital telephone line (Bildanalyssystem AB (1997)). A specially designed joystick controls the remote microscope.

In 1997, UAB's Center for Telecommunications Education & Research introduced the TelePath system (S. McClellan (1997)) that provided remote control of a robotic microscope via a TCP/IP network and used real-time video to transmit *live* pictures from the remote microscope.

1.4.2 Screen, Mouse, and Keyboard Mirroring

In 1996, Oak Ridge National Laboratory (J. Culiver (1996)) achieved remote control of an Hitachi HF-2000 electron microscope by using a commercial software package, Timbuktu Pro. This software was used for mirroring the screen, mouse, and keyboard functionality of the local computer to a personal computer of average power outside the laboratory.

1.4.3 Specially Designed Environments or Systems

In 1992, NCSA, in collaboration with the STM group at the Beckman Institute, developed a software module (J. Lyding (1993) & R. Brady (1995)) which allowed remote control of the Scanning Tunneling Microscope from within the commercial software environment called AVS⁸, a software environment that

⁸ Advanced Visual Systems

can build applications with interactive visualization and graphics and Cave Automatic Virtual Environment (CAVE)⁹.

In 1995, the Scanning Electron Microscope installed at the California State University Hayward (CSUH) microscope laboratory (C. Matsumoto (1995)) allowed distance education with other remote campuses and other classrooms on the CSUH campus, which employed a broadband networking system with the capability to transfer audio, video and visual data.

In 1997, the Neurovisualization Lab at the University of Virginia was developing the Integrated Remote Neurosurgical System (IRNS) (Remote Neurosurgical lab, University of Virginia (1997).) to allow mentoring neurosurgical procedures in remote locations. The system allows a remote neurosurgeon to control a robotic microscope through the use of a 3-D input device, communicate with the operating room (OR) team through live audio and video, and view presurgical imagery.

In 1997, Aaron Stillman at University of Illinois at Urbana/Champaign was working on the Visual STM Project. The main tasks of the project were to convert an existing (but outdated) PC-based Fortran application to a Java application with a graphical user interface and to set up the network interface between the client and the server that will operate the actual scanning tunneling microscope.

The above projects and products have made the microscope a powerful research and education tool. From our survey we found the following limitations in the existing software:

- Lack of support for multi-user/observer asynchronous access,
- Lack of three-dimensional information such as height fields, especially when video camera systems are used for capturing output of microscope images.
- Lack of provision for viewing 3D models via the Web,
- Lack of bi-directional communication for remote control of the microscope, and
- Lack of a platform independent solution.

⁹ A multi-person, room-sized, high-resolution, 3D video and audio environment.

2 A Platform Independent Solution: The IN-VSEE System

2.1 The IN-VSEE* Project

The rapidly emerging fields of nanoscience and nano-engineering has been deemed by the U.S. to be critical for the successful development of nanotechnology, which will lead to the next industrial revolution. Specifically, President Clinton's FY 2001 budget request includes a \$497 million, an increase of 84% over that for FY 2000, in the government's investment in nanotechnology research and development. The preparation of a new generation of scientists and engineers for these rapidly growing fields is essential. The following quote from the National Science and Technology Council:

“Finally, in order for the field of nanostructure science and technology to truly reach fruition, it is an absolute necessity to create a new breed of researchers who can work across traditional disciplines and think ‘outside the box.’ Educating this new breed of researchers, who will either work across disciplines or know how to work with others in the interfaces between disciplines, is vital to the future of nanostructure science and technology. People must start thinking in unconventional ways if we are to take full advantage of the opportunities in this new and revolutionary field.”

- from the Nanostructure Science & Technology: A Worldwide Study under the guidance of National Science and Technology Council (NTSC), 1999.

The integration of nano-science and technology concepts into the curricula of upper-division high school and lower-division college levels, critical transition points in a student's educational career, requires innovative educational approaches that will help students understand the structures and properties of matter on a scale below 100 nanometer (0.1 micrometers), i.e., the nanoscale.

The IN-VSEE (Interactive Nano-Visualization in Science and Engineering Education)¹⁰ project had anticipated this technological and educational needs by bringing state-of-the-art, sophisticated, 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 scanning probe microscopy to provide nanoscale imaging of material surfaces for science and engineering education, with a focus on education related to the rapidly developing field of nanotechnology. The 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 World Wide Web site to develop a new educational thrust based on remote operation of research-grade microscopes such

as the Nobel-prize-winning SPM and nanofabrication tools coupled to powerful surface characterization methods.

The primary goals of IN-VSEE are to:

- Convey the excitement of nanoscience and nanotechnology to promote student-motivated learning and pursuit of science and engineering careers
- Teach fundamental interdisciplinary concepts in science and engineering using a visual format to help students learn and integrate information more effectively
- Provide students with the capability to routinely explore materials in three dimensions with resolutions at the nanoscale and even down to the atomic scale
- Demonstrate the feasibility of remote operation of sophisticated, research-grade laboratory instrumentation for development into a powerful educational tool.

To accomplish the above goals, IN-VSEE Project has been involved in the six major thrusts to develop: (A) Web Site, (B) Remote SPM Operation, (C.) Educational Modules, (D.) Visualization Gallery, (E.) Outreach & Dissemination, and (F.) Evaluation.

The IN-VSEE initiative will impact science and engineering education by bringing nanotechnology into any classroom to help prepare the next generation of scientists and engineers so that the U.S. can assume leadership position in the above rapidly emerging fields.

A unique feature of the IN-VSEE project is the design and implementation of a live data broadcasting and remote control system for the Scanning Probe Microscope over the WWW. The system allows one or more users to remotely view and control a microscope connected to Intranet or Internet. This project makes the microscope facility sharable through the network and increases collaboration between researchers. An additional goal is to improve efficiency of online education or distance learning and distributed design.

Currently, IN-VSEE provides students at Arizona State University as well as community colleges and select high schools in the metro Phoenix area and across the country with the capability to routinely explore materials in two and three dimensions with resolutions at the nano scale and even down to the atomic scale. The leading-edge research technology is being made available as a unique education collaborator to any classroom regardless of budget, resources, facilities or expertise.

¹⁰ More information about IN-VSEE project can be found at <http://invsee.asu.edu>

2.2 IN-VSEE Architecture Design

Development of World Wide Web (platform independent) capability is key to the success 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 (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 Web. We highlight the major components below.

2.2.1 SPM Controller and the Rendering Engine

The low-level remote control interface for the microscope and the rendering engine is based on the UNC NanoManipulator. We modified the nanoManipulator (nM) server to make it suitable for our 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 feeling (hence the word *Probe* in SPM) 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, its either 256x256 or 512x512. The nM 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 being scanned. Since the scan size is known beforehand and also the scan area before a fresh cycle of each scan, the microscope only need send the height fields. The inter-measurement distance is a constant per scan. This results in very few data elements being sent to the nM controller. The rendering engine then constructs a surface and based on viewing parameters (orthographic or perspective, shading, etc.) displays a 3D 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 mmap¹¹. It also writes the height fields into the shared memory (see below). It then sets a flag in the shared memory that the new image is ready for distribution.

¹¹ mmap is memory mapped file and is a feature of the UNIX operating system file

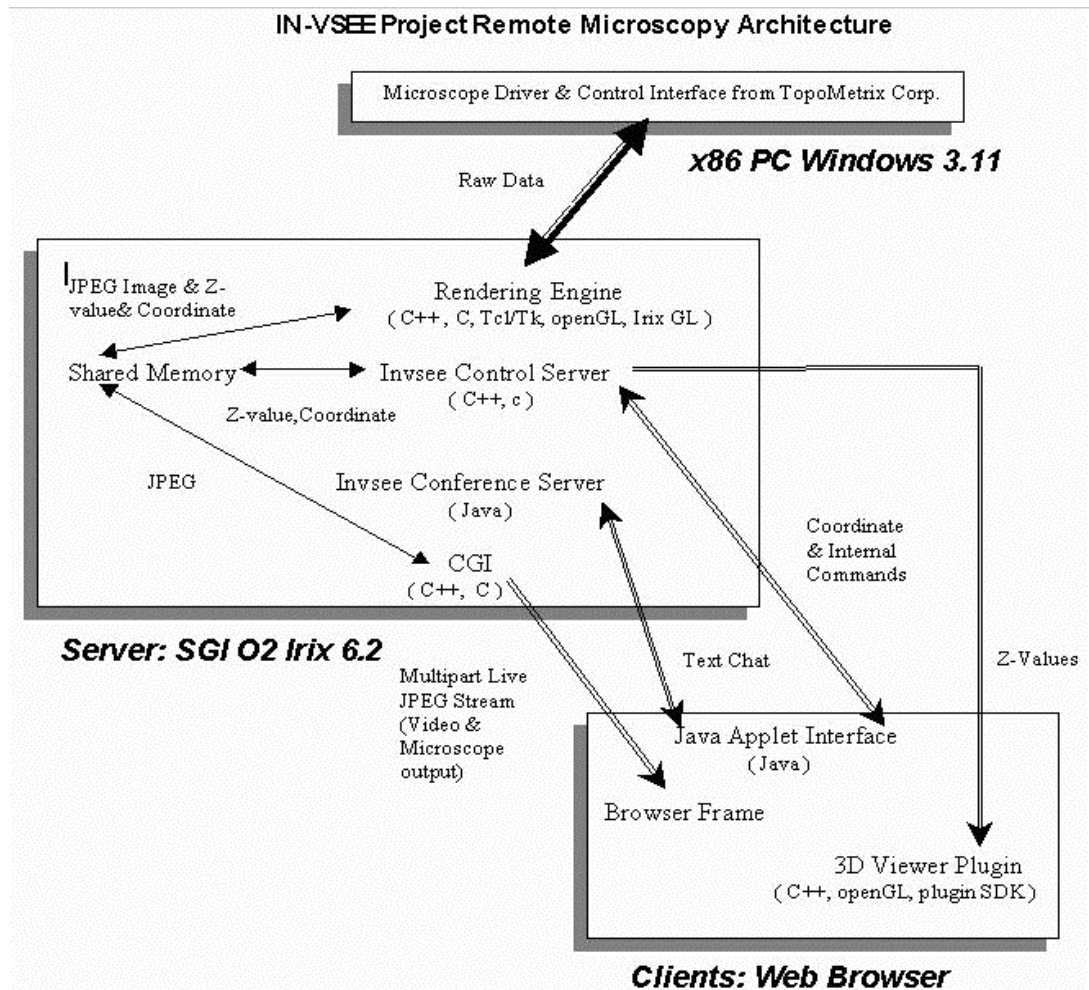


Figure 1: INV-SEE Architecture

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 2D images and 3D raw data. The latter is used by the 3D Plug in.

In order to keep the rendering engine and control server separate, we used Inter Process Communication (IPC) shared memory to share data between the two servers mentioned above. The shared memory is also

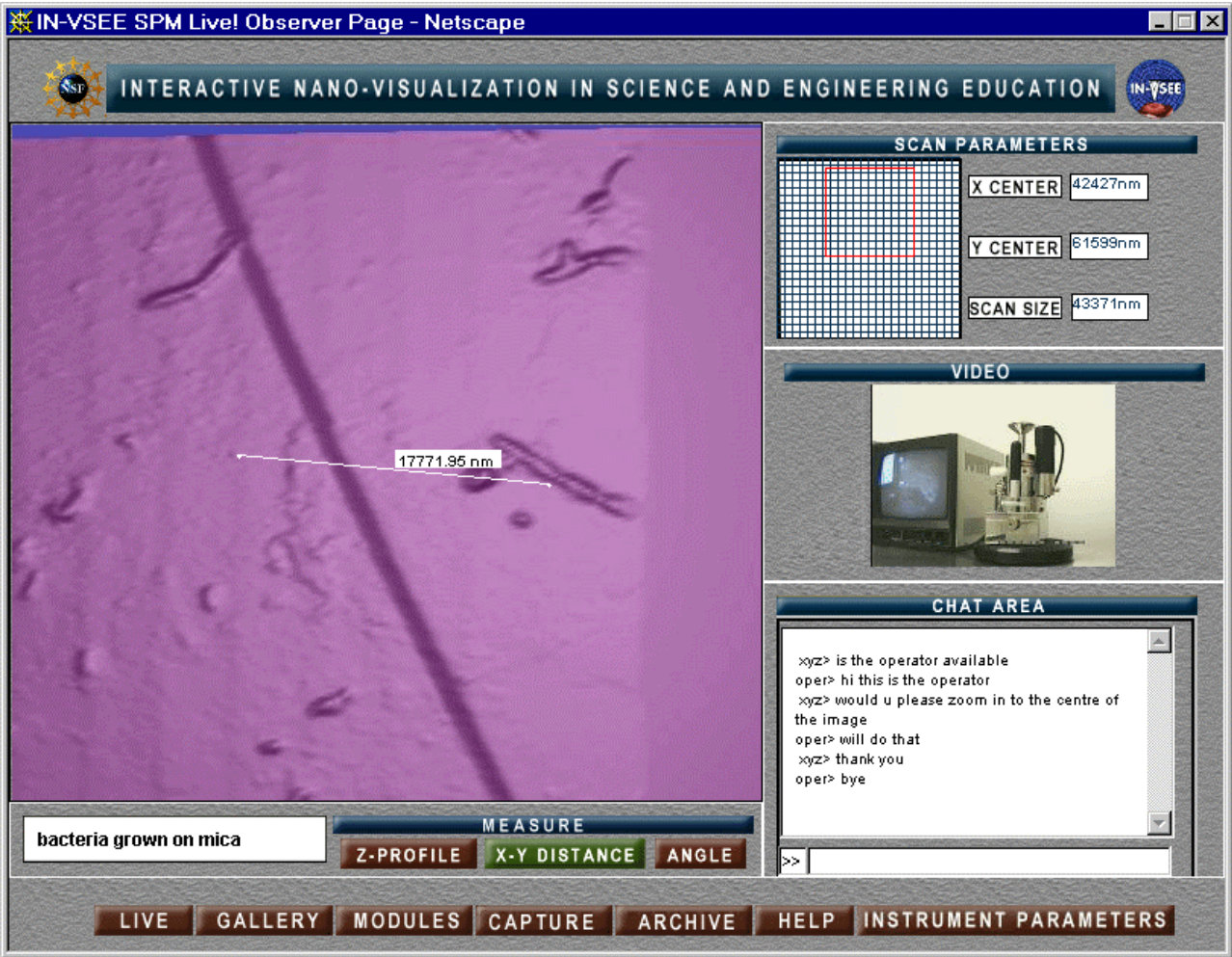


Figure 2: Observer Page

used for communication between the data servers. Error codes and commands are exchanged in the same fashion.

2.2.2 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. See Figure 2 for a snap shot of the Remote Observer web page. [Please explain more....what is shown? What scale?] Version 1.0 of the software used multi-part content (MIME image stream) to send the image to the Web browsers directly (Server Push). Version 2.0 uses the Java Applet socket connection to fetch the image. The remote observer applet is alerted by the server that a new image is ready for download and provides the URL for the image. This makes a continual 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, 14kbps connection is

good enough to see the image of every scan line of a 15 by 15 nanometer CD-ROM surface (500 by 500 pixels, 24 bits color, 200 micrometer/sec). Currently, we use the Independent JPEG Group's JPEG package in order to keep our code portable. Using 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 the live view of the status of the working SPM and also improve communication on conference. The text based chat window is used for communication between observers, remote operator and the local administrator. It provides a channel for the local administrator to communicate to remote users (observers and operator alike) in case of problems, or other circumstances where the remote users may need help or input from a knowledgeable operator.

Basic measurement tools are provided to the remote observer. Therefore, the experience is not just limited to visual but extended to the analysis domain. The Java Applet provides the capabilities of interactive linear and angular measurements. In addition to the above, 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 (a) map the picked points to the raw data matrix, and (b) fetch the height fields between those two points. The Applet then draws the graph locally on the client side. These features allow as many users to measure as many different aspects of the specimen without interfering with either the working of the microscope or the operating console.

Pushing the module button can access a number of education modules being developed under the IN-VSEE project. The IN-VSEE Visualization Gallery has around 1000 images obtained from Scanning Probe Microscopy, Scanning Electron Microscopy, Optical Microscopy and digital photos. Together, these images span the macro-, micro- and nano-world. These images can be accessed through the "Gallery" button on the Remote Observer page where a web style search engine is provided that can search the gallery database. Users can perform some basic image analyses using the z-profile, x-y distance, and angle measurement tools. Text segments that describe each image's scientific significance are also included.

2.2.3 Remote Operator

We have developed the capability to control the microscope via the Web and it is referred to as the Remote Operator capability. The IN-VSEE system provides a simple and straightforward interface

(rubberbanding Java Applet) for remote control. Students and non-experienced users do not need advanced level of training before their use of the microscope. In Version 1.0 the remote operator could only control the scanning area of the specimen. Version 2.0 provides additional capabilities such as *scan rate*, various *gain parameters*, image rendering type (orthographic vs. perspective), etc. See Figure 2 for a screen shot of the remote operator page. The access to the remote operator page is via strict password protection. In the near future, different remote operators will be allowed to control the parameters depending on their levels of expertise in running the microscope. The commands issued from the remote web page are relayed to the nM server via the shared memory protocol. These are then passed on to the computer

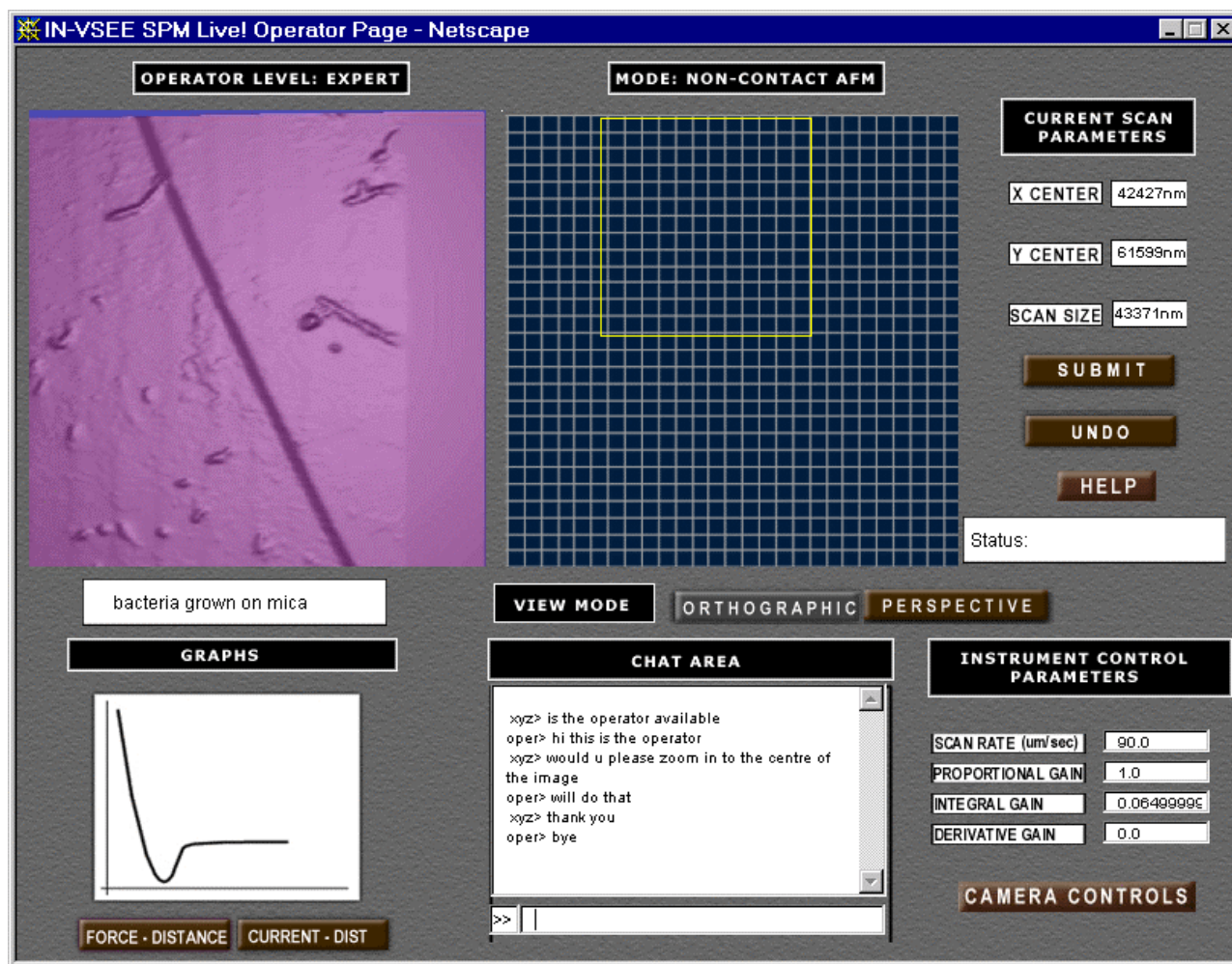


Figure 3: Operator Page

controlling the microscope that makes the necessary adjustments. Once the necessary action is taken an acknowledgement is relayed back. The remote operator is not allowed to submit any more changes until this acknowledgement (which could be an error) is received.

2.2.4 3D Plug-in

The microscope data is inherently three dimensional (3D). Therefore, in addition to delivering the data to Web clients as 2D images (much the same way as a scientist would do in a local environment), we also deliver the data such that 3D images can be created on the client side. The 3D 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 modification possible. Figure 3 shows the plug-in with the specimen of a chromosome under mitosis. This is available for the Intel X86 (Windows 95/NT) and UNIX Operating Systems that have support for OpenGL. The clients (observers) therefore utilize the full potential of topographic images from the microscope. The user can choose any view by using the mouse or a trackball. A 3D object in the plug-in can be panned, zoomed, rotated and shaded. This is recommended for

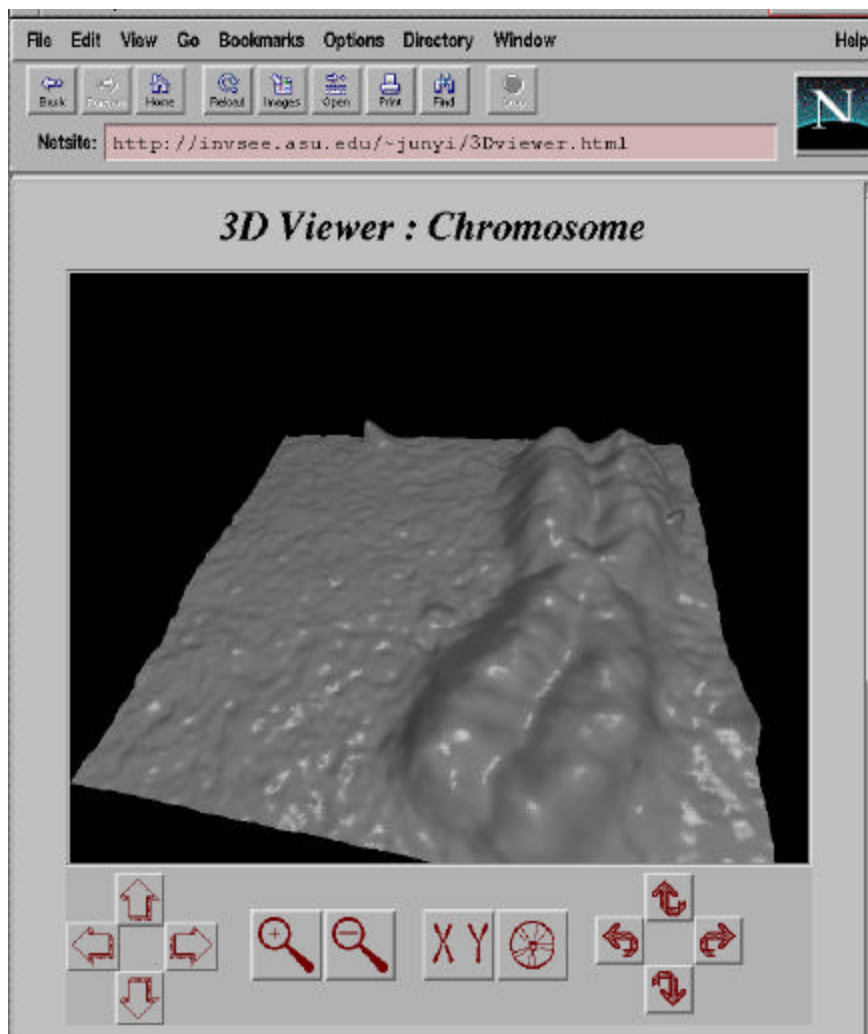


Figure 4: 3D Plug in

Web clients that have at least 233 MHZ or equivalent X86 processor with 32 MB RAM.

2.3 Limitations of the IN-VSEE System

There are still some limitations in 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 a waste of effort and time. While this is not a problem of the IN-VSEE system per se, this is always of concern and more efficient means of delivering the data including better compression needs investigation. We have adopted the JPEG image format since all web browsers support it.

We have not stressed the security issue in our system in great detail. This was an intentional oversight since our system works in an academic environment and security is not the most important issue. 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, we find problems from time to time. This is mainly due to some versions of the browsers and/or JAVA libraries not compliant with the respective standards. The system has not been stress tested with hundreds of users, although it has been tested with about 25 users simultaneously using the system and the performance was acceptable (see next section).

3 Usage and Statistics

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 library is selected. The scheduling for live experiments is done through human interaction.

The remote SPM has been used in a variety of settings that include lecture presentations and laboratory activities. It has successfully worked over the web by two local community colleges: Chandler-Gilbert Community College and Scottsdale Community College, which are more than 14 routers away from Arizona State University, as a laboratory session by the former and a lecture presentation by the latter with typically up to 25 students per session. It was well received at the 1999 National Imaging Technology in Education Conference held in Tucson, Arizona. It generated excitement at an American Society for Microbiology education conference held at Emory University in Atlanta, Georgia. Recently, Sidwell Friends High School from Washington, D.C. used the remote SPM as a primer for their students' independent projects in biology.

The general response from the survey was very positive and the network delays were worth the wait as reported by the users. At the time of writing this paper, the system was field tested in various teacher-training workshops, conference presentations, and some laboratory sessions, for a total of fourteen instances.

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. However, as an example, the survey at the 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 attitude toward participation ranked at 2.3, potential of this technology for teaching rated at low of 1.9 and high of 2.3, the knowledge gain was at a low of 1.6 and high of 2.9. Our findings suggest that teachers and students that interacted with IN-VSEE are interested in incorporating the remote SPM into their classroom, however, the students are much more eager to embrace the technology.

4 Relevance of this project for the web community

Although the focus of the IN-VSEE system is to bring live data from the SPM via the Web, the concepts and the lessons learned can be applied to a wide variety of instruments. The reason for doing so is two fold. One, 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 in our case where the focus is on distance learning using a remote lab. A number of other research-grade instrumentations at Arizona State University, such as suite of optical microscopes and ion beam analysis techniques, are being fitted to operate over the web.

Secondly, the Web has become the medium of choice for almost all network based activity. Fundamentally, the IN-VSEE project combines these two themes and we hope this work encourages others to take on similar projects. There is already an effort led by Oakridge National Research Lab (ONRL) to come up with a common API for all types of microscope interfaces so different manufacturers can design their software to work over the web in plug and play type design.

5 Conclusion and Future Work

This is the first time bi-directional communication has been used via the Web to control an instrument remotely (from our survey of published literature), at least the first time an SPM microscope has been made available to the Net. Our system is designed to combine experimental, visualization, and analysis efforts in an easy-to-use multi-client environment. Future work and extension to the current system would be in the following areas:

- Field test and incorporate feedback and concerns of the users to improve the system.
- Improve the tools for analysis for the remote observer and add controls for additional parameters for the remote operator.
- Enable remote manipulation of the specimen. The probe in the SPM can also be used to modify the specimen's surface. There, instead of recording or scanning, it becomes an extension of the user's hand. This can be used to cut specimens or arrange atoms in a particular order. Currently this capability is not provided in our system. This is hampered by the network latency since such a system requires a quick roundtrip from the issuance of the command to the arrival of visual result at the remote location. The Quality Of Service (QOS) will be looked at in collaboration with the very high Bandwidth Network System (vBNS) grant recently awarded to our institution.
- Improve the efficiency of the data delivery system by using wavelet compression schemes.
- Replace SPM with other instruments.

6 Acknowledgments

We would like to acknowledge Russell Taylor's NanoManipulator group at University of North Carolina for supplying the software, training on their software, and for providing technical support of their source code. We would also like to thank the members of the IN-VSEE group.

The National Science Foundation through grant number REC 9632740 sponsors this research.

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