MATERIAL MICROCHARACTERIZATION COLLABORATORY

Final Report

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Abstract

The Center for Microanalysis of Materials (CMM) is one of the four electron microscopy and microcharacterization user facilities participating in the Materials Microcharacterization Collaboratory (MMC) supported by the DOE-SC, Office of Basic Energy Science, and DOE Energy Efficiency & Renewable Energy Program, Office of Transportation Technology. The MMC unites the four DOE BES electron microscopy user facilities at ANL, LBNL, ORNL, and the CMM at the University of Illinois at Urbana-Champaign. Also participating in the MMC are the DOE EE microcharacterization user center at ORNL and the NAMT program at NIST. MMC also has several industrial partners. The purpose of the MMC is to bring the microanalytical and microcharacterization tools and expertise at these centers of excellence and other participating facilities together in an on-line interactive collaboratory and make them available to educators and researchers working in industry, universities, and government laboratories through telepresence access and operation. The MMC, however, is about remote ***collaboration***, not just remote instrument control. The approach of the MMC also emphasizes providing the tools for establishing a sense of community and performing research using the MMC. The CMM has several instruments and peripherals available on-line emphasizing a Web-centric approach with varying levels of access and functionality. This program has developed and implemented hardware and software tools for remote and collaborative operation.

Introduction

About the Center for Microanalysis of Materials

The Center for Microanalysis of Materials (CMM) is a user-oriented and user-friendly facility that provides the modern analytical capabilities essential to today's materials science. The Center is an integral part of the Frederick Seitz Materials Research Laboratory on the campus of the University of Illinois at Urbana-Champaign. The CMM emphasizes the microstructural and microchemical composition of materials; chemistry and electronics of surfaces; crystal structures; phase transitions and defect structures of materials; the relationship between structure and properties of solids. By using the center, materials researchers can access over 30 major instruments in the areas of electron microscopy, scanning probes, surface microanalysis, X-ray diffraction, and back-scattering spectroscopy's. The breadth of instrumentation available through the center enables researchers to find the best combination of analytical techniques for their specific needs. The center is staffed with experts in each technique who provide education and training for researchers so they can operate the instruments to conduct their own measurements. Users approved for self-operation have 24-hour access to the instruments. The CMM staff also provides guidance, consultation, and collaboration in the microanalysis of materials.

The CMM is one of five U.S. Department of Energy Electron-Beam Micro-Characterization Centers and as a national user facility and collaborative research center is open to researchers from universities, government laboratories, and industry, nation-wide as well as internationally. The CMM operates in a mode allowing open access to equipment, with *no user fees,* for non-proprietary research through a straightforward usage proposal system. We allow, encourage, and provide training for self-operation of the equipment by all qualified researchers. It is a unique resource representing an exceptional opportunity for materials micro and nano characterization.

The CMM web site can be found at http://cmm.mrl.uiuc.edu

The CMM has several instruments available on-line as a result of participation in this program. These instruments represent over 6 million dollars in advanced analytical instrumentation and are each listed below:

- ?? Zeiss DSM-960 analytical scanning electron microscope (SEM) with Oxford Instruments energy dispersive X-ray analyzer (Isis EDS), cathodoluminesence spectrometer (MonoCL2), and crystallographic orientation imaging (Opal EBSD) systems;

?? Hitachi S-4700 field emission gun SEM with Oxford Isis EDS;

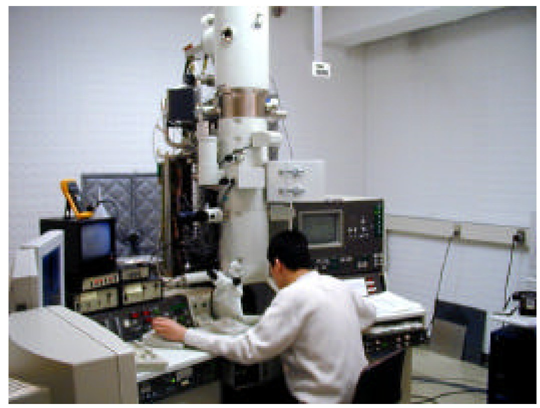
?? Physical Electronics PHI 660 scanning auger microprobe

?? Cameca ims-5f magnetic sector secondary ion mass spectrometer

?? KRATOS AXIS imaging X-ray photoelectron spectrometer

?? JEOL 2011 transmission electron microscope with Gatan CCD camera

?? JEOL 2010F field emission scanning transmission electron microscope with Gatan GIF imaging energy filter, Gatan CDD cameras, and Oxford INCA X-ray analyzer



?? Philips X'pert MRD X-ray diffraction systems (two systems)

The Materials Microcharacterization Collaboratory Concept

The Materials MicroCharacterization Collaboratory (MMC) was a partnership with the Office of Science's, Basic Energy Sciences program and the Department's Energy Efficiency and Renewable Energy Program to provide remote access to facilities and expertise located at Argonne National Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, the National Institute of Standards and Technology, and the University of Illinois at Urbana Champaign for electron beam microcharacterization of materials. This effort began as a part of the DOE2000 initiative.

This pilot project for scientific collaboration joins this set of unique national research facilities into an on-line interactive microcharacterization laboratory. This collaboratory allows scientists, educators, and even students access to an environment in which real-time collaborations can occur unencumbered by the limits of time, space and location. The MMC creates a virtual on-line laboratory around these centers of excellence in microcharacterization which are accessible from anywhere on the Internet.

The overall project MMC web site can be found at http://tpm.amc.anl.gov/MMC/ and the CMM MMC web site is located at http://surface.mrl.uiuc.edu/ .
In the collaboratory concept, the MMC's ultimate goal is to create virtual environments for new and/or enhanced means to solve scientific problems and to Improve quality and efficiency of research through increased interaction. Research is enhanced through improved access to researchers working in industry, universities, and government. Education is enhanced through improved access to educators and students at all levels. Telepresence collaboration provides enhanced opportunities for scientific collaboration, easier access to expertise and state-of-the-art equipment, easier access to unique instrumentation, education and training (distance learning), and educational outreach (pre-college, industrial). It can also offer reduce need for travel (continue unfinished experiments) and for service and diagnostic functions.

The mechanism for these virtual environments is to create systems for fully participatory and interactive collaboration over distance (in near real time) for materials microcharacterization facilities. The ultimate realization of this requires that distributed people, information, instrumentation, and analysis tools needs to be able to fully interact independent of their location. Thus systems must be provided for audio/visual communication and for the exchange of information (data, ideas, expertise). Systems for near real time instrument control and broadcasting near real time data streams are required. Specialized software for data analysis and/or simulations need to be shared or made available to remote collaborators.

This vision for an ideal collaboratory environment for the MMC would entail many various tools providing for interaction of distributed **People, Instruments, and Data.** These tools would include:

- ?? Communication tools
    - o Multipoint audio / video conferencing
    - o Text "chat"
    - o Electronic whiteboards
- ?? Remote control of instrumentation
    - o Multi-way near real time data streams
- ?? Shared data spaces
    - o Electronic notebooks

    - Archives
    - Session records
    - Recorded sessions
- Shared data analysis tools
- Application sharing
    - Remote control
    - Analysis tools
    - Report generation
- Floor control ("who's got the ball")
- Facility Management
    - User research proposal tools
    - User and project vital information databases
    - Session control and scheduling
- Security

Ideally these tools would exhibit seamless integration and provide real functionality approaching "as good as being there". The instrumentation and communication tools would interface directly to the data spaces and analysis tools. Application sharing and floor control would be available for collaborative collection, analysis, and reporting of results. Session control and scheduling would provide for reservation of instrument time and control level of access (i.e. novice vs. expert). A common underlying security layer would provide access control.

This description is a very idealized model for the collaboratory, which was not achieved here, nor anywhere else. What will be presented is what we did achieve and learn in the process. Also, not considered in this model, but is really an important factor is sustainability in a dynamic environment, where instruments come and go or are upgraded / modified. In attention to this factor, the resources required (time and expense) to maintain the collaboratory environment and integrate new instruments are a very important consideration. Ultimately this factor played a significant role in some of the decisions and directions chosen in the MMC program at UIUC

MMC Collaboratory Tools

One thrust of the Materials MicroCharacterization Collaboratory (MMC) was the development and implementation of both commercial and specialty collaboration and teleconferencing techniques. These techniques include audio and video communication, low latency streaming video, shared data spaces, collaboration, and remote control of instrumentation. Our approach at the CMM was to target Internet and preferably Web based solutions using existing and commercial technologies. The experiences of the CMM MMC with these various tools and techniques, as well as links to additional information, are documented

Video Conferencing:

Several Internet telecommunication programs offer video conferencing capability. These capabilities had been routinely evaluated while participating in the regular (weekly) MMC conference call. Internet audio was found to be currently inadequate for routine communication. For that reason, the MMC selected to utilize telephones for voice communication. However, we continued to use these programs for video conferencing, text chat, and white boarding simultaneously during the telephone conference calls.

The differentiating factor between telecommunication programs offering video broadcast is image size and network bandwidth utilized, which are necessarily related by the compression algorithm (codec) used by the broadcast. It has been MMC's experience that while image size of 120 X 160 pixels can be utilized, image size of 320 X 240 or even 640 X 480 pixels are desirable. For video conferencing, high compression ratios, lossy compression, and lower frame rates are generally found to be adequate, conserving bandwidth for the other tools.

White Pine Software CuSeeMe

The software program we most often used was White Pine Software's Cu-SeeMe package with Winnov Videum Conference Pro for Windows hardware (http://www.winnnov.com). CuSeeMe has been one of the leading Internet video conferencing solutions providing multi-point video conferencing, chat, and whiteboard over TCP/IP networks. The presence of a textual chat window has proven to be a very useful aid to pass information that is inconvenient to spell out vocally, such as URL's. White boards currently are useful for sharing other types of basic information such as images, sketches, etc. We pretty much relied on simple FTP, since most of the files we transferred were large and/or not supported formats. A particularly important feature was the conference reflector for multipoint conferencing, MeetingPoint, was available for licensing and thus we could operate our own conference server. It is also cross platform, supporting both Macintosh and Microsoft Windows PC's. First Virtual Communications (http://www.fvc.com), however, acquired White Pine Software, in 2001 and their Click-to-Meet product family now supersedes it. This product, not evaluated here, appears to provide similar features and more.

Microsoft NetMeeting™

Microsoft NetMeeting™ (http://www.microsoft.com/windows/netmeeting/) provides much of the same conferencing functionality as CuSeeMe except restricted to a point-to-point mode. NetMeeting provides video conferencing, whiteboard, chat, file transfer; and windows based application and desktop sharing tools. The application and desktop sharing tools can be used for sharing Microsoft Windows based instrument control for remote operation to a single remote site. The video conferencing window can be utilized to supply an image stream such as a microscope image video. NetMeeting is only available for Microsoft Windows operating systems and is free.

Application Service Providers

Today there are many Internet application service providers (ASP's) supplying Web and Internet based video conferencing and tools for business. These are generally subscription services charging a monthly fee based on level of services. They support multipoint conferences by serving the conference data through the provider's systems. One such ASP that was evaluated during the MMC project period was iVisit (http://www.ivisit.com). This system requires each participant download and installs a client application and log into the conference. The performance and functionality were found to be quite suitable and this and similar systems would be suitable for organizations not wishing to operate their own conference server.

Image Broadcasting:

Often it is desirable to just periodically update an image on a schedule, not needing streaming live video. For this there are numerous "WebCam" software packages available for various platforms. Two packages used here were pjWebCam (no longer available) and WebCam32 (http://www.surveyorcorp.com/) for the MS Windows platform.

Internet Video Broadcasting:

In all interfaces we make extensive use of live streaming Internet video. For instrument control, where the image provides real-time feedback to the remote operator, it is important that the video supplied is of the best quality and is of lowest possible latency. Early in the MMC project, it was found that the well-known commodity video streaming applications available (such as Real Networks RealVideo) rely on considerable buffering in the server and/or client applications. They were optimized for low bandwidth at higher frame rates with the sacrifice of quality and high latency. They also require proprietary browser plug-ins and thus an interface controlled by the provider. Thus these applications thus were not suitable for MMC applications. Prior to the MMC project, Dr. Nestor Zaluzec (MMC co-PI) at Argonne National Laboratory had been working with a streaming media software provider, Graham Technology Solutions (GTS), with their client independent low latency high performance media streaming solutions. Initially, however, GTS was a high cost solution requiring expensive hardware and software and UNIX based servers. It was desired to identify lower cost solutions that were either PC based or hardware only (embedded servers). Systems selected and utilized at UIUC for the MMC are summarized separately below. This does not reflect a review of all technologies currently available, just those selected by the CMM MMC during the project.

BroadWare Technologies (formally, Graham Technology Solutions) (http://www.broadware.com/)

BroadWare provides a scalable server-based platform used to develop real-time, networked video applications for all types of applications. The BroadWare systems provide very low latency required for remote control applications. The BroadWare streaming media system eliminates platform dependency and the need to download plug-ins or special client software using server push technology and the multipart/x-mixed-replace MIME type or Java applets on the client side. Support for on-demand streaming of stored video is also available. Graham Technology Solutions was also one of the industrial partners in the MMC project and donated the initial Unix based video server software used by the MMC. GTS later offered a MS Windows version of their software at a substantially lower cost, also with features simplifying server setup and management. We successfully used the Windows version for the MMC and had performance nearly equal to the Unix based system. BroadWare now offers a Linux based solution (not tested).

Emulive Imaging Corporation (http://www.emulive.com)

Emulive Server is a real-time media broadcasting software system that works in conjunction with Emulive producer software to create digital television-like channels on the Internet. To Java enabled web browsers, the server appears as a standard web server. The system is for the MS Windows platform and the producer software will work with any Video-for-Windows compatible capture card. In our testing, at low server loads, the Emulive system provides low latency video sufficient for remote control applications. The system consists of a central server that is connected via network to essentially any number of producer systems providing scalability. This was the first PC based system available identified to meet MMC requirements. One drawback is the producer software places a heavy constant demand on the encoding system requiring a dedicated PC. The software also provides real-time image manipulation through a set of image enhancement and post-processing features. The feature set includes controls for creating graphical overlays, text and image stamps, sharpening or blurring of the image, etc. It is also possible to encode files for rebroadcast and on-demand streaming

AXIS Communications (http://www.axis.com/)

AXIS provides several standalone TCP/IP based cameras and/or camera servers. These stand alone cameras and servers have an embedded Linux OS, video capture and compression, and web server which will broadcast a cumulative 30 frames per second of live video to up to 10 simultaneous clients. The images can be viewed directly from nearly any browser application (use either server push technology and the multipart/x-mixed-replace MIME type or an automatically downloaded ActiveX control for Microsoft Internet Explorer on Windows). Administration is web-based control of all of the unit management and configuration functions. The server can be connected directly to Ethernet or Fast Ethernet networks. The Axis camera servers provide up to four cameras to be interfaced to a single server module. The server also allows control of up to two Pan/Tilt/Zoom cameras or other devices through two built in serial interfaces. These systems are very cost effective, easy to set up and administer, provide very low latency video streaming and thus are ideal for collaboratory applications. Scalability, if required, is supported through the proxy server supplied by BroadWare Technologies.

Electronic Notebooks and Data Management:

Electronic notebooks are still in their infancy stage. Functionality, user interfaces, and robustness are the discriminating factors. Most electronic notebooks are custom written software. Basically, although we operated the ORNL electronic notebook (http://www.epm.ornl.gov/~geist/java/applets/enote/) as a demonstration and evaluated the PNNL notebook (http://www.emsl.pnl.gov:2080/docs/collab/) we found in their currently available form they were of little use in our multi-user environment at the CMM. We rely primarily on FTP / SSH file transfers and email attachments for transferring data along with access to central network storage, locally. At the CMM we do not retain control of or require archiving with us any of our users data so there is only limited potential for applicability in our operating environment. When mature they would be useful at the research group level or perhaps adapted to function as electronic instrument logs.

Remote Tours:

Remote immersive virtual tours are a methodology for familiarizing a user with facilities before their visit. These tours provide an image of the facility, narrative about the facility, and navigation around the facility. This allows the user to become familiar with the facility layout and instruments prior to arriving on-site.

Internet Pictures Corporation (http://www.ipix.com/)

Internet Pictures Corporation (iPIX) provides hardware and software for quickly producing content for an immersive virtual tour of a facility via the web. A couple of examples from the CMM facilities can be viewed at http://surface.mrl.uiuc.edu/ipix/ipix_CMM.htm

CMM and CMM MMC public websites:(http://cmm.mrl.uiuc.edu and http://surface.mrl.uiuc.edu/

The CMM and CMM MMC public access web sites also provide this through their descriptions of the facilities, photos, live streaming video, remote controlled pan-tilt-zoom cameras, instructions and documentation, etc.

Instrument Control:

The interfacing of legacy instruments (and many current instruments) for remote operation can be a daunting task. Initially, the MMC set out to develop a unified architecture, but we have found that due to closed and/or very different instrument interface architectures each instrument presents its own unique requirements and areas of difficulty. However, software components or concepts developed for one instrument are often portable to another. We believe it is important that the remote user experience needs to be as close to "as good as being there" as possible for remote microscopy to be widely accepted. This means the user interface should be highly usable, not frustrating, and provide access to data and control ideally at the same level as local use, such as full size images.

Different instruments present different possibilities for feasible remote control depending on whether the vendor provided a remote control interface and protocol (such as RS-232), a programming API, or nothing for external control. Of course another factor is whether the instrument is computer controlled and to what degree is the computer control. Often there are several functions not linked to the control software, both mechanical and electronic. Typical examples would include aperture insertion and alignment, sample stage motion, or start-up / shutdown functions. Thus, in these cases, it had to be decided whether to develop custom automation hardware / software interfaces for these functionalities and how necessary they would be to successful remote collaboration. The approach investigated and utilized by the CMM MMC was to emphasize a WWW centric approach that included custom html/cgi interfaces, custom instrument client server architectures, remote PC control software, custom hardware interfaces, and integrated combinations of these.

Conventional WWW Browser based

In this type of remote control, an interface is built with standard html browser controls (hyperlinks, html form controls, image maps, etc.) and/or custom Java applets. Once an authorized session is established, clicking a control or submitting form data executes a program on the server through the standard common gateway interface (cgi). This program can either execute the command directly or pass the command to another system or software application. Intermediate software layers may be required to queue the request, maintain information about instrument state, test the command for validity, and implement security features. Additionally the intermediate software layer can reside away from the web server, handling various interfaces to the instrumentation and potentially control from other systems such as a dedicated client, as was the case for one of our instruments. Today, more efficient technologies than the cgi interface are available such as Microsoft .NET technologies or Java Servlets. One of these likely would be the architecture of choice now for a purely Web based interface rather than cgi. An advantage of a purely web based solution is the client requires nothing other than a browser and a broadband connection to the Internet. Also, firewalls aren't likely to be an issue.

Custom Client / Server Architecture

A TCP/IP client server architecture could range from a custom system dedicated to a particular instrument to a system with customizable modular components to a full collaborative environment where, in principal, to adapt to any particular microscope all one needs to define are the microscope functions and the protocols for controlling them.

We developed a system for one of our instruments (Zeiss DSM 960 SEM) having features closer to the first case. In this system a dedicated instrument server was developed that listened for client requests, queued the request, validated them, translated them to instrument commands, issued the command to the appropriate instrument interface, maintained information about instrument state, and provided additional functionality (return to a subset of a state). This system, though currently hard coded for the Zeiss SEM, could be made more general through re-coding for instrument and command definition files. However, it is highly unlikely any architecture could be made general enough that application to a new instrument would not require significant customized coding of the software, likely for both client and server.

An example of a full collaborative system is the LBNL DeepView Architecture developed for the MMC. DeepView: can be described as a channel for distributed microscopy and informatics. A microscopy channel advertises a listing of available online microscopes, where users can seamlessly participate in an experiment, acquire expert opinions, collect and process data, and store this information in their electronic notebook. This channel is a collaborative problem-solving environment (CPSE) that allows for both synchronous and asynchronous collaboration. The DeepView testbed includes several unique electron and optical microscopes with applications ranging from material science to cell biology and included a scanning electron microscope at the CMM. In this architecture three basic services are used to meet the extensibility and functionality constraints. These include: Instrument Services (IS), Exchange Services (ES), and Computational Services (CS). These services sit on top of CORBA and its enabling services (naming, trading, security, and notification). IS providing a layer of abstraction for controlling any type of microscope. ES provides a common set of utilities for information management and transaction. CS provides the analytical capabilities needed for online microscopy and PSE.

Remote PC Control Software

If an instrument is essentially already fully controlled by a graphical computer interface an obvious solution for remote operation would be remote PC software of which there are various commercial and open source applications available. Those utilized in the MMC include Symantec PCAnyWhere (http://www.symantec.com/), Netopia Timbuktu Pro (http://www.netopia.com/), the open source AT&T Cambridge's VNC (http://www.uk.research.att.com/vnc/, http://www.realvnc.com/) and its derivatives TridiaVNC (http://www.tridiavnc.com/) or TightVNC (http://www.tightvnc.com/). PCAnywhere, AT&T VNC, and TightVNC all offer Java applet clients enabling the desired entirely web based solution to be implemented, although Symantec has completely discontinued support for it's Java client and it is no longer available. Of the VNC based applications, TightVNC offer the best performance because of its enhanced compression algorithms. PCAnywhere supports MS Windows PC's, Timbuktoo Pro supports MS Windows and Apple Macintosh PC's, and the various VNC's support many different OS's including MS Windows, Linux, and various Unix platforms.

One of the major problems associated with many current PC based electron microscopes or imaging instruments is that the image displayed is an overlay. Therefore, on the remote client for remote PC control solutions there is not an image on the client screen. Using live Internet video streaming technology, and Netscape only JavaScript 1.2 (digitally signed) features we can create a small "always on top" window container for the video image and other custom control Java applets. We have transferred this technique to ORNL, where they have employed it for their

Phillips XL-30 SEM and Hitachi S-4700 SEM. There are, however, potential limitations of this technique related to if the native users interface relies on the operator manipulating the mouse directly on the image. An example would be when the native user interface intends the operator to interact with graphics overlaid on the image field such as cursors, cross hairs, etc. or for drag and drop type operations. These are typically seen on the image field not on the image in the video window. This makes it difficult for the remote operator to correlate these positions with the precise position on the image. These problems are not considered insurmountable, but are inconvenient. Other disadvantages to the remote PC software approach are that you are giving away full control of computer and instrument, although philosophically this is little different than with local users. Also the native user interface, may be too feature rich or complicated for the intended purpose. Despite these limitations, there are many advantages to this approach. First, and foremost, for instruments with a closed architecture this may be the only reasonable approach. Other advantages are: it is WWW based, it is nearly platform independent, it does not require any special software on the remote computer, it is easy to implement, it preserves the considerable investment in the native user interface, it is readily integrated with other collaboration tools (e.g. electronic notebooks, etc), it provides easy access to all available data, and it uses mostly low cost or free commercial software. This approach does have the added benefit that data analysis tools are inherently shared and text chat is available using any text editor.

We have carefully considered the advantages and disadvantages of the remote PC software approach. We concluded the appropriateness of this approach depends on the specific application and target audience. However in the final analysis it may be the best and/or only viable option due to the closed architectures of many current and legacy instruments. This was determined to be the case for our systems where this approach was applied.

Other Software / Hardware Development

<u>*TCP/IP to RS-232 bridge server*</u>

This small TCP/IP application was developed to allow, for example, a cgi script on a web Server to send and receive commands on from a serial port (RS-232) on a different system through a TPC/IP connection. This application was written to be highly general supporting buffered and unbuffered operation. It works on all MS Windows systems and can be installed as a Windows NT type service. It was primarily developed to control video switches or pan-tilt-zoom cameras, but should work with nearly and RS-232 controlled device. It is basically a very simplified and stripped down version of our dedicated instrument server software.

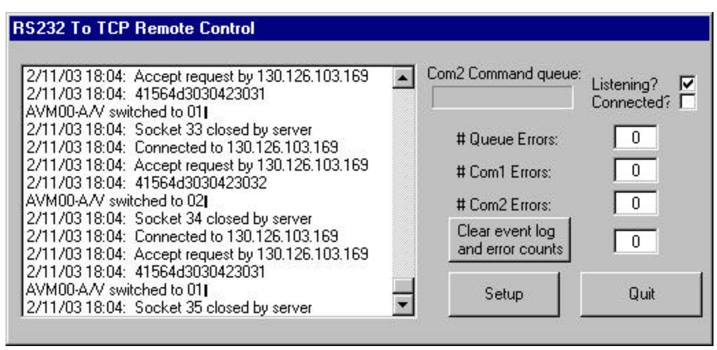


Figure 1 Interface of TCP/IP to RS-232 bridge server

The interface for interactive mode is shown in figure 1.

Precision Motion Automation and TCP/IP interface

In many cases on legacy and current instrumentation there are mechanical motion controls without automation or even motor drive that are essential to routine operation of the instrument. Prime examples of these in electron beam instruments are specimen stages and aperture controls. In the design of this system high precision and coordinated motion capabilities for multiple axes were desired. The system designed is built with mostly off the shelf components with custom software. Rather than stepper motors, we chose to develop for encoded DC servomotors for their higher torque, smaller size, and position encoding. Nearly any DC servomotor can be used with the system. The system also permits coordinated motion such as rotation about a point other than the mechanical rotation axis. In our applications small zero backlash gear head motors with over 4000 steps per revolution were selected. The software is designed for up to five axes (e.g. X, Y, Z, tilt, rotate), with joystick control and hardware and software limits. The control electronics and application development library are products for robotics and CNC machine development from J.R. Kerr Engineering (http://www.jrkerr.com/). The system in its application (scanning auger microscope specimen stage) and the user interface are shown in figures 2 and 3. The Stage control software operates as a TCP/IP server to enable remote operation of the stage. A simple client interface was developed for this capability.

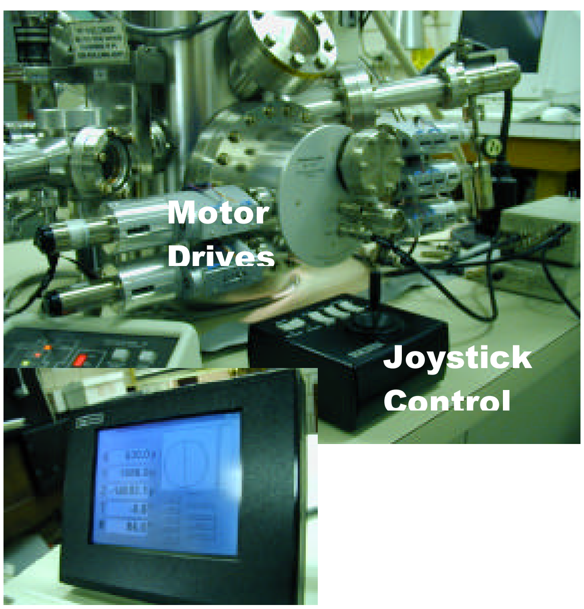


Figure 2 Motion Control System as installed on PHI 660 Auger Microscope for 5 axes with joystick and push button control.

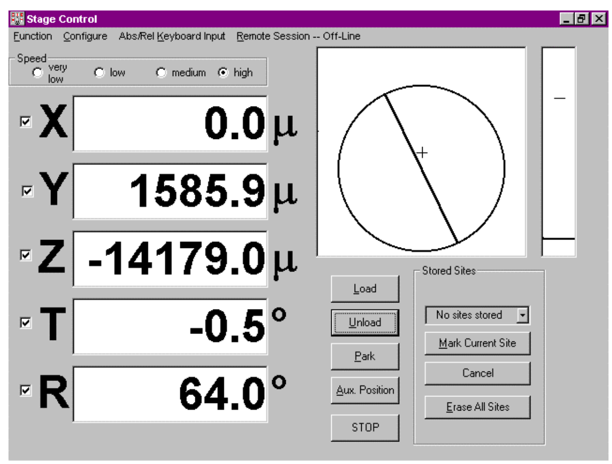


Figure 3 User interface developed for 5 axis motion control system included absolute position indication, a position mimic, preset position. Several other features not shown

Facility Management Systems

Managing usage in a multi-user open collaboratory environment requires accessible tools for potential users to submit research proposals, maintaining project and user vital information readily accessible to facility staff, and providing a system for instrument reservation and authorization. As both part of the MMC effort and outside of it we have been developing an integrated system providing for these capabilities. Within the MMC project we have developed an intelligent Web based user scheduling and reservation system that we deployed March 1, 2000 for all of our instruments in the CMM. The system interface is shown in figure 4. The reservation system is suitable for general use for the MMC and we have supplied it to ORNL for their facility. We have also developed separately a web based electronic proposal system and system for managing project and user vital information that are fully integrated with the schedule system. These systems have become *mission critical* components of our facilities daily operation.

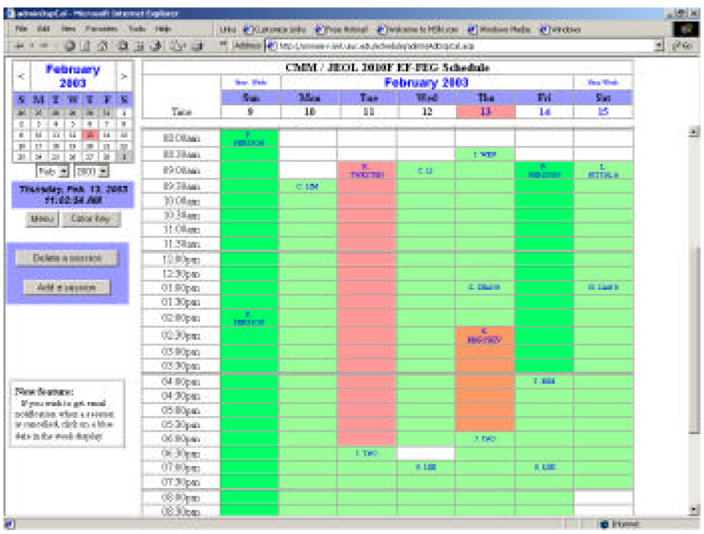


Figure 4. Showing the instrument schedule interface for our scheduling system. An approved user for an instrument can log in and reserve time by simply clicking on the start and end times for their session. Other features include a wait list, email, sign-up rules, and instrument status, among others. For facility staff numerous other functions are provided in addition to administrative functions.

Instrument Access Modes:

To meet the requirements of different levels of access needed we established three different levels of access within the UIUC MMC site. These included public access, and two controlled access modes, a passive observer mode, and an active control mode. Within the active control mode, specific to a particular instrument, more than one level of access could be implemented. Public access typically includes only streaming video from the instrument image and room cameras. The primary function of the public mode was for visibility and outreach, i.e. to create a persistent presence on the web for the MMC beyond plain web pages. The passive observer mode gives the remote collaborator much higher level of access to the data stream but without any control. Thus, in this case, the remote collaborator watches the progress of an experiment and communicates with the local researcher operating the instrument. In the active control mode the remote user may be given limited control of certain instrument function to essentially full control of the instrument.

Instruments On-Line

The CMM currently has several instruments and peripherals available on-line emphasizing a WWW-centric approach with varying levels of access and functionality. We still plan to add additional new instruments as long as available resources permit. They are placed roughly in order in which they were integrated into the MMC

Zeiss DSM 960 Analytical Scanning Electron Microscope

A web and video server donated to the MMC program by Sun Microsystems was installed and set up. This system also included video server software donated by Graham Technology Solutions. A customized version of Argonne National Laboratories (Dr. Nestor Zaluzec) telepresence microscopy (TPM) web site was set up as our initial TPM home page:(http://cmm-sun.mrl.uiuc.edu/Zeiss/TPMLVideo1024.html)

A Web site was initially developed that implemented HTML/cgi remote control of the Zeiss DSM-960 analytical scanning electron microscope (SEM) (Figure 5). This required the development of local control software for the Zeiss, which regulates and monitors communication with the instrument. Hardware and interface for computer control of the beam stigmators was developed. This is a unique microscope in that it has accessories for cathodoluminesence monochromatic imaging and spectroscopy (Oxford MonoCL) and an electron backscattered pattern (Oxford Opal EBSP) orientation / texture system in addition to the more standard SEM and X-ray microanalysis capabilities. Following an upgrade of the accessory analytical sub-systems in March 1999 to the Zeiss SEM we were able to further develop this system to include full remote access to these ancillary techniques using the Remote PC control approach for these peripherals (Figure 6).

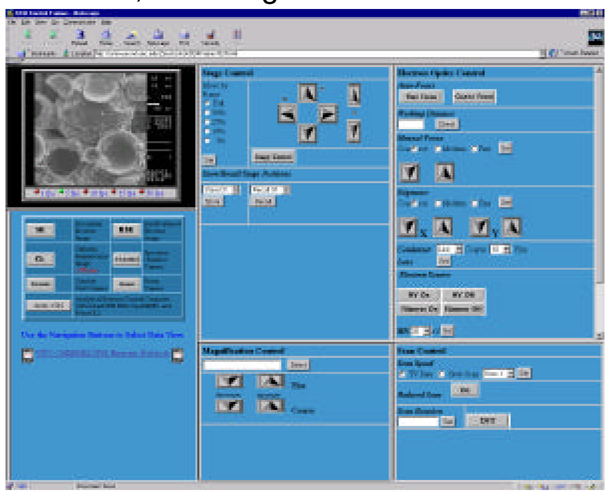


Figure 5 HTML/CGI interface developed for remotely controlling the Zeiss DSM 960 Analytical Scanning Electron Microscope.

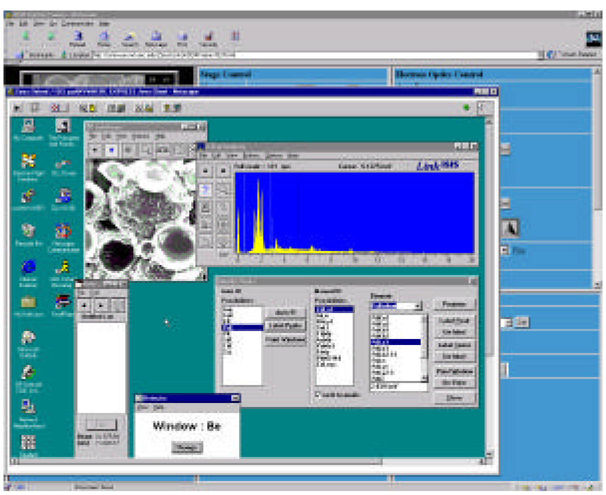


Figure 6 Remote Control of Zeiss SEM analytical subsystems via Remote PC control software in a web browser window. The microscope control window is seen in the background, thus simultaneously available to the remote user.

The Zeiss control software was modified to also incorporate TCP/IP server functions and monitor instrument state and provide a direct network control interface. A TCP/IP client GUI was developed for our Zeiss SEM. The Client GUI we developed, which is limited to the MS Windows platform, was used as the prototype GUI for developing a more user friendly, platform independent, JAVA GUI to the LBNL DeepView Architecture. The instrument server interfaces and remote client control interfaces are shown in figures 7 and 8. A web browser window with live video streaming is used to provide the microscope image.

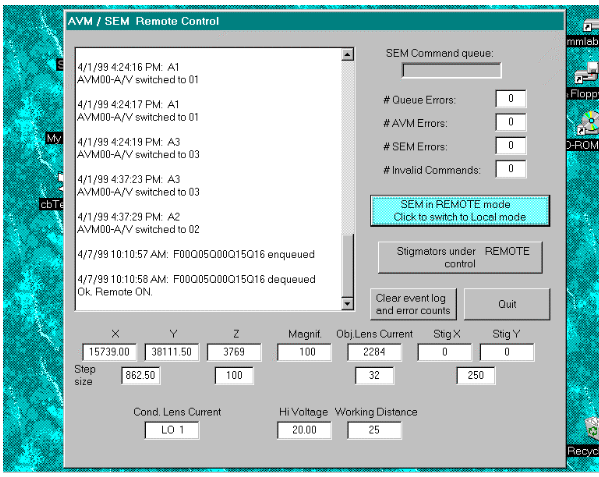


Figure 7 Instrument Server developed for the Zeiss SEM. This is a dedicated instrument server that listens for client requests, queues the request, validates them, translates them to instrument commands, issues the command to the appropriate instrument interface, and maintained information about instrument state.

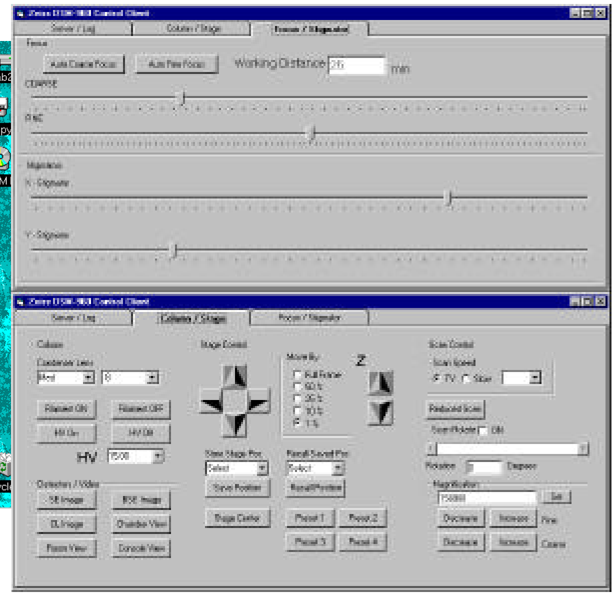


Figure 8 TCP/IP Client for controlling many common microscope functions. This version specifically adapted to Zeiss SEM. Model for DeepView generic microscope control client

The LBNL DeepView system was set up to control the Zeiss SEM, interfacing to our instrument server. Our client graphical user interface was then ported to JAVA and adapted for DeepView as a client control interface to integrate the Zeiss into the DeepView environment.

We have used the Zeiss SEM as a test and development test bed, in which, we have developed and/or deployed the three different Internet remote control architectures mentioned above. This allows us to directly evaluate and compare the strengths and weaknesses in each system on a single platform providing direction and feedback for selection and refinement of approaches. For example, when we first tested our dedicated client/server it was beyond our expectations the performance and feature benefits, in particular live update of the client with the instrument state, over the HTML/cgi (perl script) interface. The DeepView architecture extends this further by providing a service based environment that can provide all the desirable collaboratory functions in an integrated environment. These functions may include security, session control, data storage and analysis, etc.

Hitachi S-4700 High Resolution Scanning Electron Microscope

The Hitachi S-4700 SEM remote interface consists of remote PC control of the SEM control computer and the analytical peripheral (X-ray spectrometer) control computer. This instrument is an example of the video overlay problem for most PC controlled microscopes, therefore the live microscope image is presented in an “always on top” browser window in the field where the image would otherwise be in the interface. For this instrument, also included in this window are controls for the stage and a video feed switch (Java Applets). The interface is shown in figure 9. Hitachi later supplied remote capability in a very similar manner using Microsoft NetMeeting which provides for peer-to-peer application sharing and an “always’ on top” video conferencing window. Stage control was provided directly in the S-4700 control application. Recently, Hitachi and Quartz Imaging Corporation demonstrated (Microscopy and Microanalysis ’02 conference) a complete microscopy collaboration architecture, which included the streamed video image directly embedded in a customized VNC-like client. Video conference and object cameras are also provided and their video can be accessed by remote control of a video switch.

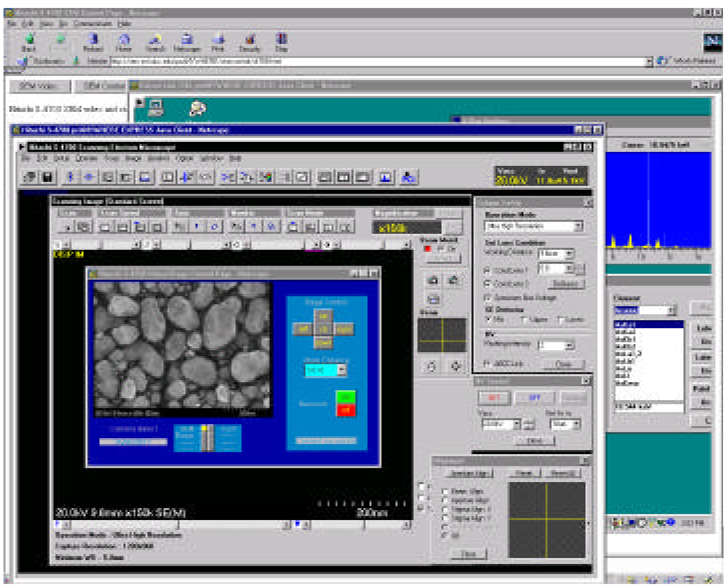


Figure 9. Hitachi S-4700 remote control interface consisting of an access controlled browser window in the background to startup each window for the user interface. The remote PC windows are also each separately access controlled. With the use of web browser based remote PC control clients a single access point can be presented without requiring the user to download and install special software. The video window contains Java applets developed for stage and video switch control.

Cameca IMS-5F Secondary ion mass spectrometer

The Cameca IMS-5f SIMS was initially set up only for public and observer modes because of instrument limitations. In addition to teleconference and object cameras, a scan converter with remote controlled pan and zoom capabilities was used to stream an image of the instruments control and data monitor. An upgrade to the instrument computer interface was acquired and is currently being debugged. This upgrade will permit remote control capability via remote PC control software. This new update also provides a much improved observer mode since the instrument data can be displayed at full resolution without the scan converter using a VNC based solution.

Physical Electronics 660 Scanning Auger Microprobe

The Physical Electronics 660 Scanning Auger Microprobe has a remote interface similar to that of the Hitachi S-4700 SEM. In this instrument, the microscope image is displayed separately on a video monitor not on the screen of the instrument control and data acquisition computer. Remote PC software is used to control the instrument computer and an “always on top” browser window provides two video streams along with a Java applet (video switch) (figure 10). This instrument is also an example of a legacy instrument that doesn’t provide computer control of several functions. One function deemed necessary for remote operation was specimen stage control and this was developed as discussed previously.

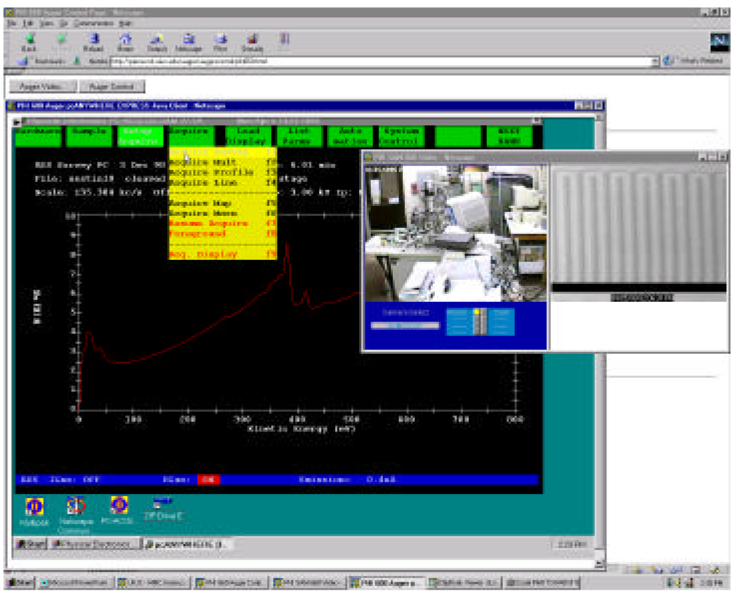


Figure 10. PHI 660 remote control interface consisting of an access controlled browser window in the background to startup each window for the user interface. The remote PC browser window is also separately access controlled. The video window contains two video streams, one for the microscope image and another for conferencing and object cameras along with a Java applet for video switch control.

Kratos Axis X-ray Photoelectron Spectrometer (XPS)

A Kratos AXIS high-resolution imaging XPS was integrated into the MMC collaboratory. This 0.8 M$ instrument, acquired during the MMC project period, is controlled by a UNIX workstation. Much like the previous instruments, an X-server running on the PC workstation, connected to the UNIX workstation, could then be remote accessed. A private network was set up to a PC workstation to provide a remote interface via remote PC software. The UNIX workstation was not directly networked because of security issues and previous experiences with UNIX computers controlling instruments. Specimen, conferencing, and object video is provided through and AXIS video server.

JEOL 2010 Transmission Electron Microscope

This instrument is set up for public and observer mode access. An extremely limited, remote control mode is available (remote collaborator controls image acquisition computer). For this Instrument, a dual mode image acquisition TEM camera was acquired to integrate into the MMC. Gatan developed this camera specifically for remote microscopy and real time composite video applications. It can be operated in a slow scan integrating mode or TV –rate mode while always providing a composite NTSC video output of its image memory. An Axis Communications video server provides streaming Internet video as shown in figure 11. Observer and remote control modes also utilize remote PC software.

Figure 11 Observe mode browser window for JEOL 2010 TEM. Four video streams including a remote controlled pan-tilt-zoom camera, an infrared camera (room is often darkened for operation), the microscope image, and instrument status screen are provided.

JEOL 2010F Scanning Transmission Electron Microscope

The JEOL 2010F, a new state-of–the-art TEM/STEM facility, was acquired by the CMM during the MMC project period. This 1.4 M$ instrument was acquired complete with remote control capabilities and software. JEOL has stated that the MMC has had a significant impact on their development of this capability as will be further described later. JEOL's architecture for this instrument is a dedicated client / server with the optional capability of using control hardware at the client (joystick and knob pad) for controlling some instrument functions. The MMC project provided some of the resources to make this instrument fully remote controllable. This instrument has been used several times for remote collaboration and demonstrations, including many in cooperation with JEOL. We have augmented these capabilities with higher performance multi-channel video streaming. As a very complex instrument JEOL engineers also frequently use the video capabilities to monitor the instrument status during service.

Philips X'pert Materials Research X-ray Diffractometer (2)

In addition to a room pan-tilt-zoom camera, there are cameras dedicated to monitoring the instrument. Otherwise these instruments are completely PC controlled, thus remote PC software is used to provide both the observer and control interfaces.

Future Instruments

We plan to continue to integrate future instruments into the MMC environment, however, emphasizing only passive observer mode. This mode has proven quite useful in many instances not only for remote collaboration but also for routine monitoring, user assistance, and instrument service and maintenance. These plans may include as resources permit (big advantage to low cost solutions):

- ?? FEI DB 235 Focused Ion Beam / Scanning Electron Microscope
- ?? Physical Electronics TRIFT III TOF SIMS
- ?? Planned Analytical Scanning Electron Microscope

Demonstrations

We have actively participated in many of the demonstrations requested from or organized by the MMC, in addition to performing many local demonstrations ourselves. Most notable was the Expo on the Future of Experimental Science: A Novel Use of the Internet. This expo was held in the House of Representatives Committee on Science Hearing Room on June 17,18 1998. A list of the major demonstrations given by the MMC as a whole can be seen at http://www.ornl.gov/doe2k/ornl/demo.htm

Papers, Posters, and Presentations

We presented a paper "Remote Access to Microanalytical Instrumentation at UIUC MRL/CMM" at Scanning'99 in Chicago, IL, April11-14 and participated in the telepresence microscopy tutorial organized by Dr. Edgar Voekl and Dr. Larry Allard of ORNL. Co-authored paper,. E.Voekl, K. B. Alexander, J. C. Mabon, M. A. O'Keefe, M. T. Postek, M. C. Wright, and N. J. Zaluzec, Proceedings of the 14th conference of the ICEM(1998), Cancun, Mexico, Vol. I, pp. 289-290. The MMC was also highlighted in a poster "Center for Microanalysis of Materials: A National User Facility" we presented at Microscopy and Microanalysis '99 in Portland, Or, August 1-5, 1999. We have also been co-author to several other posters / presentations involving the MMC as a whole.

Research and Education

We plan to continue the utilization of the MMC in research and education. Modes of use of the MMC infrastructure have been found to be quite diverse. Researchers can continue or complete work after an on-site visit. Students can consult with their advisor or another expert across campus (or an ocean). Demonstrations and educational instruction can be given to small or large groups at or away from the actual instrument. Enhanced visibility for the facilities is achieved making researchers internationally aware of their availability. Ready access is available to researchers wishing to collaborate with the facility staff without travel.

Infrastructure

We have assisted with justification and planning for an internal high-speed Fast Ethernet Network connected to the campus backbone. This high-speed connectivity is not directly an MMC effort and supports MRL programs in general, but addresses a significant MMC need. This infrastructure upgrade is part of an overall upgrade of networking in the college of engineering that will provide the connectivity necessary in classrooms to support educational utilization of programs like the MMC. We have also obtained access to Internet2 through the campus backbone for the MRL to support the MMC and other projects.

Industrial Interactions

The MMC is influencing science, but its impact is also being felt in industry. From the beginning, the MMC had partnered with JEOL USA, Inc., Philips Electron Optics, NSA-Hitachi Scientific Instruments, RJ Lee Instruments Ltd., Gatan Inc., and EMiSPEC Systems, Inc. Later LEO Electron Microscopy Inc. and Soft Imaging System GmbH had joined the collaboratory.

One of the most significant successes of the MMC project is that electron microscopes are now designed by their manufacturers to be "collaboration ready". The visibility of the MMC project in the microscopy community has created a significant user demand for remote control capability and the manufacturers use the remote control features of their new instruments as a marketing tool.

For example, JEOL handed out an interesting advertisement at their trade show booth at a recent technical meeting (the joint annual meeting for the Microscopy Society of America and The Microbeam Analysis Society held in 1999) The advertisement proclaimed that “Someday all TEMs will be in Nebraska” and “All Microscopists can be in Aruba”. It continued saying that “You might ask JEOL—‘Why will all TEMs someday be in Nebraska?’ and “Our answer might be—‘Because they can be.’” Their booth demonstrated remote operation of their new FasTEM microscope.

JEOL is the first of the MMC industrial partners to reach the market with a real product whose design was significantly influenced by the MMC. The following excerpt from a letter sent by Mike Kersker, Director of JEOL USA, to the head of the MMC states how JEOL has been influenced by MMC. The FasTEM is the result of the development effort mentioned in the letter.

"As a representative of JEOL I'd like to go on record as saying that the DOE 2000 project, of which we are an integral though peripheral participant, has stimulated and motivated our company to think more seriously about the future of remote microscopy and has precipitated an active and aggressive program to

complete a better computer interface and a consequent remote capability for our front line TEM and SEM instruments. We would not have pursued this important development without the stimulation of the DOE 2000 Program. I can assure you that the world of microscopy will be a different one because of your collective efforts."

Quartz Imaging Corporation, in collaboration with Hitachi has recently released a software and hardware solution they call Wide Area Microscopy or WAM (http://www.imagedatabase.com/pages/products/wam.html), advertising that this suite of products combines to form a complete solution to the problem of collaborative microscopy. Hitachi was an industrial partner in the MMC and it can be assumed that this product development was significantly influences by the MMC.

Physical Electronics Industries (PHI), a manufacturer of surface analysis equipment, has expressed interest in what we have developed for their system, which resulted in a visit to our facility by two of their engineers. They have also conducted, as an experiment, two remote training sessions with staff and users here at UIUC to evaluate the viability of training users in the use of the advanced data analysis features available on the Auger. These sessions were considered very successful.

Conclusions

Collaboratories can effectively remove the limitations of time and distance for accessing instrumentation and expertise. However, for the immediate future we believe that remote operation will play a more minor role but with the other collaboratory features becoming common and mainstream. We have developed WWW based collaboratory interfaces for advanced analytical instrumentation based heavily on existing commercial technologies such as Internet streaming video and videoconferencing, remote PC control software, TCP/IP client / server applications, and web browser interfaces (HTML/CGI, Java Applets).

We feel that this project and other similar projects will eventually have a significant impact in how national resource facilities operate and how they are utilized. This type of remote access will eventually make long-distance collaboration and access to highly specialized facilities more routine, allowing for more effective ongoing investigations, access to precisely the right equipment and expertise, and ultimately better science.

Our opinion is that eventually real time application sharing will play an important role in remote collaboration. This would include word processing, presentation software, technical simulation or analysis software, etc., in addition to remote observation or operation.