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SCANNING ELECTRON MICROSCOPY IN THE NEXT MILLENNIUM

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Abstract

This paper is a speculative preview of the probable advances in scanning electron microscopy in the early years of the next millennium. The guiding principle of the new century will be full exploitation of what is already available and what is likely to become available. Remote microscopy can be expected to flourish in an era of rapidly increasing network bandwidth Virtual microscopy or the simulation of the microscopy in software, will play an increasing role in teaching of microscope principles and techniques. Tomorrows instruments will have increased and more effective automation through the application of knowledge-based techniques. Improvements to the instrument in terms of new lens designs, aberration correction methods and improved detectors will improve image resolution and signal to noise ratio, allowing the scanning electron microscope to operate at higher magnifications than currently practical. Viewing technology will be flat panel displays and projection systems. Specimen preparation will be largely eliminated by wider adoption of variable pressure and environmental systems. Advances in mainstream computing technologies will be swiftly mirrored in the specifications and potential of computer-controlled instruments.

Key Words: Scanning electron microscopy, telemicroscopy, remote microscopy, distance learning, virtual microscopy, expert systems.

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Introduction

This paper is intended as a speculative preview of some of the advances in scanning electron microscopy which can be expected to occur in the early years of the new millennium This speculation is based on what is being done to-day, what could be done to-day and emerging technologies that could be applied to microscopy in the future.

The modem scanning electron microscope (SEM) is a sophisticated computer-controlled software-driven instrument, yet the average modem microscopist perhaps utilises a small percentage of the instrument's capabilities. The guiding principle of the next millennium for microscopy will be to exploit to the full what is currently available and what can be expected to become availabie. Hence this paper will discuss current capabilities and draw predictions for future innovations from the present state-of-the-art.

The Remote Microscope [1]

The past few years have seen a remarkable convergence of computing and communications technologies, most notably through the advent of the Internet and the World Wide Web. Despite the hyperbole that naturally surrounds such a sea-change, it is clear that the Internet has been adopted by millions of professionals, entrepreneurs, and laymen alike. It is also clear that networking is currently the impetus behind all mainstream software applications development.

In microscopy, the network was initially used just for transferring electronic files of SEM images and associated results amongst researchers. However the ability to network the microscope itself by virtue of the mainstream computers used to control modern instruments meant that more significant applications of networking could be achieved. For many microscopists, the possibility of remotely controlling their instrument has long been attractive, whether for monitoring purposes in multi-user facilities allowing an experienced operator to assist others without needing to be at the SEM itself, or simply to permit instrument operation without the necessity of entering "clean-room" laboratories.

The feasibility of near "real-time" distance collaboration has spurred interest and development. SEMs are expensive instruments, which need to be justified by all organisations in terms of purchase and maintenance and in the recruitment and retention of suitably trained operators. Quite often organisations still have a need for advanced SEM services, and will turn to consultancy firms or research universities. Samples will be posted to the consulting microscopist, investigated and the results returned to the originating organisation. The possibilities for samples being misinterpreted, or for unexpected observations derailing the intended investigation are obvious. Sending an observer to the microscopy session can be problematic for some organisations in terms of expense and loss of time.

Two distinct routes to remote microscopy have thus far been adopted. The first method has been to develop customised web-based interfaces for the microscope. The second method has been to utilise proprietary software packages, which allow PCs to be remotely controlled and hence allow remote access to microscope control software.

In the web-based approach, a typical architecture involves a web server resident either on the microscope itself or on a locally networked computer. Remote users (clients) connect to the web server (host) via a standard web browser, such as Netscape Navigator or Internet Explorer, and download the user interface, which is normally a collection of web pages. Icons and forms in the web pages usually represent microscope controls. Client requests are transmitted via the normal hypertext protocols to the web server. At the web server, they are translated and communicated via a CGI (Common Gateway Interface) program to the SEM as microscope instructions. Results are returned to the client via the same chain. Images may be returned as single static images or as a continuous stream of images displayed in a Java applet. There is an option to save these images for redisplay at a later time.

In the proprietary approach, a package such as PCAnywhere or VNC (Virtual Network Computer) is installed both on the host microscope and on the client's computer to be used for remote control. The remote client connects to the host microscope via the relevant package, and the microscope desktop appears on the remote user's monitor. Remote control is then achieved via the conventional microscope software, albeit with some delays due to network latency.

Both approaches have their strengths and weakness. The web-based browser approach allows for complete flexibility as the user interface can be tailored for specific remote microscopy applications such as control, monitoring, fault diagnosis or collaboration, and the remote user is virtually unrestricted in terms of computer hardware, operating system environment and web browser. Its major disadvantage is the development time invested in creating the customised interfaces. The proprietary approach uses off-the-shelf software and so development time is negligible. The disadvantages are twofold in that the software packages are not designed specifically for microscopy and so are not optimised for transferring SEM images, and these packages are designed to permit complete control of a computer via the network - hence the remote user has access not only to the microscope software but also to every other program and file on the microscope computer.

The first commercial products for remote microscopy (such as NetSEM marketed by LEO Electron Microscopy Ltd., Cambridge, UK) have already arrived. Specialist systems for remote monitoring, remote instrument fault diagnosis and remote collaboration have already been demonstrated. The use of remote microscopy will continue to grow, especially in the areas of collaboration, where organisations will offset the cost of SEM ownership by providing microscope consultancy services to other companies or universities with telemicroscopy obviating the need for investigators to travel to the microscope site, and in instrument diagnosis, where service engineers will perform tests (via the network) on a suspect instrument to determine the nature of the fault and hence effect swifter repairs.

The Virtual Microscope [2]

What is a "virtual microscope"? The easiest analogue is to consider aircraft simulators - it is much easier, safer and less expensive to train a pilot in an aircraft simulator than in a real aircraft. An SEM simulator (or "virtual microscope") need only consist of a personal computer and appropriate software to emulate instrument operation.

A virtual SEM should include a user interface, comparable if not identical to actual SEM user interfaces so that the user learns how to use the microscope control software as well as the microscope. A database of real SEM images is essential so that the novice acquires microscopical intuitions concerning the sorts of images of varying quality levels which may be obtained from an SEM. Image processing techniques are then employed to mimic operational changes by manipulating stored images - focusing, magnification, astigmatism correction, beam alignment etc. are but a few of the simulations that can be achieved.

For a virtual SEM to be an effective teaching tool, it must also support the student in terms of the theoretical principles of microscopy so that the novice gains an understanding of SEM and sample behavior. This could involve a dedicated intelligent pedagogical module to monitor the student's progress and tailor the presentation towards the individual needs of the student. Cambridge University Engineering Department has conducted some preliminary work in this area via a series of final-year undergraduate projects to prove the feasibility of various components required in a final system.

The advantages of using virtual microscopes for SEM training, in terms of reduced expense, ability to teach multiple students simultaneously, and reduced demands on actual instrument time and skilled operators, should lead to virtual microscopy being the principal teaching method of the future.

The Intelligent Microscope [3]

It is sometimes assumed that because modern instruments are software-driven, they are therefore easy to use. This is a non sequitur. Very little software is actually easy to use and the accumulation of new "features" with each new version can readily make life more difficult for the would-be user.

Instrument manufacturers have attempted to ease the burden on the microscopist with a number of mechanisms. Many instruments allow the operator to save the current parameter settings of the instrument so that the instrument can be restored to that configuration in the future. This is usually in the form of a data file or Macro. "Macros", or instruction sequences, can also be created to perform sets of commands, which modify the instrument configuration for a particular need. Some instrument tasks such as focusing, alignment, astigmatism correction, etc., can be performed by image processing algorithms to varying levels of success.

Whilst these techniques are helpful, they do have limitations such as an inability to adapt to the actual circumstances at the time of invocation and are local rather than global optimisations. There is no overall guidance within the software to mesh each component into a cohesive whole. The microscope control software lacks knowledge.

Research is ongoing at Cambridge University Engineering Department to design and implement "knowledge-based" solutions to this problem. This approach has involved the creation of a model of the task of SEM operation and the acquisition of heuristic knowledge on SEM procedures and parameter settings for each aspect of the task from expert microscopists and other sources. The captured knowledge was then converted into a formal representation designed for computer comprehension and an "inference engine" was constructed to "reason" using the formalised knowledge.

The resulting prototype system, known as XpertEze, is a standalone package, which is resident on the SEM itself and can currently interface to any LEO 400 series instrument. XpertEze requires the operator to indicate general sample type (conductor, semiconductor, insulator, biological or unknown), the required detection mechanism (secondary electron, backscattered electron, etc.,) and either an exact desired magnification or a magnification range. XpertEze then activates the instrument, ensuring that the control software is running, an adequate vacuum exists, a working filament is fitted and so forth. Next it initialises the SEM in terms of core parameters (such as accelerating voltage, probe current, gun alignment, screen brightness, etc.) using the constraints specified by the operator and drawing upon its own knowledge of what settings are appropriate for a given sample at a certain magnification using a particular detector. At the end of this initialisation phase, a reasonable image of the specimen is obtained. XpertEze then employs image processing algorithms to obtain image quality measures in terms of charging (and its absence), image resolution, signal-to-noise ratio, contrast and brightness. Where the obtained image yields an unsatisfactory quality measure (for instance charging is occurring), XpertEze proceeds to alter instrument parameter settings to improve the image quality measure. This process will iterate until satisfactory image quality is obtained in all aspects, yielding a final optimised image.

The advantages of this approach are numerous, and include such benefits as enabling relatively novice users to achieve results with an SEM that would have previously required an expert microscopist, higher throughput by faster, better and more consistent performance, and the potential to completely automate some microscopy applications. The trend in instrument development is towards increasing automation and the coming decade should see intelligent microscopes at the forefront of scientific and industrial endeavours.

The Improving Instrument

The SEM can also be expected to improve both in terms of the instrument itself and the computer hardware and peripherals.

In terms of the instrument, enhancements in emitters (tungsten, lanthanum hexaboride, and field emission) can be expected through novel designs and better manufacturing processes. SEM electron lens design will benefit from recent and ongoing work in scanning transmission and transmission electron microscopy, leading to SEM lenses with reduced aberrations, either by different physical design or by image processing for aberration correction. Signal collection in detectors will improve and specialist detectors such as electron energy loss spectroscopy will achieve much wider acceptance. Variable-pressure and environmental instruments will dominate most areas of microscopy, rendering much specimen preparation redundant. Overall, instrument performance in terms of achievable resolution and signal-to-noise ratio will improve by an order of magnitude.

For image display, the unwieldy and bulky cathode ray tube will be superseded by slim liquid crystal display panels with reduced power consumption, electromagnetic pollution and space requirements. Dye-sublimation and other advanced printers will deliver very high-resolution quality output. Optical technologies capable of storing thousands of images per disc will handle image archiving needs and next-generation intelligent database management systems will tame the information overload represented by these archives. The technology already exists for voice controlled microscopes - voice control will become omnipresent in home and business computers in the next five years and hence will find its way into the microscopy mainstream soon thereafter. All of these advances will be underpinned by continuous improvement in computer processors, memory and storage devices.

Conclusions

The scanning electron microscope will remain one of the most important tools in the advancement of science in many fields of knowledge. The instruments of tomorrow will be as far superior to today's instruments as today's instruments are superior to the very first commercial instruments.

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