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COMPUTER TECHNIQUES FOR TOPOGRAPHICAL ANALYSIS IN THE SCANNING ELECTRON MICROSCOPE

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Résumé

Nous rappelons les techniques utilisant l'ordinateur et permettant les mesures en trois dimensions dans le SEM.

Abstract

We survey the computer techniques which can facilitate three-dimensional measurements in the SEM.

1 INTRODUCTION

There are several means by which three-dimensional (3D) surface microscopy may be performed with the SEM, and computer techniques can generally assist in this.

The basis of the stereo technique is to record a pair of images, the specimen, or beam, being tilted between exposures. The images may be recorded photographically, or by an on-line digital system. To obtain the 3D shape from the stereo pair, the correspondence problem must first be solved; that is, the point in each image corresponding to each specimen point must be located. Knowledge of the projection geometry of the two views then permits the calculation of the surface topography. The human visual system can perform this correspondence analysis when the appropriate micrograph is presented to each eye, and allows the SEM user to visualise the specimen topography.

Contrast interpretation techniques have been developed, based upon models of contrast formation mechanisms. Analysis of the signals from one or more detectors (whose response varies with surface slope) permits the computation of topographical data.

Finally, automatic rangefinding techniques have been used, where a region containing a point of interest is scanned repeatedly as the focus current is varied. The focus current giving optimum image contrast may be used to calculate the surface height.

These techniques are now described in more detail.

2 STEREOMETRY

The stereometric technique, because it is based upon precise geometrical relationships, is potentially the most accurate of the methods discussed here. It is also convenient, generally needing no modifications to the microscope, and approximate or qualitative results may be obtained very simply. For accurate quantitative results, however, the method can be very time-consuming, and a complex calibration procedure may be required.

Various aspects of the correspondence and geometrical stages of the analysis are discussed in the following sections.

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2.1 Correspondence analysis

Correspondence analysis of a stereo pair is easily achieved by eye, although the procedure becomes tedious and error-prone if the number of points to be measured is large. Matching points may be found by scrutiny of the two pictures, when the position of a feature is measured independently in each image. An alternative is to present the images stereoscopically, and to use a device such as a 'floating spot' marker injected into the images. The fusion mechanism of the human stereopsis system allows the operator to judge when the spot apparently lies on the surface of the specimen. An extension of this idea is the stereoplotter, which permits simultaneous tracing of the height contours.

A possibility for the future is automatic correspondence analysis using image processing techniques. Many attempts have been made to achieve this, both in the field of photogrammetry, and with the aim of modelling human visual processes. A popular approach is that of cross-correlation of the images [1,2]. It has been pointed out by several authors, however, that this scheme is basically unsound. The remaining algorithms may be divided into symbolic approaches [3,4,5,6,7], and whole-field or non-symbolic approaches [8,9]. In the former, an algorithm searches for features in both images independently, then an attempt is made to locate the correspondence partner for each feature. The whole-field techniques try to locate a partner for every point in each image. None of these methods has yet been demonstrated to work reliably on natural images.

A new algorithm under development at this laboratory uses a 3D probability space, modified by surface smoothness constraints, to estimate the most likely topography of a specimen surface from a stereo pair. It explicitly caters for the projection geometry used, and the noise level of the images.

2.2 Geometrical parameters

In the simplified case of approximately parallel projection, and a known specimen tilt about an axis in the image plane, the interpretation of stereo pair correspondence data is straightforward [10]. Complications arise in practice, however, which require consideration .

(i) The parallel projection approximation is inappropriate for magnifications below 500 to 1000 x (depending on working distance - see [11]).

(ii) The parameters required to model the projections (equivalent focal length; position of the tilt axis; amount of tilt; x, y, and z shifts required to maintain the field of view whilst tilting) may not be known sufficiently precisely.

(iii) There are systematic distortions in the imaging system.

In the past it has been considered desirable to use the parallel projection approximation because of the complexity of the perspective projection equations. The availability of inexpensive small computers now makes these calculations much more practical.

Attempts have been made to calibrate the SEM such that the relationships between the operator controls and the parameters of (ii) are precisely known [12]. This reduces the uncertainty considerably, but for the greatest accuracy photogrammetric self-calibration is required [13,14]. In this procedure, equations are set up connecting the projection parameters with the positions of corresponding points, and are solved so as to minimise some error criterion. The accuracy obtained in this way is one or two orders of magnitude better than can be achieved with other methods.

Systematic distortions (iii) can occur due to [15] :

a) non-linear scanning in the electron-optical column;
b) non-linear scanning in the recording CRT;
c) the optical system (camera and lenses);
d) the photographic process itself (film shrinkage).

These distortions have been measured and calibrated by imaging a standard specimen. The distortions have been represented both by a self-distortion grid [12], and by tangential, symmetric and spiral distortion polynomials [14]. Maune [14] found that a different set of distortion parameters was significant for each angle of tilt of the specimen stage.

It should be pointed out that on-line digital storage of the images avoids distortion sources b, c, and d [15].

It is suggested that for high productivity and moderate accuracy, the following scheme is appropriate:

a) Digital storage of the stereopair micrographs.

b) Once-only calibration of the column distortions.

c) Solution for the projection parameters from a number of corresponding point coordinates, using either least-squares adjustment or direct solution [16].

3 CONTRAST INTERPRETATION

Lebiedzik and White [17] developed a system whereby the local slope and orientation of the surface may be instantaneously determined. The signals from five detectors (a secondary electron detector and four electron backscatter (EBS) detectors) were analysed by a computer, which compared them with calibration responses. A disadvantage of this method is that the specimen must be coated with a layer of metal of known response. Also, it requires the installation of the EBS detectors. It is not very accurate, particularly when the surface contains discontinuities in height. The principal attractions of the technique are that the analysis can be very rapid, and microtopographical characterisation of the surface (the calculation of statistical properties of the surface) may readily be performed.

A more sophisticated, iterative algorithm was applied in [18] to obtain the 3D shape of a specimen from a single secondary electron image.

4 AUTOMATIC RANGEFINDING

It is relatively simple to measure spot heights in the SEM using the automatic rangefinding method [19,20], and computer control speeds the process considerably, although each height determination takes approximately 30 seconds [20]. The method requires two operations for each point:

(i) The focus current which maximises the image intensity gradient at the point of interest is found.

(ii) This value of focus current is converted to the equivalent height by means of a calibration table.

The fundamental limit to the accuracy attainable by this means is the (rather large) depth of field of the SEM, although the precision to which the objective current can be set may prove to be the practical limit. Results have been obtained with a height uncertainty of 10 µm, although the theroretical limit is 1 µm for a typical SEM.

5 CONCLUSIONS

The characteristics of the methods discussed in this paper are summarised below.

TECHNIQUE	COST Modifications Computation	TIME per point	OPERATOR REQUIREMENT	LIMITING ACCURACY	CALIBRATION PROCEDURE
Stereometry (photogrammetric calibration)	- High	1-30 s +photo	Very great	~330 nm (5000x) *	Complex
Stereometry (Instrumental calibration)	- Low	1-30 s +photo	Very great	~3000 nm (5000x) *	Tedious
Contrast Interpretation	High Moderate	scan rate	-	specimen - dependent	Moderate
Automatic Rangefinding	High Moderate	30 s	-	1 µm	Simple

* Approximately inversely proportional to magnification.

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