A PC-BASED INTERACTIVE IMAGE PROCESSING SYSTEM FOR 3-D ANALYSES OF SEM STEREO IMAGES

Yoshiro Nishimoto*, Shin-ichi Imaoka* and Hiroaki Yasukuni**
* Electronics Technology Center, Kobe Steel, Ltd.
** Electronics Division, Kobe Steel, Ltd.

* 1-5-5, Takatsukadai, Nishi-ku, Kobe 673-02, Japan
** 1-3-18, Wakinohama-cho, Chuo-ku, Kobe 651, Japan

ABSTRACT

A PC-based interactive image processing system for 3-D analyses of stereo images of a scanning electron microscope (SEM) using an advanced feature-based stereo model is described.

Integration between the global and qualitative human vision and the local and quantitative computer vision makes it possible to greatly reduce the computational load and to highly improve the reliability of stereo correspondence.

The system consists of a PC with a co-processor and a frame buffer, an image scanner, a mouse, and an analogue color CRT. The stereo correspondence algorithm, implemented on the PC with MS-C, is carried out from point to point interactively referring to a stereoscopic display to obtain 3-D digitized data. Geometrically defined properties including surface orientations, sectional profiles, depths and thicknesses are analyzed based on the 3-D data of necessary points.

Some experimental results are presented for crystal analysis, surface 3-D shape recognition and thickness measurement. Discussions are also presented on accuracies in 3-D measurement.

INTRODUCTION

Scanning electron microscopes (SEM) have been widely used for 2-D observations and analyses of micro-structures. Aquisition of 3-D data has, however, become required in crystal analyses, bio-element analyses, inspection of VLSI patterns, and roughness measurements for precisely-machined surfaces in recent years.

Several methods to obtain 3-D information for micro-structures using SEM have been proposed. These are classified into two categories;

(1) A method to obtain surface orientations by calculation of reflective or secondary electron signals picked up with a pair of detectors at different positions and to reconstruct surface shapes by integration of the orientation data[1].

(2) A method to reconstruct 3-D shapes by correspondence between a stereo pair of images taken by SEM with samples inclined at different angles[2].

Method (1) is suitable for surfaces with smooth curvatures, but not applicable to common surfaces with edges or steps where the gradient becomes indefinite or infinite, such as edges of crystals and steps of VLSI patterns. In addition, the method requires a specially equipped SEM.

Method (2) can be carried out with a common SEM, but it requires so much and so complex computation in stereo correspondence that introduction of a large-scaled image processor is necessary and, nevertheless, considerable errors are inevitable in order to reconstruct 3-D shapes over the whole image.

The state-of-the-art situation is that neither method can respond to the demands to obtain 3-D information from SEM images. Surveys of the demands have revealed that the demands include not only 3-D reconstruction on the whole image plane, but also 3-D measurements of geometrical properties solely on particular areas to be investigated. This paper describes the introduction of an advanced feature-based stereo model and interactive processing from point to point to the method (2) which makes it possible to obtain stereo correspondence and to reconstruct 3-D properties in real time even on PC.

PRINCIPLE

1. SEM stereo imaging

SEM is a kind of parallel projection optics. Imaging of a sample inclined at $\pm\theta$ is equivalent to imaging by electron beams with inclined incident angles $\pm\theta$. If a sample 3-D coordinate (O-xyz), and left and right 2-D image coordinates (O_L-$X_L Y_L$, O_R-$X_R Y_R$) are defined as shown in the Fig. 1, conversions from the sample coordinate to the image coordinates are given as follows;

$$X_L = k\,m\,(\,x\cos\theta + z\sin\theta\,) \quad \text{----(1)}$$
$$Y_L = k\,m\,y \quad \text{----(2)}$$
$$X_R = k\,m\,(\,x\cos\theta + z\sin\theta\,) \quad \text{----(3)}$$
$$Y_R = k\,m\,y \quad \text{----(4)}$$

where k is a magnification rate in digitizing of images (pixel/μm), and m is a magnification power of SEM (μm/μm).

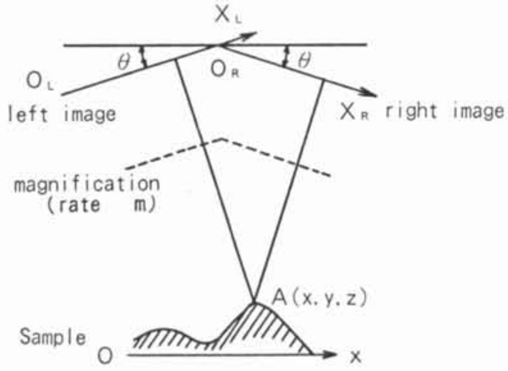


Fig.1 SEM stereo imaging

Inversions of Eq.(1)~(4) give the following relations.

$$x = (X_L + X_R)/ (2 k m \cos\theta) \quad \text{-----}(5)$$
$$y = Y_L / k m = Y_R / k m \quad \text{-----}(6)$$
$$z = (X_L - X_R)/ (2 k m \sin\theta) \quad \text{-----}(7)$$

Where the factor($X_L - X_R$) in Eq.(7),which gives the height of a measured point, z , stands for the so-called disparity d , and d can be obtained only after stereo correspondence is successfully established.

2. Stereo correspondence

The stereo correspondence process includes feature extraction, matching and calculation of 3-D coordinates as shown in Fig.2.

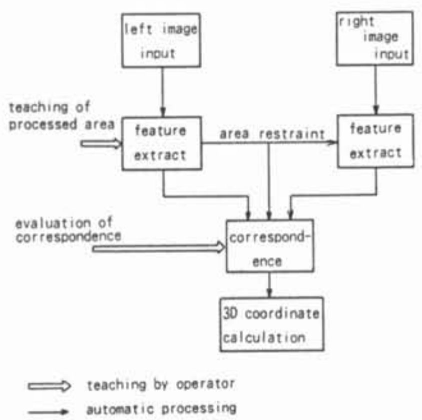


Fig.2 Stereo correspondence flow

Here, the following three constraints are introduced to reduce the huge computation load in stereo correspondence.

a. points or regions to be investigated are specified by the operator
b. the range of height of the sample is no more than that of the width
c. disparities smoothly change within a local area[3]

2.1 Feature extraction

After a stereo pair of SEM images are loaded from SEM to PC, an interested point P_L is specified with a mouse by the operator based on constraint a. The left image $E^{(L)}(i,j)$ is convolved with a Laplacian-Gaussian Filter[4]

$$\nabla^2 G(i,j) = \frac{(r^2 - 2\sigma^2)}{2\pi\sigma^6} \exp\left(-\frac{r^2}{2\sigma^2}\right) \quad \text{-------}(8)$$

in a local area W_L around P_L, and zero-crossing points (ZCs) are detected as points with brightness changes, where $r^2 = i^2 + j^2$, and σ means a standard deviation of the 2-D Gaussian distribution G(i,j). A left feature image $F^{(L)}(i,j)$ including edges and textures are extracted from the ZCs according to the gradient values of a Gaussian-filtered image $G(i,j)*E^{(L)}(i,j)$ on ZCs in order to pick up features with large contrasts alone, where * stands for the convolution operation[3].

The Laplacian-Gaussian Filter introduced above is a kind of band-pass filter with a central frequency

$$\omega_0 = \sqrt{2}/\sigma \quad \text{------------------}(9)$$

and σ is determined in accordance with the spatial frequency distribution of the features in each SEM image. A feature point Q_L is selected from $F^{(L)}(i,j)$ on the condition that Q_L has the same j-coordinate and is the nearest to P_L.

The right image is processed to obtain a right feature image $F^{(R)}(i,j)$ in the same way as the left one, but within a wider local area W_R around points which can be corresponded with P_L if disparities are ranged from 0 to d_{max}, where d_{max} is determined by the constraint b. mentioned above.

2.2 Matching

A local disparity histogram L(d) defined by the following equation and based on the constraint c. is calculated to investigate the similarity between $F^{(L)}(i,j)$ and $F^{(R)}(i,j)$[3].

$$L(d) = \sum_{(i,j)\in W_L} M(i,j;d) \Big/ \sum_{(i,j)\in W_L} F^{(L)}(i,j) \quad \text{----}(10)$$

where d is a disparity and $0 \leqq d \leqq d_{max}$, and M(i,j;d) is a matching function defined by the following conditions.

$$\text{If } F^{(L)}(i,j)=1 \text{ and } (F^{(R)}(i-d,j)=1 \text{ or } F^{(R)}(i-d,j\pm 1)=1)$$
$$\text{then } M(i,j;d)=1, \text{ otherwise } M(i,j;d)=0 \quad \text{--}(11)$$

Now, let a disparity with a maximum L(d) be denoted by d_{op}. If $L(d_{op})$ exceeds a threshold, point Q_R is selected in W_R as the best corresponding point to Q_L on the condition that Q_R has a disparity nearest to d_{op}. Otherwise, ' no correspondence ' is shown.

The left feature point, Q_L, and the best corresponding point, Q_R, are superimposed on the input images on a color CRT for the operator to judge the validity of the stereo correspondence and to correct it in mismatching cases using a mouse.

2.3 Calculation of 3-D geometrics

Once the stereo correspondence is successfully established and disparity d is obtained, the 3-D coordinate of feature point Q is calculated by substituting d into Eq. (5)～(7).

Various kinds of geometric properties can be calculated according to 3-D digitized data, obtained in the manner mentioned above, point by point.

IMPLEMENTATION

1. System configuration

The feature-based stereo model is implemented on a PC based system, which consists of a PC with a co-processor (80287 ; Transputer T800 in near future), a frame buffer (1.5Mbyte) and a mouse, an analogue color CRT and an image scanner, as shown in Fig.3.

Fig.3 System configuration

2.Functions

All the image processing routines are executed using the MS-C language. The system has the following eight menus.

A. Stereo image input and output
   input ---- through image scanner
              directly from SEM (NTSC)
              from MS-DOS floppy disk file
   output --- into MS-DOS floppy disk file

B. Initialization
   initial set of parameters such as scale factor, zero level, σ of Gaussian, window size, threshold for L(d) etc.

C. stereoscopic observation
   stereoscopic observation using stereo glasses

D. Height measurement
   height of specified point is measured

E. Surface orientation measurement
   orientation of surface specified by three points is measured

F. Measurement of angle between two surfaces

G. Profile analysis
   sectional profile specified by arbitrary cutting line is analyzed

H. Thickness measurement
   thickness of thin films is measured

PERFORMANCE

1. Example of analysis

Now, let us explain the interactive operation of the system taking the case of menu A, C and E for a single diamond crystal. A menu plane is first displayed on the PC's CRT for the operator to choose one using the mouse. In menu A a pair of SEM stereo images are loaded onto the frame buffer in the digital form of 256×256×8bit respectively using the image scanner, and displayed on the upper half of the color CRT, as shown in Fig.4. After initialization by menu B a stereoscopic display is presented on the lowerri ght quarter of the color CRT, as shown in Fig.4 in menu C for the operator to observe the microstructure three-dimensionally. In menu E the operator specifies a point, either on or near edges of a surface to be investigated, based on the 3-D observation. The system recognizes the local area, extracts the feature image in it, displays the feature image on the lower half for a monitor and finally detects and superimposes the feature point and its best corresponding point on the input images, as shown in Fig.4. If the correspondence is confirmed to be true, the system calculates the 3-D coordinate from the disparity, that is, the displacement between the left feature point and the best right corresponding point. 3-D digitization mentioned above is repeated three times and finally orientation of the surface to be investigated is obtained, and the normal vector is depicted on the input left image. The computation time for 3-D digitizing is about 8 sec.

Other two examples are shown in Figs.5 and 6. Fig.5 shows an example of profile analyses (menu G) for a roughness standard test piece. Fig.6 shows an example of thickness measurements for thin films. Thickness t can be given by

$$t = \boldsymbol{P}\cdot\boldsymbol{n} \qquad \text{------------------(12)}$$

where $\boldsymbol{n}$ is the normal vector of the surface of the film and $\boldsymbol{P}$ is one of vectors which starts on the upper surface and finishes on the lower one.

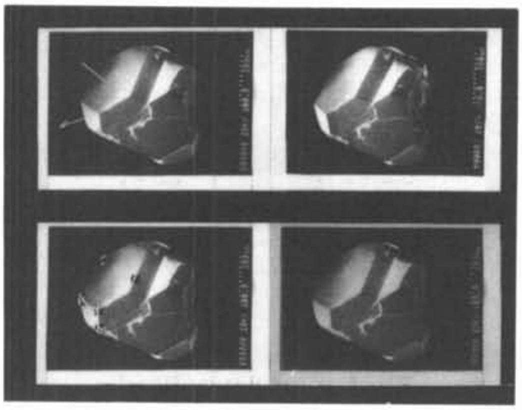


Fig. 4 Crystal analysis for single diamond

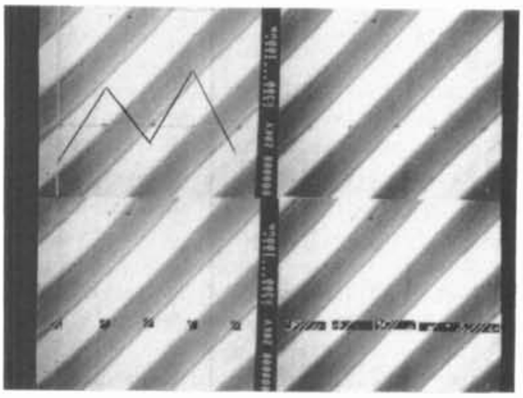
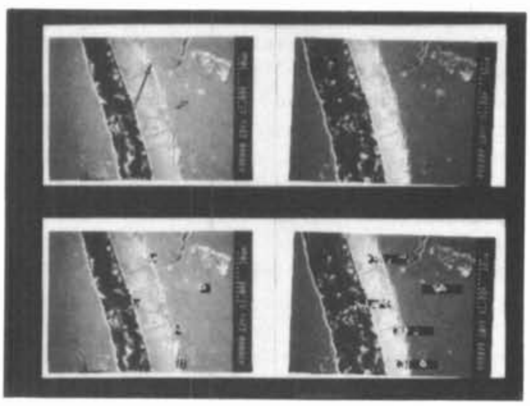


Fig. 5 Profile analysis for rough surface



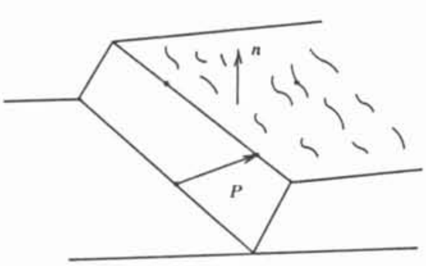


Fig. 6 Thickness measurement

2. Accuracy in 3-D measurement

Accuracy in height measurement was investigated using a stereo pair of SEM images of impressions of the micro-Vickers test taken with 700 times magnification power, as shown in Fig. 7. The impression has a 3-D shape well-defined by JIS and gives a good standard for investigation of accuracy. Fifteen points specified along an edge of the impression were successfully 3-D digitized, and the results shown in Fig. 8 were obtained. These revealed that the system has an accuracy of 1.5μm when the magnification power of SEM is 700 times and that the accuracy is determined by horizontal resolution as long as SEM images have sufficient contrasts.

Fig. 7 SEM stereo image of micro-Vickers

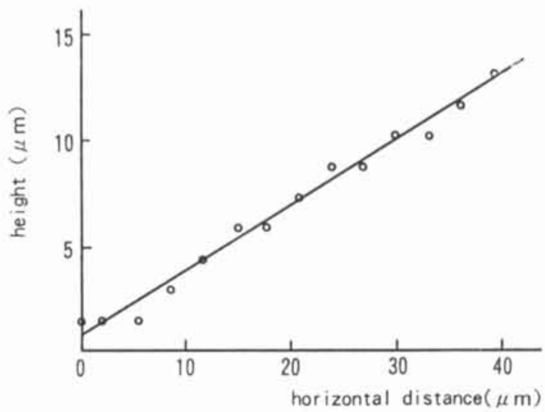


Fig. 8 Height measurement along edge

Orientation measurement showed that angles between neighboring surfaces were 149°, 152°, 155°, 146° for the true angle 150°. Four data had a mean value 150.5° and a standard deviation 3.2°.

DISCUSSION

1. Accuracy in height measurement

An error in height measurement is obtained from Eq.(7) and given by

$$\Delta z = \Delta d / (2 k m \sin \theta) \quad \text{-------}(13)$$

which is inversely proportional to the magnification power of SEM, m, where Δd is an uncertainty in feature location, and k is 2.8×10^{-3}.

Now, suppose that m is 100,000, θ is 10° and $\Delta d \leq 1$, then it is concluded that $\Delta z \leq 0.01 \mu m$ and that depth measurement for a considerably shallow step is possible as long as the contrast of the SEM image is kept high.

An error in orientation measurement is obtained from Eq.(5) and (7) and approximately expressed by

$$\Delta \phi \sim \Delta z / x \sim \frac{\Delta d}{(X_L + X_R)\tan\theta} \quad \text{---}(14)$$

which does not depend upon m. The standard deviation value, 3.2°, obtained in the experiment, is consistent with a case when the width of the measured surface is 40 pixel.

2. Further improvements

2.1 Location of features to sub-pixel precision

Features to be matched are defined as ZCs of a $\nabla^2 G$-filtered image and located to a pixel precision in the system. ZCs can, however, be located to a sub-pixel order if an input SEM image has a high S/N[5]. Errors in location of ZCs, Δd, are generally given by

$$\Delta d \sim \Delta E / g \quad \text{------------------}(15)$$

where ΔE is a noise level in the input image and g is a gradient value of the filtered image on ZCs. Common SEM images have a S/N no less than 40 dB, which means that the noise level ΔE is approximately 2.5 levels when the grey scale resolution is 256 levels. If features are defined as ZCs with $g \geqq 25$ levels/pixel, Δd turns out to be less than 0.1 pixel and ten times improvement in accuracy in 3-D measurement becomes possible. The improvement depends upon ΔE and g, that is, the S/N and the contrast of SEM images.

2.2 Improvement in efficiency

It is true that the larger the magnification power of SEM imaging is, the worse the contrast of SEM images become. Specification ofeach point by the operator is, therefore, desirable for the system to recognize the point, surface or cross-section to be investigated and to improve the reliability in 3-D reconstruction.

It is, however, sufficient solely to specify the interested surfaces or cross-sections if the contrast of SEM images is high enough for the system to search for necessary feature points.

2.3 Use of grey level information

The system adopts the so-called feature-based stereo model and can detect 3-D coordinates on points with large contrasts, such as edges and textures, but not on points with smooth shadings. It is, however, possible to complement the weak point by using grey level information in SEM images, which may be a function of gradients of surfaces just like in a photometric stereo method.

CONCLUSION

An interactive image processing method for 3-D analyses of SEM stereo images using an advanced feature-based stereo model were developed and implemented on a PC-based system.

Integration between the global and qualitative human vision and the local and quantitative computer vision makes it possible to greatly reduce the computation load, 8 sec/point, and to highly improve the reliability in stereo correspondence. The accuracy was revealed to be $0.01 \mu m$ with SEM of a 100,000 times magnification power in height measurement, and 3.2° in angle measurement.

The system has room for improvement in accuracy and in efficiency. If SEM images have large contrasts, location of feature points to a sub-pixel precision makes it possible to improve the accuracy by one order and direct specification of properties to be investigated will reduce the load of the operators.

REFERENCES

1) S.Kimoto and H.Hayashi: Stereoscopic Observation in Scanning Microscopy Using Multiple Detectors, The Electron Microprobe edited by McKinley, Heinrich and Wittry, and published by John Wiley and Sons Inc. (1966) pp.480
2) Y.Kokubo and K.Suzuki: 3-D Reconstruction System Using SEM Images, PIXEL, No.62 (1987) pp.95
3) Y.Nishimoto and Y.Shirai: A Feature-based Stereo Model Using Disparity Histograms of Multi-resolution Channels, Advanced Robotics No.73 (1988)
4) D.Marr and E.Hildreth: Theory of Edge Detection, Proc. Royal Society, vol.B207 (1980) pp.187
5) Y.Nishimoto and Y.Shirai: A Feature-based Stereo Model Using Small Disparities, Proc. Int. Workshop on Industrial Appl. of Machine Vision and Machine Intelligence (1987) pp.192