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Calibration-free quantitative surface topography reconstruction in scanning electron microscopy

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ABSTRACT

This work presents a new approach to obtain reliable surface topography reconstructions from 2D Scanning Electron Microscopy (SEM) images. In this method a set of images taken at different tilt angles are compared by means of digital image correlation (DIC). It is argued that the strength of the method lies in the fact that precise knowledge about the nature of the rotation (vector and/or magnitude) is not needed. Therefore, the great advantage is that complex calibrations of the measuring equipment are avoided. The paper presents the necessary equations involved in the methods, including derivations and solutions. The method is illustrated with examples of 3D reconstructions followed by a discussion on the relevant experimental parameters.

1. Introduction

Upon using secondary electrons, contrast variations in scanning electron microscopy (SEM) are caused by the topography of the sample. However, the extraction of topographical information from SEM images is rather complex. Different approaches have been defined in order to find a solution to that problem [1–4]. However, they require specific equipment or complex calibration procedures. In addition to those, so-called stereographical methods have been reported in literature [5–10]. The most important ones can be grouped in feature-based (based on edge detection) and area-based methods (based on image correlation) [6]. The latter ones bear the advantage of obtaining a high density of points and circumvent problems when operating with rather inhomogeneously distributed features [6].

This type of approach is very versatile, and has been applied to different materials such as inorganic particles [11] or biological specimens [7,12]. Nevertheless, several publications do not provide a clear comparison between the original images and the 3D reconstructions, and/or they do not include information about the range of values in the depth direction, we call z [5–7,12–14]. In other cases, geometrical information is a prerequisite [9–11]. In fact, a recent publication by Zhu et al. showed a *quantitative* method for 3D reconstruction, but it requires *a priori* calibration of the SEM stage movement [8]. However, such calibration may introduce several additional errors into the final results [15].

The method presented in this paper aims at recovering the topographical information hidden in the contrast of the SEM pictures, avoiding the necessity of calibrations and other complex geometrical considerations. On the contrary, the only requirement to obtain the 3D reconstruction in practice is the acquisition of at least three images of the surface region under study at different tilt angles, without further information about details of the tilting parameters. The remaining procedure is based on data handling.

In fact, the method can be applied on sets of images acquired without knowledge of the imaging and/or rotation conditions. Thus, the sample will be just slightly tilted in the SEM equipment, but there is no need of a fine control of the direction and magnitude of rotation. As depicted in Fig. 1, the consequence of tilting is the displacement (δ) of the points of the image. However, the magnitude of this displacement varies depending on the z coordinate of the point (*cf.* situations a, b and c). As a consequence, by evaluating the displacement of every point in the images after tilting, it will be possible to reconstruct the z coordinates. This evaluation will be carried out by conventional 2D digital image correlation (DIC) [16] between the images before and after the tilting. In this work we describe the data handling to reconstruct the three-dimensional profile from the DIC data.

The structure of the paper is as follows. First the theoretical background is described, followed by experimental considerations.

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Next, the method to obtain the 3D maps is described. Finally, three 3D reconstructions are presented followed by a discussion of the method.

2. Theoretical background

This section presents the background used in all the calculations. It is worth mentioning that all the descriptions are done in laboratory coordinates (i.e. using the SEM equipment as a static reference system, keeping track of the movements of the sample), instead the coordinates of the specimen. This section will be subdivided into two parts. First, the equations related to the rotation and translations will be summarized. Then, the influence of the optics of the system will be analyzed. The interconnection between motion and imaging is depicted in Fig. 2.

2.1. Movement

A SEM image can be considered as a matrix of data where each pixel is characterized with its position (x and y coordinates) and a grayscale intensity. For a rigid body, the modification of coordinates before and after the tilting (situations labeled as A and B, respectively) can be described as a combination of rotations and translations (see Fig. 2). Therefore, a point i with starting coordinates $[A]=(x_{i,A},y_{i,A},z_{i,A})^{real}$ is transformed to final coordinates $[B]=(x_{i,B},y_{i,B},z_{i,B})^{real}$ as

$$[B]=[R][A]+[T] \tag{1}$$

where $[T]$ is the translation matrix

$$[T]=\begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} \tag{2}$$

and $[R]$ is the rotation matrix

$$[R]=\begin{pmatrix} R_{xx} & R_{xy} & R_{xz} \\ R_{yx} & R_{yy} & R_{yz} \\ R_{zx} & R_{zy} & R_{zz} \end{pmatrix}=\begin{pmatrix} \cos\theta+a_x^2(1-\cos\theta) & a_xa_y(1-\cos\theta)-a_z\sin\theta & a_xa_z(1-\cos\theta)+a_y\sin\theta \\ a_xa_y(1-\cos\theta)+a_z\sin\theta & \cos\theta+a_y^2(1-\cos\theta) & a_ya_z(1-\cos\theta)-a_x\sin\theta \\ a_xa_z(1-\cos\theta)-a_y\sin\theta & a_ya_z(1-\cos\theta)+a_x\sin\theta & \cos\theta+a_z^2(1-\cos\theta) \end{pmatrix} \tag{3}$$

θ is the angle of rotation around the vector a with components a_x, a_y, a_z. This vector is unitary, so

$$a_x^2+a_y^2+a_z^2=1 \tag{4}$$

Both movements are sketched in Fig. 2. Without loss of generality, the z coordinate of every point i can be expressed as a combination of a plane with components p_x, p_y and p_z and the vertical shift of every point to this plane (Δz_i), as

$$z_{i,A}^{real}=p_xx_{i,A}^{real}+p_yy_{i,A}^{real}+p_z+\Delta z_i \tag{5}$$

It is important to mention that the Δz_i vertical shifts are only perpendicular to the plane if $p_x=p_y=0$ (horizontal). This is a consequence of the aforementioned choice of the system of reference (laboratory frame instead of the moving frame of the specimen). This plane can be characterized by a vector located at the origin normal to the plane with components $\left\{\frac{-p_z}{1+p_x^2+p_y^2}(p_x,p_y,-1)\right\}$.

Combining Eqs. (1–3) and (5), the following expressions are found:

$$x_{i,B}^{real}=R_{xx}x_{i,A}^{real}+R_{xy}y_{i,A}^{real}+R_{xz}(p_xx_{i,A}^{real}+p_yy_{i,A}^{real}+p_z+\Delta z_i)+t_x \tag{6a}$$

$$y_{i,B}^{real}=R_{yx}x_{i,A}^{real}+R_{yy}y_{i,A}^{real}+R_{yz}(p_xx_{i,A}^{real}+p_yy_{i,A}^{real}+p_z+\Delta z_i)+t_y \tag{6b}$$

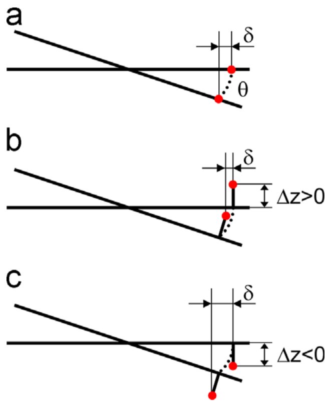

Fig. 1. Influence of the height (Δz) of a point (in red) on the displacement observed (δ) depending on the tilt angle (θ). (a) point in the plane of the sample. (b) point above the plane of the sample. (c) point below the plane of the sample. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Both expressions combine the rotation and the translation of the sample before and after the movement (situations A and B, respectively).

2.2. Optics

We have no access to the *real* coordinates of the specimen, but only to *images* taken before and after the movement (see Fig. 2). Therefore, in addition to the pure physical motion of the rigid body we have to consider the influence of the optics, which can introduce additional displacements (i.e. a distortion). As a consequence, a new set of *observed* coordinates has to be also considered in the lab reference system. This effect is related to the distance between the sample and the optics, the so-called working distance (WD). As sketched in Fig. 2, all points measured out-of-plane away from the center of the image (x_0, y_0) show a difference between the observed coordinates (x_i,y_i), and the real coordinates $(x_i,y_i)^{real}$

$$x_i-x_0=(x_i^{real}-x_0)\frac{WD}{WD-\Delta z_i} \tag{7a}$$

$$y_i-y_0=(y_i^{real}-y_0)\frac{WD}{WD-\Delta z_i} \tag{7b}$$

The magnitude of the distortion does not influence the measurements in SEM, since the working distance is much larger than the values of Δz. In general, it is confined to the sub-pixel regime and it is negligibly small. However, the present method is based on a comparison of images acquired before and after tilting the sample by small amounts. In this case, the displacements are also in the sub-pixel regime, and the optical distortion may become relevant. For instance, this effect has to be considered when comparing lower magnification images (i.e. large image size) before and after tilting. In such cases, the points next to the border of the image are strongly shifted, which causes important deviations. The correction of this effect requires a specific iterative