The Error Calculations between the Original Image and the Restored Image Using the Computer Simulated Peaks as an Object and a Pyramidal Shaped Tip by the Blind Tip Estimation Algorithm.

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Abstract: Images produced by AFM are distorted due to the dilation of AFM tip with the features of sample. To overcome this problem it is necessary to estimate the tip geometry in order to reduce such distortions and reconstruct specimen surface. Even though tip characterization can be achieved by various approaches, blind tip reconstruction is uniquely important since it estimates the tip using the AFM image of an unknown sample geometry (therefore its name). Here we present two types of results for estimating the AFM tip shape and for sample surface reconstruction, namely via computer simulation results and by actual experimental results. In both approaches, a dilation has been used for imaging, an iterative process employing the equation of the blind tip reconstruction algorithm has been used for the tip estimation process, and an erosion procedure has been used for surface reconstruction.

Keywords-AFM; dilation; erosion; blind estimation; image restoration.

المستخلص: الصور التي ينتجها AFM مشوهة بسبب AFM tip dilation مع ميزات العينة. للتغلب على هذه المشكلة، من الضروري تقدير tip geometry من أجل تقليل مثل هذه التشوهات وإعادة بناء سطح العينة. على الرغم من أنه يمكن تحقيق توصيف AFM tip بطرق مختلفة، فإن طريقة blind tip estimation مهمة بشكل فريد لأنها تقدر الطرف باستخدام صورة AFM لعينة هندسية غير معروفة (وبالتالي من هنا اتى اسمها). نقدم هنا نوعين من النتائج لتقدير شكل AFM tip ولإعادة بناء سطح العينة، أي عبر نتائج محاكاة الكمبيوتر والنتائج التجريبية الفعلية. في كلا النهجين ، تم استخدام التوسيع للتصوير ، وقد تم استخدام عملية تكرارية تستخدم معادلة خوارزمية إعادة بناء الطرف الأعمى لعملية تقدير الطرف ، كما تم استخدام إجراء erosion لإسترجاع صورة العينة.

الكلمات المفتاحية: استرجاع الصورة، التوسع، جهاز تصوير العينات الدقيقة، صورة لعينة هندسية غير معروفة

1. INTRODUCTION

[i] Scanning probe microscopy (SPM), which mainly comprises Atomic Force Microscopy (AFM) and Scanning Tunnelling Microscopy (STM), provides three-dimensional topographical images with a resolution that is at, or is near to, the atomic level (**Villarrubia,** 1997; Binning et al., 1986). However, whilst such a high resolution image is an important requisite for accurate measurement, distortions induced by the tip of the Atomic Force Microscope may become significant whenever the sample consists of features with aspect ratios that are similar to that of the AFM tip. These distortions are reflected by the tip-sample interaction during the imaging process, wherein the tip is scanned over the sample surface. Various methods may be used to reduce, or remove such distortions. An algorithm for this purpose is the blind tip estimation approach (Villarrubia 1997), which has been reproduced here by the author for both computer simulation and experimental results. This involves the process of estimating the tip shape from an image of a tip characterizer sample that does not have an accurately pre-known geometry.

Images produced by AFM are distorted due to the dilation of AFM tip with the features of sample. To overcome this problem it is necessary to estimate the tip geometry in order to reduce such distortions and reconstruct specimen surface (Tian et al., 2008). Even though tip characterization can be achieved by various approaches, blind tip reconstruction is uniquely important since it estimates the tip using the AFM image of an unknown sample geometry

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(therefore its name). This technique was first introduced theoretically and independently by (Villarubia,1996; Williams, 1996). Then, this algorithm was numerically implemented by (Villarrubia 1997). It is based upon the self-imaging principle, thus information about the tip geometry and the specimen surface are provided by the AFM image at each location (Villarrubia, 1994;Tranchida, 2006).

Here we present two types of results for estimating the AFM tip shape and for sample surface reconstruction, namely via computer simulation results and by actual experimental results. In both approaches, a dilation has been used for imaging, an iterative process employing the equation of the blind tip reconstruction algorithm has been used for the tip estimation process, and an erosion procedure has been used for surface reconstruction.

2. Blind tip estimation algorithm

The blind tip estimation algorithm relies on set theory and morphological operations (Shuai et al., 2008).This problem of reconstructing the actual surface topography of an AFM sample has been investigated by many researchers. AFM images were restored by (Pingali and Jain, 1992)using mathematical morphological operators. The blind tip reconstruction technique was first introduced theoretically and independently by (Villarubia,1996; Williams et al.,1996). Then this algorithm was developed by (Villarrubia1997), which is based on the mathematical morphology. Dongmo used this algorithm successfully for reconstructing a stylus profilometer tip, then a comparison was carried out between the reconstructed tip shape and its SEM image (Dongmo et al., 2000). Subsequently (Todd and Steven, 2001) showed that noise in the AFM image causes a distortion in the tip estimation and proposed an approach to improve the algorithm. Recently (Tranchida et al., 2006) has taken the effects of operating parameters (for instance, sampling intervals and instrumental noise) into consideration in the practical use of the algorithm. After that he introduced guidelines and the appropriate experimental conditions that are relevant to the blind estimation algorithm.

Here we introduce Villarrubia's method where it is based upon set theory(Villarrubia 1997). Using this technique, where the surface topography is unknown, it is possible to estimate the tip shape from an AFM image of the sample which has an unknown surface geometry.

The image of the object is obtained by the dilation of the sample and the reflection of the tip P.

$$I = S \oplus P \qquad (1)$$

Where I is the image of the sample, S is the genuine surface topography, and $(P = -T)$ is the reflection of the tip T.

In the case where the actual surface topography is known then by using erosion, the estimated tip shape is

$$P_r = I \ominus S \qquad (2)$$

Where P_r is the estimated tip surface shape of the AFM tip.

Sample reconstruction by erosion can be written as

$$S_r = I \ominus P \qquad (3)$$

Where S_r is the reconstructed sample surface topography.

The iterative process for blind tip estimation is defined by the following equation:

$$P_{i+1} = \bigcap_{\vec{x} \in I} [(I - \vec{x}) \oplus P'_i (x)] \cap P_i \qquad (4)$$

In Equation (4.17), the calculation of the $(i+1)th$iteration result is based on the $(i)th$ result.

Where $\vec{x}$ is a point of interest in the image I

$$P'_i(X) = (\vec{x} - I) \cap P_i \qquad (5)$$

$P'_i(X)$ is a set of points in P_i that can contact the image I at a point of interest $\vec{x}$ with the apex point contained in the image *I*.

At convergence, the result of the estimated tip shape P_r can be determined as

$$P_r = \lim_{i\to\infty} P_i \qquad (6)$$

The preceding results of Equation (4) is larger than or equal to the result of each iteration of Equation (4)

Upon convergence, the final result gives the best estimate of the tip shape that is obtained by this blind reconstruction method.

3. Simulation results for the blind tip estimation algorithm

In this section we present the simulation results for the blind tip estimation algorithm. The author has implemented this method (blind tip estimation) based on the algorithm which is described by (Villarrubia1997) in the previous section. This simulation has been performed in order to compare the tip shape that is estimated from a dilated image with the original tip shape, which was reconstructed using C code. Also, the approach was used to compare the original raw image with the restored image that was obtained using the erosion of the dilated image by the blind estimated tip.

4. RESULTS

Fig. 1 shows simulation results for the blind tip estimation approach using the Matlab *peaks* function as a sample object and a pyramidal shaped tip. In these simulations computer models of the *peaks* object geometry and the pyramidal tip were constructed, as are shown in Fig. 1(a), (b), (c), and (d) as a two dimensional image of the *peaks* object, a three dimensional image of the *peaks* object, a two dimensional image of the pyramidal shaped tip, and a three dimensional image of the pyramidal shaped tip, respectively. Then, the AFM image of the *peaks* object was calculated from the sample (*peaks* object) and the tip (pyramidal shaped tip) by a dilation operation, which is illustrated in Fig. 1(e) and (f) as two dimensional and three dimensional images, respectively. The result of the iterative process of applying the equation for the blind tip estimation algorithm is depicted in Fig. 1(g) and (h) as two dimensional and three dimensional images of the estimated AFM tip, respectively. Fig. 1(i) and (j) show the two dimensional and three dimensional images of the restored AFM image of the sample, respectively after applying the erosion operation between the raw AFM image (dilated image) and the estimated AFM tip shape.

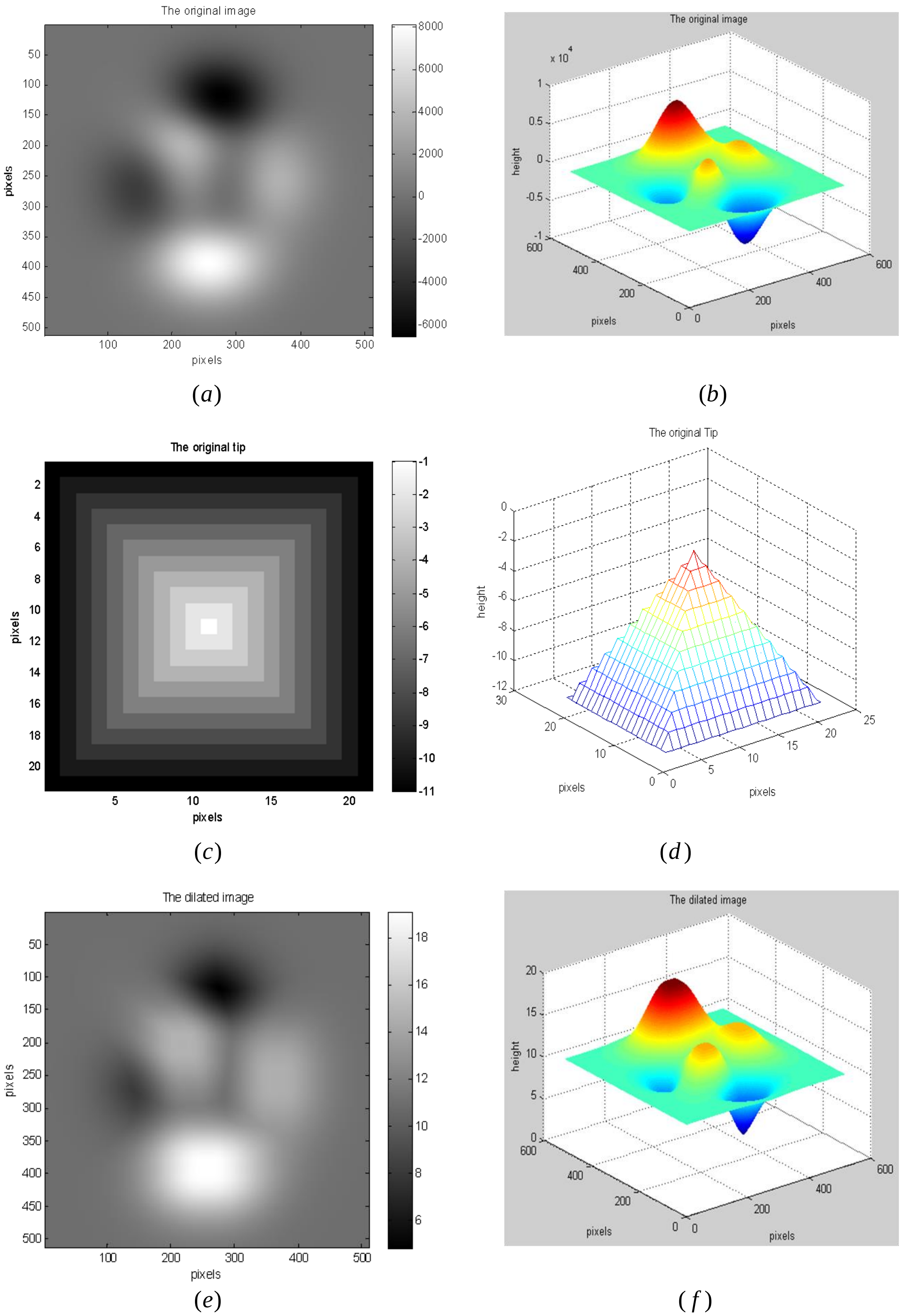


Fig. 1 Continued on the next page.

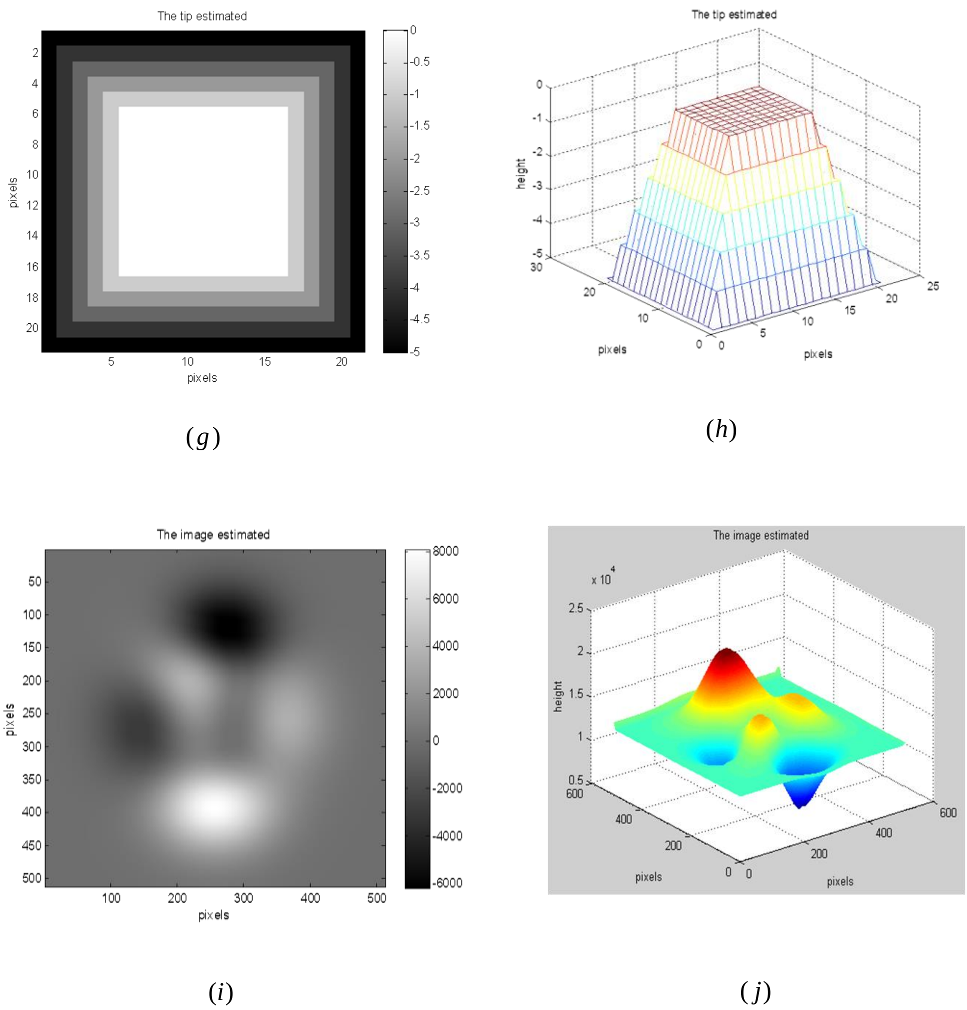
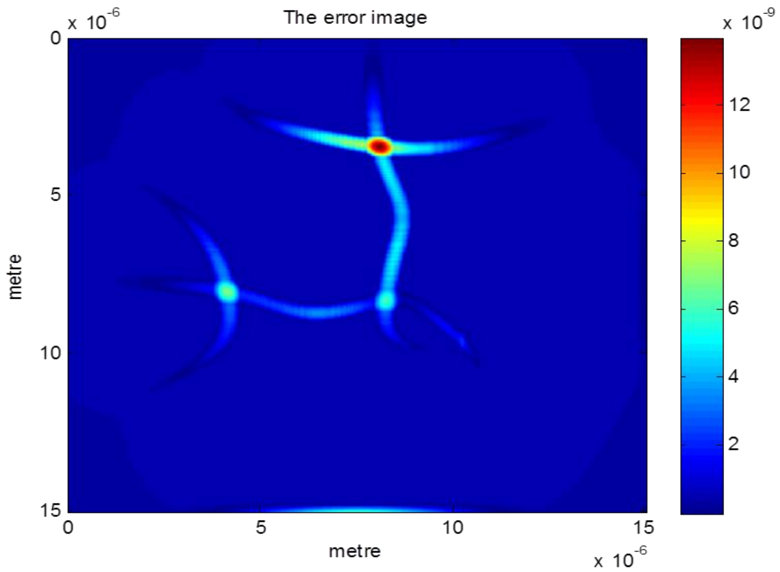


Fig. 1 Computer simulation results of the blind tip estimation algorithm using the peaks function as the object and a pyramidal shaped tip; (a) the 2D original image (peaks); (b) the 3D original image; (c) the 2D image of a pyramidal shaped tip; (d) the 3D image of a pyramidal shaped tip; (e) the 2D raw AFM image (dilated image); (f) the 3D raw AFM image (dilated image); (g)the 2D blind estimated tip image; (h) the 3D blind estimated tip image; (i) the 2D reconstructed image that is the result of an erosion operation between the blind estimated AFM tip shape and the raw AFM image (dilated image); (j) the 3D reconstructed image; (k)the 2D error in the reconstructed image; (l) the 3D error in the reconstructed image.

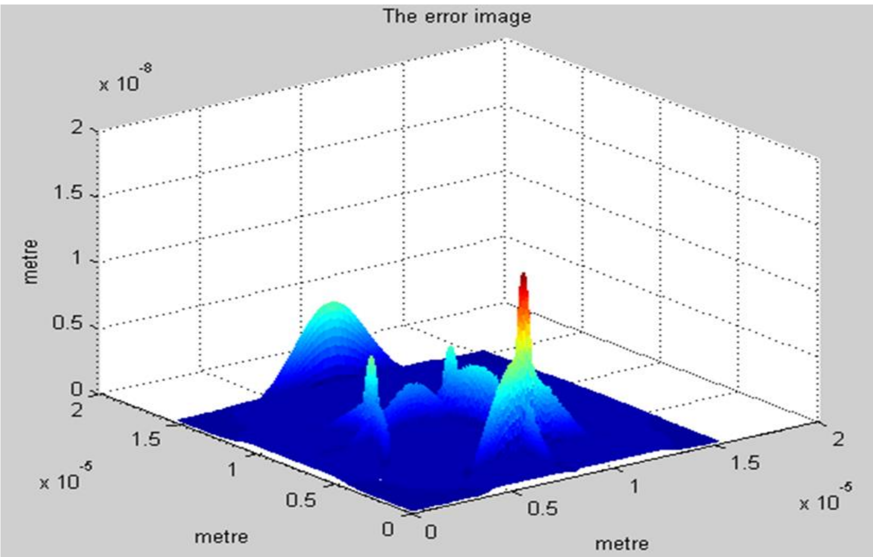
Table 1 presents the error calculations between the original image and the restored image for computer simulation results of the blind tip estimation algorithm using the Matlab *peaks* function as an object and a pyramidal shaped tip. From this table, it can be seen that the mean value of error between the original image and the restored image is 0.672 nm, the standard deviation is 0.708 nm, the minimum value of error is 0 nm, the maximum value of the error is 13.977 nm, and the root mean square error is 0.672 nm.

Table 1 The error calculations between the original image and the restored image for computer simulation results of the blind tip estimation algorithm using the Matlab *peaks* function as an object and a pyramidal shaped tip.

Mean of error [nm]	Standard deviation of error [nm]	Minimum error [nm]	Maximum error [nm]	RMSE [nm]
0.672	0.708	0	13.977	0.672



(*a*)



(*b*)

Fig. 2 The error image between the original image (Matlab *peaks* function) that is shown in Fig. 2(a) and the restored image that is illustrated in Fig. 1(i) ; (a) the 2D error image; (b) the 3D error image.

5. CONCLUSION

In this paper, the blind tip estimation algorithm was investigated via computer simulation. simulations were performed in terms of the blind tip estimation algorithm for AFM tip geometry (a pyramidal shaped tip) with object (the *peaks* function object). In terms of the computer simulated the *peaks* function object, table 1 presents the error calculations between the original image and the restored image for computer simulation results of the blind tip estimation algorithm using the Matlab *peaks* function as an object and a pyramidal shaped tip. As a result from the computer simulation, it can be seen that the mean value of error between the original image and the restored image is 0.672 nm, the standard deviation is 0.708 nm, the minimum value of error is 0 nm, the maximum value of the error is 13.977 nm, and the root mean square error is 0.672 nm.

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