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Image Restoration by DOG Multi-Scale Analysis

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This paper describes a newly developed image restoration method, which uses a multi-scale analysis of an image with wavelet-like sub-band decomposition. In conventional wavelet methods, the decomposition has been done by the quadratic dilation of wavelet frame size, which is based on the pyramidal algorithm [1]. On the contrary, we separate multi-scale operators and a signal completely in the decomposition procedure and generate optimum 2D filters for images with a wide range of frequencies, which allows a simple structure and faster calculation. The application of this method to SEM images is depicted.

Image J can be divided into a blurred image and its differentiation shown in eq. (1).

$$J = J_0 = J_n + (G_0 - G_n) \otimes J . \qquad (1)$$

G_k means a Gaussian distribution with a standard deviation $\sigma = \sigma_k$ and k is a suffix on the condition: $\sigma_n > \cdots > \sigma_k > \cdots > \sigma_1$:(k=1,…,n). G_0 means the Dirac delta function, then $J = G_0 \otimes J (= J_0)$ and $\otimes$ means the convolution. We expand the second term into smaller differentiations and define each of them as an operator M_k of 'k-th DOG kernel' shown in eq. (2). Conventionally M_k is called as DOG (Differentiation of Gaussian) function [2], but we use it as an elemental kernel of frequency expansion shown in Fig.1.

$$J = J_n + \{(G_0 - G_1) + (G_1 - G_2) + \cdots + (G_{n-1} - G_n)\} \otimes J = J_n + [\sum_{k=1}^{n} M_k] \otimes J . \qquad (2)$$

Our purpose is to transform the input image J to an improved image J^*, that is, sharpened and edge enhanced. This can be done by setting coefficients β_k of the k-th DOG kernel and α of the n-th blurred image J_n. Fitting these coefficients to heuristic evaluation functions is done statistically by maximizing the SNR (Signal to Noise Ratio) of the processed image with holding a natural image quality. By the definition of $M^* \equiv \alpha G_n + \sum_{k=1}^{n} \beta_k M_k$, J^* can be re-written in eq. (3). It can be easily determined that M^* is an optimum 2D filter and allows a faster calculation of the image processing rather than conventional ones.

$$J^* = \alpha J_n + [\sum_{k=1}^{n} \beta_k M_k] \otimes J = M^* \otimes J . \qquad (3)$$

System configuration of our system is shown in Fig.2. In the block 'Dynamic Analysis', the optimum 2D filters and the power spectrums are calculated in pairs against for images with a wide range of spatial frequencies and are stored in (A) and (B) respectively. Ordinary, when an image J is input to the block 'Static Analysis', pattern matching is done between the power spectrum of the image J and the stored ones, which means the selection of an optimum 2D filter, and then the image J^* is restored by a convolution of the selected optimum 2D filter and the image J.

It is also possible to do multi-scale analysis. Several examples of SEM images (different values of *k*) are shown in Fig. 3 and the restored one is shown in Fig. 4, which is dramatically improved in edge enhancement. For SEM images of gold particle on carbon, the improved ratio of resolution, i.e. $reso.(J)/reso.(J^*)$, is 1.3～3.5 and 2.4 in average (resolution was measured by the FT method [3]). Calculation time is about 0.7 sec for 1280 x 1024 pixels of an image with 2.93 GHz Intel(R) Core(TM)2 Duo CPU.

References:
[1] S. G. Mallat, *IEEE. Trans. Pattern Analysis.* Vol. 11. (7) (1989) 674.
[2] D. Marr et al., *Proc. R. Soc. Lond.* B 207 (1980) 187.
[3] To be published as ISO/TS 24597.

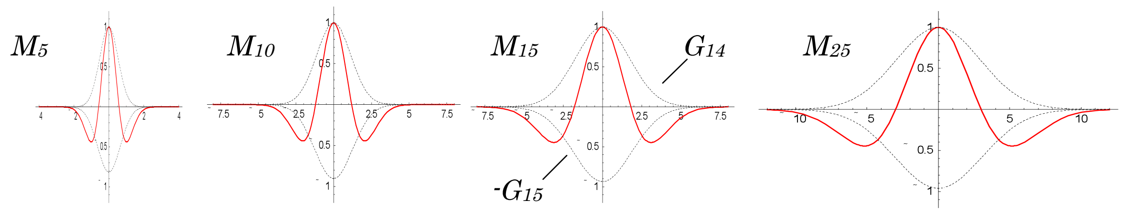

Fig. 1 Several examples of DOG kernels (normalized); M_k (k=5,10,15,25).

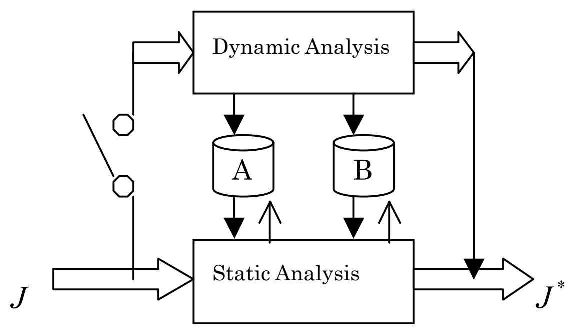

Fig. 2 System configuration.

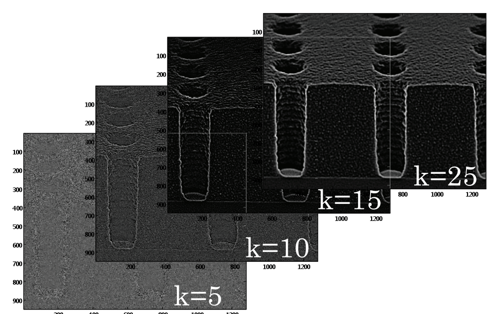

Fig. 3 Several examples of multi-scale images.

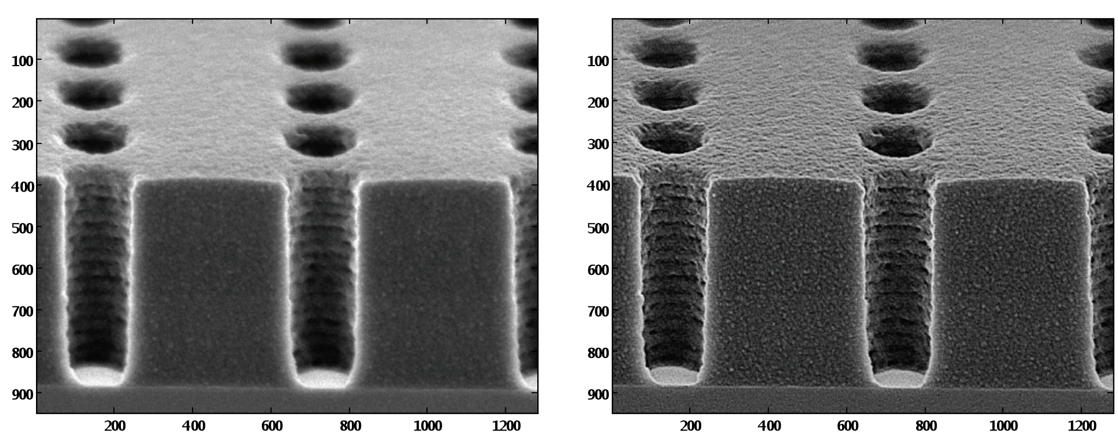

Fig. 4 Original image (left) and processed image (right): cross-section of contact holes.

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