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The spacing transform: Application and validation

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ABSTRACT

The measurement of spacing via the linear intercept method is a stereology technique for quantifying microstructures. Spacing measurements have traditionally been acquired using manual or semi-automatic methods. However, in recent work, the stereology idea of spacing was shown to be closely related to the computer vision idea of distance. If the distance transform can be defined as providing the minimum distance required at a given location to reach the nearest edge, a spacing transform would be defined as providing the distance required at a given location to reach the desired number of nearest consecutive edges along a linear path. The resultant transformed image provides local spacing data which should be the same as those measured by an expert stereologist. This spacing transform addresses the problem of measuring spacing in an interpretable and easily validated fashion. In this paper, spacing transform is defined, applied to real world images, and validated against traditional stereology methods.

1. Introduction

Stereology is the science of the geometrical relationships between a structure that exists in three dimensions and the images of that structure that are fundamentally two-dimensional (2D). Spacing measurement is a stereology metric used in a variety of fields from metal casting to biology [1,2]. Traditional methods for measuring spacing involve either manual or semi-automatic drawing of lines and counting features along these directions [1,3,4].

Methods do exist for automatic spacing quantification. Wang et al. discuss a method for returning a spacing metric for dendrite arms in images of polished aluminum [5]. The proposed method in their work uses concentric circles to probe the structure present. The advantage of this circle method is insensitivity to image directionality. Regardless of the orientation of the image, their method should return the same answer. However, their method should work on only isotropic and uniform structures. This assumption is consistent with the type of image and field of view required for the measurement. Increasingly, non-uniform structures are of interest in stereology. These structures manifest themselves near surfaces and anomalies resulting in bimodal structures or spatial gradients. Traditional stereological measurements or the discussed circle method both will return a single mean value for the structure with no quantification of the structure variation. Also, the automatic circle method does require an expert user to look at each field of view to determine if certain features internal to the microstructure degrade the measurement, such as a pore. In such cases a different field of view is required.

Biology has also used the line intercept method for measurement such as in measuring air space in lungs Knudsen et al. In this case, the method presented uses a grid of horizontal lines and spacing is computed from the line intercepts (chords). This method assumes isotropic lung structures, an assumption which Mitzner, et al. have demonstrated does not hold for all types of lung parenchyma [6]. Mitzner showed that even searching for chord intercepts in 2 directions can yield 2 distinct results. Thus, whereas the method could account for some spatial variation, the method of using a horizontal line grid does not return results valid for anisotropic structures.

In previous work, the measurement of spacing is considered an image transform [7]. An image transform replaces each pixel in the original image with data from a performed metric. This is an established practice in computer vision. For example, a distance transform is defined as providing the minimum distance required at a given location to reach the nearest edge. A spacing transform would be defined as providing the distance required at a given location to reach the desired number of nearest consecutive edges along a linear path. Such a transform result is interpretable and effective in the measurement of anisotropic, heterogeneous structures as well as consistent in isotropic, homogeneous structures. As an image transform, the result will become interpretable, with it being visually clear which areas of the image show inhomogeneity in spacing. The transform also allows us to acquire measurements at every location in the image, allowing for the easier application of statistics as well as provide some flexibility to account for some common problems in segmentation of salient structures.

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To measure a spacing metric through the use of an image transform, first we begin with the traditional distance transform. A distance transform provides the distance required to reach a single nearest edge from a given location [8]. Spacing, as measured by a stereologist, is the mean distance between edges along a linear path. Therefore, we can define a spacing transform as a generalization of the distance transform. A spacing transform provides the distance required to reach the desired number of nearest consecutive edges along a linear path intersecting a given location. The spacing result is then reported normalized by the number of edges crossed to provide mean structure spacing with units of distance.

The applications used in the description and validation of the spacing transform algorithm in this work are motivated by examining measurement typical in metal microstructures.

2. Materials and Methods

2.1. Manual Spacing Measurement

The traditional manual spacing measurement is taken by placing a set of random test lines across a subset of the image containing the features of interest [1]. The line angle is chosen by attempting to place the line perpendicular to the structure orientation, leading to the smallest line length needed per feature set. The line length is determined to include at the least enough of the structure to generate a reasonable mean distance between edges along the line (spacing). The ends of the line should terminate at the midpoint between edges. As a matter of practicality, the line must cover at least 3 edges to cross over a portion of foreground and background.

$$\lambda = \frac{2^{*} L_L}{N_E} \tag{1}$$

Eq. (1) gives the basic formula for the spacing metric, where N_E is the number of edges crossed and L_L is the length of the line required to cross those edges. λ is the spacing, sharing the same units as L_L [1]. From Eq. (1) we can see that spacing is the mean distance between edges along a linear path.

To demonstrate both manual spacing and the operation of the spacing transform, a ground truth segmented image will be used (an image of a block of text). The text block image provides a rigorous binary image where the edges are precisely defined and provides a real structure to analyze. To measure the spacing, one would place a line on the image. The placement of the line is chosen using two criteria. First, the location of the line must be such that it covers the structure of interest, in this case the text. Second, the line angle is chosen to minimize the length of the line for a given number of edges. Fig. 1 shows a line which satisfies both criteria. Any line location which intersects the text structure would suffice. Fig. 2 shows how the length of the line varies if the line angle is altered while maintaining a constant number of desired edges. The line shown in Fig. 1 crosses 12 edges, or N_E equals 12. In the original image, the line placed has a length, L_L, equal to 208 pixels. Therefore, we can compute the spacing, using Eq. (1) as λ equal to 34 pixels. This λ is representative of the mean distance from midpoint to midpoint of either background or foreground features. As a matter of reference, manually checking the distance of the midpoint of the “D” to the midpoint between the “D” and the first “O” gives a value of 32 pixels. To improve the accuracy of the measurement, additional randomly placed lines would need to be used.

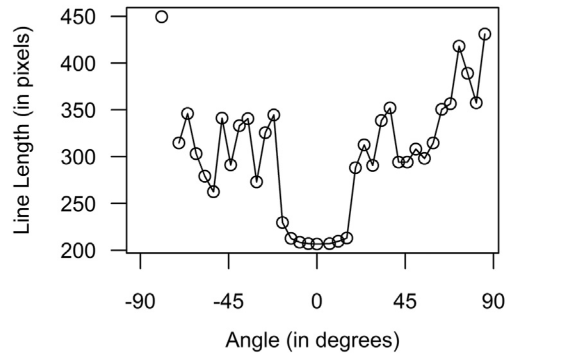

Fig. 2. A plot of line length vs angle probed for the location of the measurement line shown in Fig. 1. The plot shows that the original 0 degree line is also the minimum line.

2.2. The Transform

As discussed in the introduction, a spacing transform provides the distance required to reach the N_E nearest consecutive edges along a linear path and intersecting a given location.

To produce the spacing transform, a series of lines extending from a specific pixel in the image are generated until the required number of edges are crossed. Using the lengths of these lines a distribution like that in Fig. 2 is obtained. The minimum line length found through this sweeping of the angles becomes L_L. Using L_L and N_E, the λ value using Eq. (1) is returned as the new value of that pixel location.

Fig. 3 is the image from Fig. 1 transformed using this definition and then normalized using Eq. (1). The edges from Fig. 1 are shown as an overlay on the transformed image. As would be expected, in areas of higher text density, the spacing computed is smaller, resulting in darker regions within the image. If we probe the transformed image where the

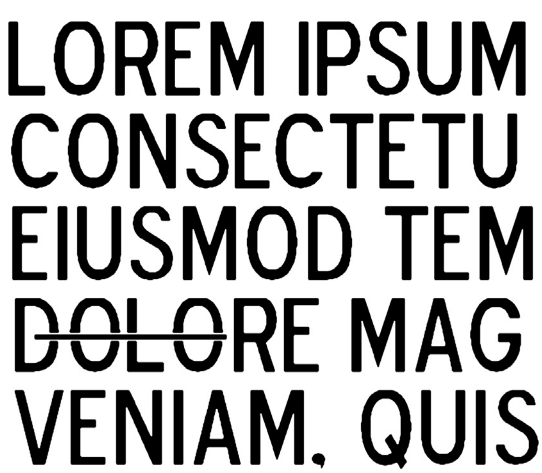

Fig. 1. A block of text with a line placed to demonstrate how the manual spacing measurement is taken.

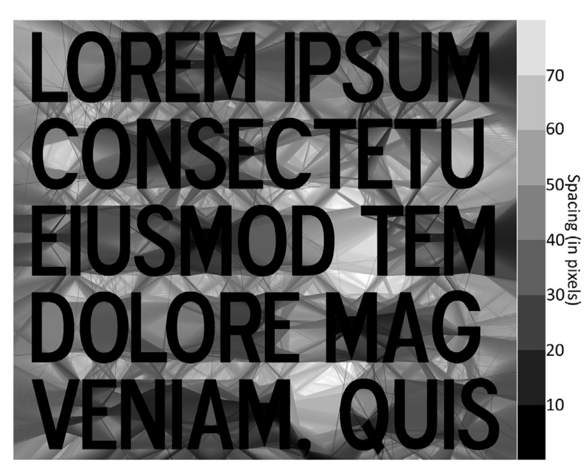

Fig. 3. The original image from Fig. 1 transformed by replacing each pixel with the spacing measurement appropriate to the corresponding location. The original text structure is subtracted from the transform result provide visual reference.