The Generalized Orientation Field Transform

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Abstract. We extend earlier work on the Orientation Field Transform as an effective method for enhancing curve like features in images. Whereas the original Orientation Field Transform was formulated for straight lines, we generalize the formalism to general curves, resulting in improved accuracy for detecting circular objects. The method only requires one parameter, the curve width, to be selected by the user and does not require any pre- or post processing, even for noisy data sets with low contrast. We demonstrate the method for several electron microscopy tomograms.

1 Introduction

In this paper we consider the problem of enhancing curve like structures in images while suppressing noise and non-curve like objects. We focus on electron microscope tomograms, but our method is general and can be applied to many areas of image processing.

We base our method on a generalization of the Orientation Field Transform (OFT) introduced in [1]. In previous work the OFT was defined for straight lines, and in this paper we extend the formalism to curved lines.

Detecting curve like structures is often complicated by the presence of noise and well-defined non-curve like objects, problems that are often overcome by introducing one or more adjustable parameters [2], [3]. Although it is often possible to find a parameterization that solves a segmentation problem satisfactory, methods relying on too many parameters may be impractical for wide usage in a laboratory settings. The method in this paper only requires one parameter to be set, the width of a typical structure, a parameter that is often known a priori or is easy for the user to estimate.

We demonstrate the method for electron microscope tomograms of cells. Our study includes some particularly challenging data sets where we demonstrate that the method is capable of detecting curve like objects despite the challenging nature of the data.

2 The Generalized Orientation Field Transform

2.1 Idea

The method we present consists of three steps. First, we assign an orientation to each pixel in the image, where each orientation consists of a direction and a significance weight [4],[1]. Second, we measure the net alignment along a family of curves through each pixel and record the curve that results in the best net alignment. In the final step we record the net alignment value along the maximizing curve for each pixel, resulting in an image where curve like objects are enhanced.

2.2 Definition

Let $I(\mathbf{x})$ denote the image to be processed such that $I(\mathbf{x})$ gives the (gray scale) intensity at location $\mathbf{x} = (x, y)$. We define an orientation $\mathcal{F}$ as the tuple $\{w, \theta\}$ where θ is a direction that ranges between 0 and 180° and w is a positive weight indicating the importance of the direction. An orientation field $\mathcal{F}(\mathbf{x}) = \{w(\mathbf{x}), \theta(\mathbf{x})\}$ is the assignment of an orientation to each location in the image. In this paper we generate the orientation field with the method in [3].[1].

Let $\{\mathbf{r}_k(t)\}_{k\in\mathcal{I}}$, $-1 \leq t \leq 1$, denote a family of differentiable curves in the plane indexed by some set $\mathcal{I}$. Each curve is of length L and parameterized such that $\mathbf{r}(0) = \mathbf{0}$. Let ν_k denote the direction of the tangent vector $\frac{d\mathbf{r}_k}{dt}$ mapped to the interval $[0, 180°)$. [2]

In order to measure the alignment of the orientation field along a curve $\mathbf{r}_k(t)$ we define the *alignment integral*

$$\Omega[\mathcal{F}](\mathbf{x}, k) = \int_{-1}^{1} w(\mathbf{x} + \mathbf{r}_k(s)) \ \cos\left(2(\theta(\mathbf{x} + \mathbf{r}_k(s)) - \nu_k(s))\right) \left|\frac{d\mathbf{r}_k}{ds}\right| \ ds. \tag{1}$$

(Compare the definition of a work integral in physics written in its polar representation.) We now define the (generalized) Orientation Field Transform as

$$\mathcal{O}[\mathcal{F}](\mathbf{x}) = \Omega[\mathcal{F}](\mathbf{x}, k_{max})$$

where

$$k_{max} = \arg\max_{k\in\mathcal{I}} \left|\Omega[\mathcal{F}_0](\mathbf{x}, k)\right|.$$

In this formalism that generalizes the defintion in [1] and [3], we allow for the possibility to use two different orientation fields; one for the computation of the maximizing curve (denoted by $\mathcal{F}_0$), and one for the evaluation of the alignment integral along the maximizing curve (denoted by $\mathcal{F}$).

2.3 Example

In this section we illustrate the method defined in the previous section. As an example, we consider the image in Figure 1a.

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[1] For a simpler but less robust method, see [1]

[2] As opposed to vectors, orientations lack a sense of ¨backward/forward¨, and are only defined for angles in the range $[0, 180°)$. If the tangent vector $\frac{d\mathbf{r}_k}{dt}$ has an angle in the interval $[180°, 360°)$, we map such angles to $[0, 180°)$ by subtracting 180°.

Step 1. We first generate the directions $\theta(\mathbf{x})$ of the orientation field using the method in [3]. However, in a departure from [3], we assign the unit weight $w(\mathbf{x}) = 1$ to each orientation.

Step 2. For each pixel, we search for the curve through the pixel that maximizes the absolute value of the alignment integral (1). Whereas the papers [1] and [3] used a family of straight lines of varying angle, we will in this paper consider a larger family of curves.

Let $\mathbf{r}_{\alpha,\kappa}(t)$ denote the curve with constant curvature κ and tangent direction α at $\mathbf{r}_{\alpha,\kappa} = 0$ (see Figure 1b). Using a finite set of such curves in the range

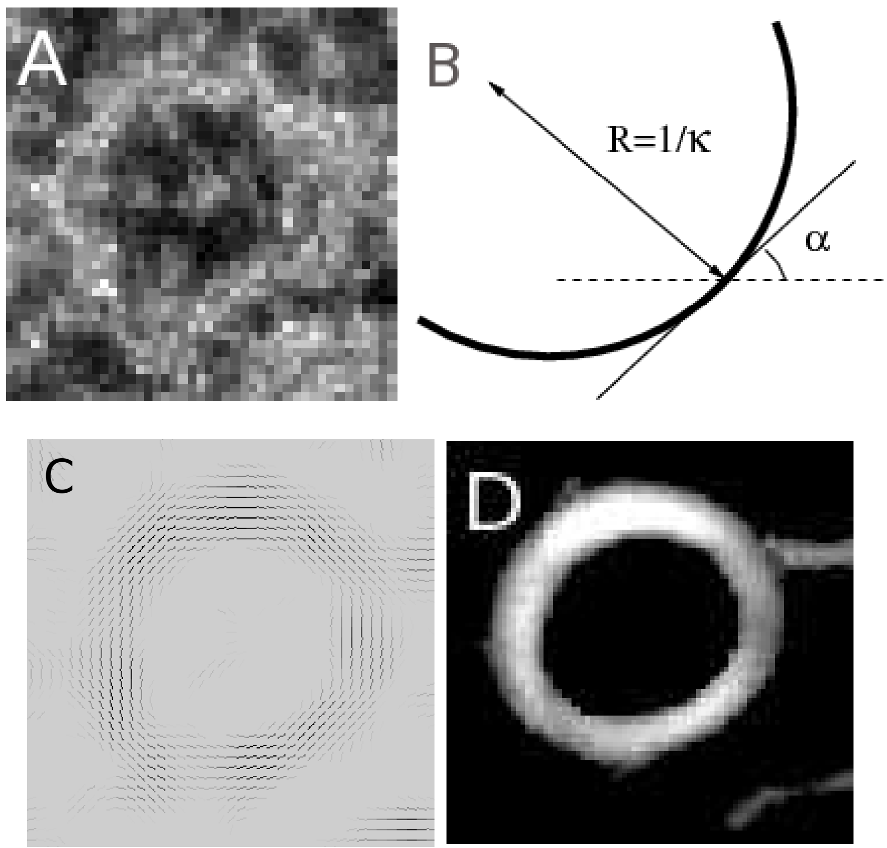

Fig. 1. a) Original image. b) Illustration of a curve $\mathbf{r}_{\alpha,\kappa}$ (illustrated by the thick curve). Note that κ can be interpreted as $1/R$, where R is the radius of a circle. c) The orientation field for the image in a). d) The OFT response for the image in a).

$\alpha \in [0, 360°)$ and $\kappa \in [0, \infty)$, we now evaluate the alignment integral (1) at each pixel for each curve. We record the tangent angle α and curvature parameter κ that produces the largest magnitude response of this integral. We note that a negative alignment value at a location $\mathbf{x}$ indicates the exterior of a curve, and a positive alignment value indicates the interior of a curve.

Step 3. To compute the final OFT response, we evaluate the integral (1) at each location using the maximizing curve from Step 2. In this step we compute the orientation weights according to [3]. The orientation field is illustrated in Figure 1c and the resulting OFT response is shown in Figure 1d.

Remark. An important property from using the the orientation field constructed using either the method in [1] or [3], is that the OFT can effectively detect the interior and exterior of a curve like structure. This ¨interior/exterior distinguishing property¨ is particularly strong when using a unit weight. We have found this property useful for finding the maximizing curves in Step 2 as these weights will generate strong negative response outside the objects of interest. However, once the maximizing curves have been found, the weights in [3] gives better result when used for the final computation in Step 3.

3 Results

In order to demonstrate the quality of the curve enhancement method, we will now provide examples from slices of 3D electron microscopy tomograms. We stress that all these were produced by only setting one parameter, the curve length L, which was chosen as 2-3 times the width of a typical curve. No additional pre- or post processing was used.

In Figure 2a and b we demonstrate the method on a data set with relatively well defined curves. In Figure 2c and d we apply the method to a more challenging data set, and note that despite this most challenging data set we are still able to get decent results. (See also Figure 1 where we have processed a subset of this data set.) In Figure 3a and b we demonstrate the method for a cryo electron microscopy data set.

In our last example (Figure 3c and d), we demonstrate how the method can detect objects that are almost invisible to the naked eye. In 3c and d we show close ups of Figure 3a and b respectively. In this case, the marked structure in Figure 3d is almost invisible in the original, but well defined in the OFT processed image. For this data set, we had access to neighboring slices as well, and were able to confirm that the detected structure is indeed the upper cap of a valid biological structure. This illustrates how the method can be useful for detecting objects in images with extremely poor contrast.

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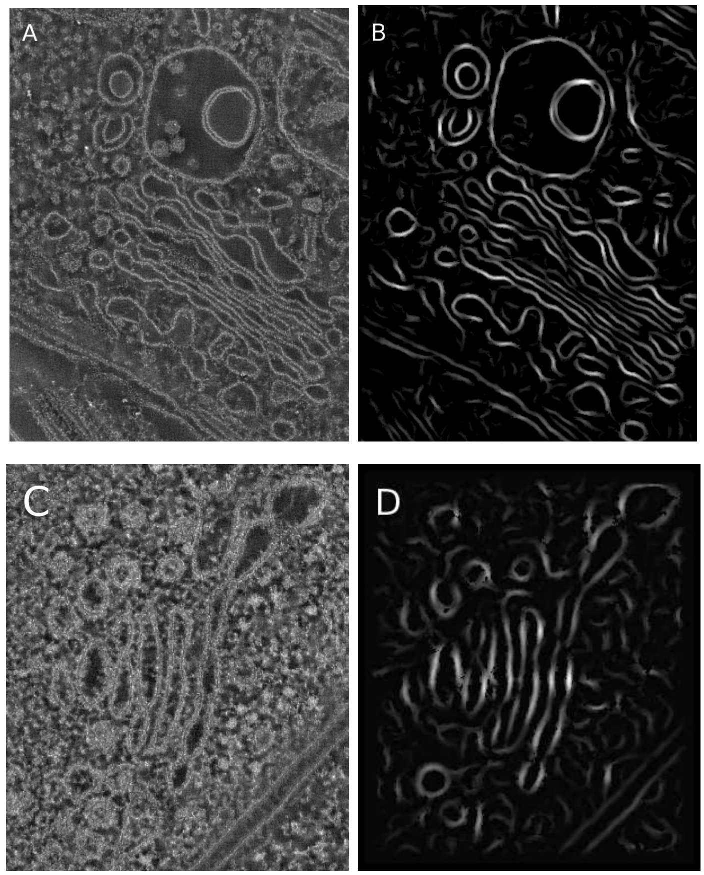

Fig. 2. a) Original image. (Tomogram of a Trypanosome.) b) OFT response of the image in a). c) Original image. (Tomogram of a T-lymphocite.) d) OFT response for the image in c).

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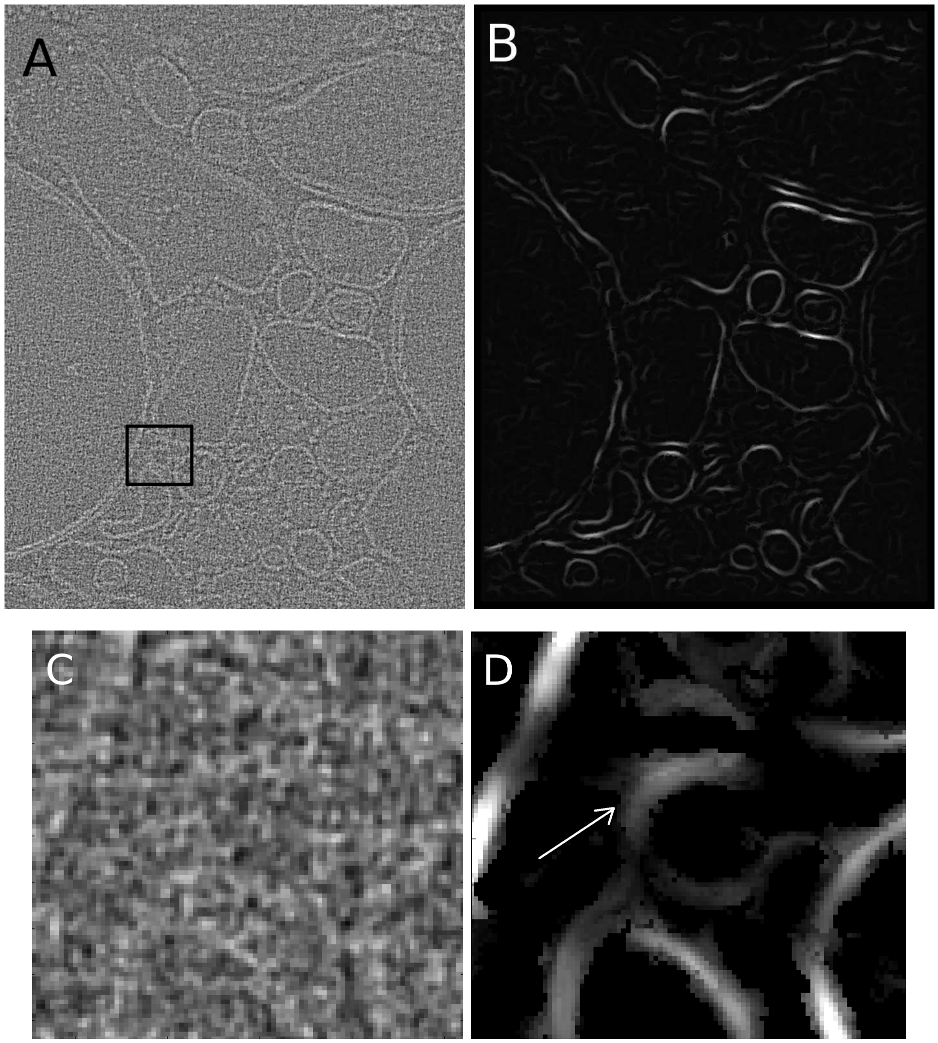

Fig. 3. a) Original image. (Cryo EM tomogram of a Thylakoid membrane.) b) OFT response of the image in a). c) Close up of boxed region in a). d) OFT response for the image in a). Note the marked structure, which is almost invisible in the original image. (By studying adjacent slices in the full 3D data set, we have been able to verify that the marked structure is the cap of a valid biological structure.)