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On the projection similarity in line grouping ☆

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ABSTRACT

This paper is concerned with the grouping of elementary line segments which are comprised of pairwise projected entities. In a dynamic and densely cluttered scene we consider a feature-driven recognition of objects with predominantly linear or quasi-linear structural elements. The motivation arises from the field of biological imaging such as the detection of mitochondria in a complex subcellular environment. Subsequent line extraction operations result in a set of line segments with different lengths, density and orientations. We observe that a distinct criterion to distinguish such a salient group of line segments from the background can be formulated as *Projectivity*. We introduce a new similarity measure *Projection-to-Distance Ratio* which combines the proximity and the amount of spanned orthogonal projections between two line segments. Further, we perform investigations on the Euclidean properties of the proposed similarity measure. We construct the similarity matrix and show that it translates into an indefinite pseudo-covariance matrix. In order to test the introduced similarity measure we examine the applicability of NN (nearest neighbor) and non-NN clustering methods for the grouping of line segments.

1. Introduction

Some 8 decades ago Gestalt psychologists formulated the fundamental principles of the human visual recognition system. Our ability to perceive and identify non-accidental and significant objects in a complex environment relies on the fact that we intuitively favor the organization of objects exhibiting *Proximity*, *Similarity*, *Continuation*, *Symmetry*, *Closure* and *Familiarity* properties [11,3]. The formalism of perceptual organization governs and influences artificial grouping strategies. Grouping itself as a process can vary from grouping of low-level geometric primitives to grouping of complex objects. Any object can be parameterized and represented by a token which can be used for grouping.

A line segment, often referred to as an elementary line segment (ELS), forms an important category of low-level primitives. A network of short line segments is usually extracted from an image using Hough transform, line fitting or curve smoothing operations on the edge map. Lowe [11,12] examines the connectivity relations between line segments from the perspective of perceptual organization and postulates inferences of *Proximity*, *Collinearity*, *Parallelism*, *Equal Spacing*, *Cotermination* and *Convergency To A Common Point* as a combination of basic Gestalt laws.

The decision on how to analyze a set of linear segments and to extract salient structures from the complex background greatly depends on the underlying application. Much attention in the literature is given to the detection of salient curves and lines, composed of a number of short line segments [20,1,8]. Shaashua and Ullman [20] define a global saliency measure to identify smooth curves and use the instances of *Collinearity*, *Cotermination* and *Parallelism* among straight line segments. Jang and Hong [9] consider the detection of long line segments and indirectly apply the inferences of *Collinearity* and *Proximity*. Stahl and Wang [21] apply the *Symmetry* principle to the detection of closed convex boundaries with symmetry. The most recent works on line segments grouping include [23] and [24].

We now examine a new principle for the grouping of line segments. Fig. 1(b) shows two synthetic elongated objects A and B with flexible shapes and transverse elements. In the following we consider two perspectives from which this example can be viewed. The first is closely related to the field of perceptual organization and concerns our ability to recognize the objects A and B from the set of lines in Fig. 1(a) without any a-priori knowledge about their shape and composition. The second belongs to the computer vision domain and attempts to establish analytic relationships between line segments which are necessary for the recovery of both objects. Despite being conceptually different the two approaches are rather complementary than contradictory. Naturally, the visual scan of Fig. 1(a) will result in a number of different interpretations depending on the observer's preference for factors such as parallelism, density, size or collinearity and not at least on the observer's experience with similar structures.

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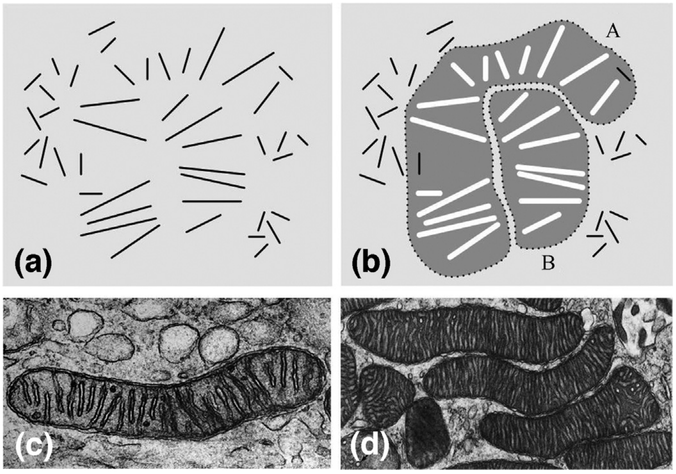

Fig. 1. Line grouping objectives. (a) Set of line segments. (b) Two distinct elongated objects of interest. (c) Electron microscopy (EM) image of *lamellar*.-type mitochondrion from mouse epididymis. (d) EM image of *tubular*.-type mitochondria from hamster's adrenal cortex cell.

At first we may argue that the lower part of Fig. 1(a) appears to be the most salient. However, it is an acceptable assumption that in a search for a smooth contour we may at some stage discover object B by cognitively filling the gaps between its transverse elements – a process described by the *Continuation* and *Closure* principles. Having realized, in other words *learned*, that this discovery may stem from a causal relationship we may proceed scanning the space to register object A.

Encouraged by the above discussion we introduce a new similarity criterion denoted as *Projectivity*. We reason that this measure uniquely resolves the problem of forming object B and particularly object A which otherwise exhibits no similarity in size, orientation or density of its line segments. Indeed, every line segment in A and B is bounded by a "just right" amount of projection of its two spatial counterparts. The aspect of randomness is particularly interesting in this context.

It has been well noticed by Lowe in [11] that features that resemble a non-accidental object are likely to be located close in space. This fact constitutes our preference for an *orthogonal* projection which has an inherently geometric connection with the notion of a shortest distance. Although orthogonal projections are an integral part of various grouping methods [21,5], an investigation on a stand-alone similarity, which would describe orthogonally projected line segments, has not been previously reported.

Our motivation to explore the role of projections in line grouping originates in the field of nano-biophotonics and imaging of subcellular regions, in particular of mitochondria. Mitochondria form an important category of membrane enclosed, on average 200 nm large *organelles* which reside inside every living cell. Mitochondrial morphology depends on the type of biological tissue and further undergoes changes during induced or naturally occurring biochemical processes [22]. This fact accounts for the vast range of mitochondrial shapes and textures and challenges a unified approach to localization and segmentation. Presently the segmentation of mitochondria is performed manually [16], though automatic classification has also been recently reported in [14,7].

In many cases transmission electron microscope (TEM) images of mitochondria show characteristic quasi-linear structural elements (Fig. 1(c)–(d)) which can be converted to the proper line segments. Therefore a structural approach to the recognition of mitochondria exhibiting a predominantly linear or quasi-linear pattern may benefit from our *Projectivity* inference as we intend to demonstrate in the experimental part of this paper.

2. Similarity measures

For the aim of grouping we do not pose any constraints on length, orientation or density of line segments but rather consider the combination of the following inferences:

(i) ***Projectivity***: Line segments form a cluster with pairwise orthogonally projected entities.

Let $P_X Y$ be named *left-projection* and denote the orthogonal projection of ELS Y onto ELS X. The *right-projection* is the orthogonal projection of ELS X onto ELS Y with the notation $P_Y X$. In order to obtain $P_Y X$ in closed form we define two supporting vectors **a** and **b** (see Fig. 2(b)) as follows: $\mathbf{a} = [s_y, e_x]$ and $\mathbf{b} = [s_y, s_x]$.

The angles θ_a and θ_b are directly related to the dot product between the corresponding vectors: $\cos\theta_a = (\mathbf{a}\cdot\mathbf{y}^{\mathrm{T}})/(\|\mathbf{a}\|\cdot\|\mathbf{y}\|)$ and $\cos\theta_b = \mathbf{b}\cdot\mathbf{y}^{\mathrm{T}}/(\|\mathbf{b}\|\cdot\|\mathbf{y}\|)$. The orthogonal projections of vectors **a** and **b** onto ELS Y therefore are: $P_Y a = \|\mathbf{a}\|\cdot\cos\theta_a$ and $P_Y b = \|\mathbf{b}\|\cdot\cos\theta_b$. In analogy, in order to obtain the $P_X Y$ projection, we define two additional support vectors **c** and **d** as: $\mathbf{c} = [s_x, e_y]$ and $\mathbf{d} = [s_x, s_y]$. Let us introduce a binary cost function Ω such as:

$$\Omega = \begin{cases} 1 & \text{if } \cos\theta > 0, \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

Then the orthogonal projections $P_Y X$ and $P_X Y$ are:

$$\begin{aligned} P_Y X &= \mid P_Y a \cdot \Omega_a - P_Y b \cdot \Omega_b \mid, \\ P_X Y &= \mid P_X c \cdot \Omega_c - P_X d \cdot \Omega_d \mid . \end{aligned} \tag{2}$$

(ii) ***Proximity***: Line segments in a cluster follow some proximity principle in Euclidean space.

For this paper, we define the distance D between two elementary line segments (ELS), X and Y, as the Euclidean distance between the ELS centers c_x and c_y (see Fig. 2):

$$D(X, Y) : D(c_x, c_y) = \|\mathbf{c}_{xy}\| \tag{3}$$

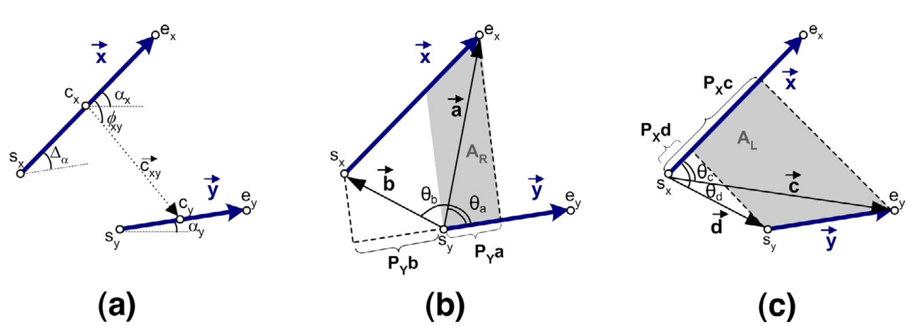

Fig. 2. Similarity measures. (a) Notations. (b) Right-orthogonal projection. (c) Left-orthogonal projection.