

A Transform for Detection of Multiscale Image Structure

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1 Introduction

This paper introduces a new transform to facilitate integrated edge and region detection in an image at all geometric and photometric scales at which structure is present. A major motivation and contribution of the presented approach is to avoid the use of a priori models of edge geometry which is an inherent limitation of linear approaches, but still allow detection of region boundaries with arbitrary curvature. The inspiration for the proposed solution comes from physics where microscopic homogeneity of physical properties results in islands of similar elements, e.g., alignment of microscopic domains in large areas of a ferromagnetic material. Accordingly, the proposed transform allows the structure to "emerge" from "interactions" among the pixels. A pixel's interaction with all other pixels is considered instead of testing specific neighborhoods for a specific structure. Computations are performed on pairs of pixels followed by vector integration of the results, rather than scalar, weighted averaging over pixel neighborhoods. For pixels on either side of a region boundary, the transformation yields high "affinities", but there is little affinity between pixels across regions. Due to the global interpixel interaction allowed, the transform can be viewed as collecting spatially distributed evidence for edges and skeletons and making it available at their locations. In this sense, the transform performs Gestalt analysis.

The objective of this paper is to introduce the transform. Algorithms for structure detection from the transformed image are beyond the scope of this paper. For brevity, experiment results are not presented as well as references to related previous work by others are not included. These and other details can be found in [1, 2]. We will illustrate the use of the transform for edge detection, and then outline its use for region skeleton extraction. For concreteness, we will assume that image regions have uniform gray levels and are surrounded by step edges, although the approach extends to other types of regions and edges.

2 Background and Motivation

There are two major aspects of edge detection which are of central importance to its performance. The first one has to do with the photometric and geometric model of an edge. It is common to treat the problem of edge detection as mainly that of selecting a point along the intensity profile across edge, while

implicitly or explicitly using a model of edge curvature, e.g., to identify the edge profile through a pixel. The issue of the validity of the models of edge profile has been addressed and different models of edge have been mentioned. However, the limitations and impact of the assumptions made about edge geometry have received much less attention. The second major aspect of edge detection is related to scale. There are two important ways in which edges are associated with scale: geometric and photometric. For example, geometric scale captures size of image structure and photometric scale represents sensitivity to edge contrast.

The above discussion leads us to the following desired characteristics of an edge detector:

A. Shape Invariance: The edge should be correctly detected regardless of the local curvature. Thus, an edge point must be detected at only one and correct location, regardless of whether the edge in the vicinity of the point is straight, curved or even contains a corner.

B. Contrast Scaling: It should be possible to detect edges according to their contrast. For example, as scale increases, the required contrast of detectable edges may increase.

C. Geometric Scaling: It should be possible to detect edges of regions according to their sizes. For example, as scale increases the required size of detectable geometric features may increase.

D. Stability and Automatic Scale Selection: Image structures at different scales correspond to locally invariant (stable) descriptions with respect to geometric and contrast sensitivities. Since for an arbitrary image these scales are a priori unknown, they should be identified automatically.

In the next section, we propose a family of transforms which is aimed at satisfactorily addressing the two aspects of edge detection and to achieve the desired characteristics discussed above.

3 A Family of Transforms for Multiscale Edge Detection

Consider a transform over the image which computes an attraction-force field wherein the force at each point denotes its net affinity to the rest of the image. The force vector points in the direction in which the point experiences a net attraction from the points in the rest of the image. For example, a point inside a

region would experience a force towards the interior of the region. Let $F(\mathbf{p}, \mathbf{q})$ denote the magnitude of the force vector $\mathbf{F}(\mathbf{p}, \mathbf{q})$ with which a pixel P at position \mathbf{p} is attracted by another pixel Q at location \mathbf{q} . Thus, $\mathbf{F}(\mathbf{p}, \mathbf{q}) = F(\mathbf{p}, \mathbf{q})\hat{\mathbf{r}}_{\mathbf{p}\mathbf{q}}$, where $\hat{\mathbf{r}}_{\mathbf{p}\mathbf{q}}$ denotes the unit vector in the direction from P to Q.

In the continuous image plane, an image is transformed into a continuous vector field. The resultant attractive force vector \mathbf{F}_p at P is given by

$$\mathbf{F}_p = \int_{\mathbf{q} \in \text{Image}} F(\mathbf{p}, \mathbf{q})\hat{\mathbf{r}}_{\mathbf{p}\mathbf{q}}d\mathbf{q} \quad (1)$$

We must now specify what forms could the force function $F(\mathbf{p}, \mathbf{q})$ take. We will do so by considering the properties that \mathbf{F} must possess. These properties will define a family of transforms. Any choice of \mathbf{F} that has these necessary properties will suffice. A specific choice of \mathbf{F} will yield one member of this family.

Since the presence of an edge must be determined by its immediate vicinity (adjoining regions) rather than by distant points across other intervening regions, the force should be a decreasing function of distance. This will be accomplished by making the force exerted on a given pixel P by another pixel Q to be inversely proportional to the distance between P and Q. Further, a pixel should be attracted more to a pixel within its own region than to one in a different region. This is accomplished by making the force to be inversely proportional to the difference between the gray levels of P and Q. The rate at which the force decreases with distance (gray level difference) determines the geometric (photometric) scale captured by the force field.

We will now list some basic properties of the force field \mathbf{F} which illustrate qualitatively why the family of transforms of Eqn (1) is useful. Proofs of these properties and detailed performance evaluation of the transform with respect to properties (A-D) are presented in [2].

1. Magnitude and Directionality: The magnitude of \mathbf{F}_p increases as P moves closer to the region boundary. The direction of \mathbf{F}_p points toward region interior.

2. Orthogonality: Consider a point P just inside the boundary of a region W, such that the boundary within a disk D of radius r centered at P, $r \gg \sigma_s$, is symmetric about P. Then the direction of \mathbf{F}_p points into the region and is normal to the boundary at P.

3. Smoothness: If $F(\mathbf{p}, \mathbf{q})$ is a continuous (or differentiable) function for any \mathbf{p} and \mathbf{q} , and the intensity value within any image region is continuous (or differentiable), then so is \mathbf{F} at all nonboundary points of the region.

From these properties, it can be shown [2] that:

RESULT: Region borders are characterized by a discontinuity in the direction of \mathbf{F} . The magnitude of the discontinuity is $\pi/2$ for optimal choice of scale parameters at each point and decreases gradually for suboptimal choices.

We now describe a specific transform belonging to the family defined by Eqn (1). We define $F(\mathbf{p}, \mathbf{q})$ in

Eqn (1) as a product of two Gaussians, one a decreasing function of the distance $d(\mathbf{p}, \mathbf{q})$ between P and Q, and the other a decreasing function of the gray level difference, $g(\mathbf{p}, \mathbf{q})$ between P and Q. The standard deviation for the spatial variation is the spatial scale parameter σ_s , and the standard deviation for the gray level variation is, the scale parameter for gray level difference, σ_g . The choice of Gaussian for each part is made mainly because of its optimal localization properties in both spatial and transform domains, although other properties such as separability are also desirable.

Therefore, the proposed transform \mathbf{F}_p at an image point P at location \mathbf{p} is defined by:

$$\mathbf{F}_p = \int_{\mathbf{q} \in \text{Image}} e^{-\frac{d^2(\mathbf{p}, \mathbf{q})}{2\sigma_s^2}} e^{-\frac{\Delta g^2(\mathbf{p}, \mathbf{q})}{2\sigma_g^2}} \hat{\mathbf{r}}_{\mathbf{p}\mathbf{q}}d\mathbf{q} \quad (2)$$

Empirically, the performance of the transform for edge detection seems to be quite insensitive to the nature of the decreasing function [2]; the formulation of interpixel interaction as a vector integration of pairwise pixel similarities, rather than scalar weighted averaging over neighborhoods, appears to be the key factor in capturing the image structure.

4 Multiscale Shape Description

There are two ways in which the proposed approach yields multiscale description of region shape along with multiscale edges. First, we have seen that the detected edges form closed contours surrounding the corresponding regions. Therefore, multiscale edge detection implies detection of multiscale regions. The second way in which the transform extracts multiscale region shape information is by making explicit their skeletons. Recall from Property 1 above that in the vicinity of an edge point the magnitude of \mathbf{F} decays away from region boundary and its direction points away from the boundary point. This implies that for the appropriate values of the scale parameters at each point, as one moves away from region boundary towards the interior there is a curve across which the force changes direction, from facing one side of the region boundary to another. This curve corresponds to region skeleton.

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References

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