Multi-Scale Edge Detection with Bilateral Filtering in Spiral Architecture

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Abstract

Real images are often corrupted by noise from various sources. Bilateral filtering is a nonlinear filter that considers intensity variations as well as spatial closeness in the noise smoothing process. It has been demonstrated to have a better edge-preserving quality than linear filters in certain applications. This paper presents the new edge detection algorithm with the application of a bilateral filter in Gaussian form in Spiral Architecture. Spiral Architecture is a relatively new concept in the area of image representation and offers distinctive advantages. The approach to edge detection is multi-scale. Edge maps of the original image and its successively smoothed versions are used to produce the final edge map.

Key Words: bilateral filtering, Spiral Architecture, edge detection, multi-scale.

1 Introduction

Edge detection is a process of detecting areas of abrupt changes or discontinuities in some visual property (light intensity, texture or colour) [1]. It is a critical preprocessing step towards high-level image understanding. Edges are essentially surface boundary discontinuities, thus they hold important feature information about objects in an image (e.g. size, shape and location) that subsequent processing highly depends on.

1.1 Gradient edge detection

Major generic approaches to edge detection are model fitting and differentiation [2]. Model fitting involves matching the actual image data against ideal edge model. If the fit is sufficiently close, an edge is assumed to exist. The differentiation approach [3,4,5] has been the classical and most often used edge detection method. It is computationally less intensive than the model fitting methods.

Edges are most frequently defined as areas where abrupt changes in light intensity occur. Hence mathematically they will manifest in the derivatives of the image function.

Differential method uses approximation of spatial gradient at each pixel location. Denote $f(x, y)$ to be the function that maps gray scale value at a particular pixel a_0 to its Cartesian co-ordinates. Let $G(x, y)$ be the rate of change in gray scale value at pixel a_0. $G(x, y)$ can be computed in terms of the derivatives along x and y directions, $G_x(x, y)$ and $G_y(x, y)$ as follows:

$$G(x, y) = \{ [G_x(x, y)]^2 + [G_y(x, y)]^2 \}^{\frac{1}{2}}$$

The technique for approximation of derivatives $G_x(x, y)$ and $G_y(x, y)$ is through a mathematical operation termed *convolution* [6]. Differentiation is a noise enhancing operation and the higher the order of derivative the more pronounced the effect. Therefore differentiation often has to be preceded by smoothing for images corrupted by noise.

1.2 Smoothing

Smoothing reduces the sharpness of transitions in intensity values to achieve noise reduction or detail suppression. Two approaches to smoothing are linear and nonlinear.

Linear filtering is implemented by convolution of the original image function with a predefined kernel or mask. Although simpler to implement, linear methods tend to blur edges. In the past decade nonlinear filters have been developed to achieve a more desirable level of smoothing in applications where important visual cues provided by edges need to be preserved. Many efforts have been devoted to edge-preserving smoothing [7,8].

In 1998, bilateral filtering was introduced by Tomasi and R. Manduchi [9]. In essence a bilateral filter replaces a given pixel value with an average of similar and nearby pixel intensity values. In this form of filtering, a range filter is combined with a domain filter. Domain filtering enforces spatial closeness by weighing pixel values with coefficients that fall off with distance. A range filter, on the other hand, assigns greater coefficients to those neighbouring pixels with light intensity that is more similar to the centre pixel value. Hence the original intensity value at a given pixel would be better preserved thanks to range filtering. Range filtering by itself is little use because pixel values that are far away from a given pixel should not contribute to the new value.

The challenge to precisely detect edges in real images has inspired a variety of advanced edge detection algorithms. Multi-scale analysis is a systematic approach to edge detection. This approach relies on the inspection of intensity changes on different scales.

1.3 Multi-scale edge detection

Objects in the world only exist as meaningful entities over a limited range of scale. Hence the physical description strongly depends on the scale. When analyzing measured data such as images, without any prior knowledge, there is no reason to favour any particular scale. The idea is that for any image, a set of gradually smoothed or simplified images should be generated, in which fine scale structures are successively suppressed. A formal definition for continuous signals of arbitrary dimensions N was given by Lindeberg [10].

1.4 Spiral Architecture

In this research project, the image arrays are mapped into Spiral Architecture [11]. Spiral Architecture is made up of rosette-like clusters of hexagonal cells. Each element (hexagon) in the Spiral Architecture has only six neighbouring hexagons and enables the traditional two-dimensional visual field to be represented as a one-dimensional array. Figure 1 displays such architecture with a collection of 49 hexagons. Each cell is uniquely addressed and the spiral addresses grow from the centre clockwise in base of seven. Hence using Spiral Architecture to represent images implies less memory space and computation required for processing.

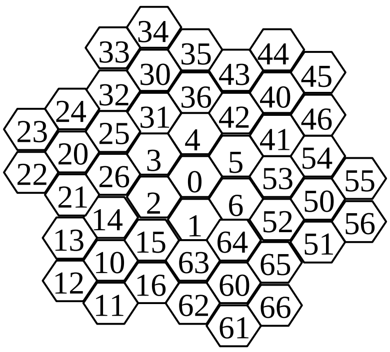

Figure 1: Spiral Architecture with 49 hexagons.

Figure 2: 'Lena' in Spiral Space.

Because currently there is no supporting hardware for Spiral Architectural sampling, a mimic system was introduced by Dr He [11]. The mimic system retains the organizational character of the original Spiral Architecture. Hence it inherits the computational power of the original structure. In the mimic system, one hexagonal pixel is formed by four neighbouring pixels in the traditional system and its gray scale value is the average of those four pixels values. Figure 2 is a sample image represented in mimic Spiral Architecture.

2 Multi-scale edge detection with bilateral filtering in Spiral Architecture

In this research, edge detection is accomplished by applying a new bilateral filtering technique specifically designed for Spiral Architecture, integrating the multi-scale approach to edge detection. The kernel coefficients of a bilateral filter are determined by the combined closeness and similarity function.

Let $f:\Re^2 \to \Re$ be the original brightness function of an image which maps the coordinates of a pixel (*x*, *y*) to a value in light intensity. Then for any given pixel a at (x, y) within a neighbourhood of size n, which has a_0 as its centre, its coefficient assigned by the range filter $r(a)$ is determined by the following function:

$$r(a_i) = e^{-\frac{[f(a_i)-f(a_0)]^2}{2\sigma_r^2}}$$

Similarly, its coefficient assigned by the domain filter $g(a)$ is determined by the closeness function below:

$$g(x, y; t) = e^{-\frac{x^2+y^2}{2t}}$$

where *t* is the scale parameter.

For the central pixel of the neighbourhood a_0, its new value, denoted by $h(a_0)$,

$$h(a_0) = k^{-1}\sum_{i=0}^{n-1} f(a_i)\times g(a_i)\times r(a_i)$$

k is the normalization constant and is defined as follows

$$k = \sum_{i=0}^{n-1} g(a_i)\times r(a_i)$$

The normalizer *k* is necessary because the average image intensity should not be affected by multiplying the mask with the original image.

Application of the new bilateral smoothing filter produces, for each pixel in the image, a weighted average such that the central pixel a_0 contribute more significantly to the result than its neighbouring pixels. Pixels with more similar intensity value or closer to the central pixel contribute more than those with more different value or further away. Level of smoothness depends on the value of the scale parameter chosen and σ_r. The stronger the scale and σ_r, the higher level of smoothness will be achieved.

Following bilateral smoothing the edge detection algorithm performs edge point marking based on the method developed by He [11]. First-order derivatives are obtained using adjacent pixel value difference along *x* and *y* directions. Definition of edge points is based on the gradient magnitude at the given location and the gradient direction.

This research attempted to construct several edge maps of the given image, each representing intensity changes when a different and systematically controlled smoothing strength is applied. Edge map from a less smoothed image will have edge locations closer to the centre of the original edge map before any smoothing. Edge map from a stronger smoothing strength will have fewer noisy or false edge points. Therefore to ensure precise localization of edge points and detection of real edge points, these edge maps should be systematically compared. Major steps of edge detection algorithm developed by this research with bilateral smoothing for Spiral Architecture is presented below:

1. **Initial edge detection**. Edge map of the original input image gives the most precise locations of edge points because it is not affected by smoothing. Set this edge to *E;*
2. **Bilateral smoothing;**
3. **Edge detection for newly smoothed image**. Edge points are marked according to the method defined in [8]. Denote this edge by E_s ;
4. **Edge Map Update**. Edge map *E* and E_s are compared. Edge map *E* is depended on for its more precise edge locations and edge map of the smoothed image E_s is used to eliminate some false edge points for the smoothed image has less noise than the original one. The new edge map after comparing will contain those edge points from the initial edge map that have at least one immediate neighbouring pixel from the edge map of the smoothed image.
5. **Repeat** Step 2, 3 and 4 with systematically increased smoothing strength until the new current edge map is not significantly different from the one obtained at the end of last iteration.

3 Experimental Results

Final edge map of 'Lena' and two other images are shown below.

The magnified portion of the result with bilateral filtering is clearly less blurry then that of the result with linear Gaussian filtering. Figure 4 is the final edge map of 'Lena'. Another classic test image 'peppers' was used to test the edge detection algorithm. The original image and corresponding result is shown in Figure 5.

Figure 3: Comparison of results from bilateral filtering (left) and linear Gaussian filtering (right).

Figure 4: Final edge map of 'Lena' obtained from multi-scale edge detection with bilateral filtering.

Figure 5: Image 'Peppers' and its edge map.

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