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Frequency domain filtering of gradient image for contour detection

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ABSTRACT

A novel computational step, frequency-domain filtering of gradient image, is proposed to improve detection of object contours and region boundaries in natural scenes for gradient-based edge detectors. The step is inspired by analyzing the spectrum distribution of object contours and texture edges in the frequency domain of gradient image. We illustrate the principle and effect of the proposed step by adding it to the Canny edge detector. The resulting operator can selectively retain object contours, and meanwhile can dramatically reduce non-meaningful elements resulting from a texture background. Experimental results demonstrate the effectiveness of the proposed additional step.

1. Introduction

Edge detection is one of the most important areas in image processing and computer vision that has been studied for decades. Reviews and comparison of state-of-the-art edge detectors can be found in [1–3]. One most common and widely used type of edge detection algorithms are those based on gradients, such as Sobel, Prewitt, Roberts and Canny edge detectors. However, these detectors react to all local luminance change above a given threshold, irrespective of whether they are due to the contours of the objects represented in a scene or due to natural textures like grass, foliage, water and so forth. As a result, their results contain lots of unwanted or spurious edges which make part of texture, making the subsequent processing difficult. In this paper, we use the term texture to refer to the unwanted or spurious edges.

To enhance contour detection and remove texture edges as much as possible, researchers have done a lot of works. Some works [4,5] tried to reduce noise and texture edges by finding a single optimal scale parameter or using multi-scale techniques [6,7]. However, the single scale methods has to make a tradeoff between noise and texture removal and edge localization even it is optimal to some extent while the multi-scale techniques are usually computationally unattractive. Other studies [8–10] attempted to determine an optimal threshold that can better separate contours from texture edges. These methods achieve considerable improvement in detection of contours and removal of unwanted texture edges; however, they may fail in the situation when edges due to textures are stronger than edges due to object contours which often happen in natural images. Because in this situation, no matter how optimal the threshold is, the texture edges with high gradient magnitude will survive the thresholding process in the final edge map. This means that it is usually not easy to differentiate between object contours and region boundaries, and texture edges, only in the spatial domain of gradient image.

However, contours and texture edges exhibit different characteristics in the frequency domain of gradient image. Texture edges in the gradient image is often distributed densely so that the gray level varies slowly in texture regions, see the grass region in Fig. 1(b), therefore texture regions can be considered corresponding to the low frequency components of the gradient image according to the relationship between the frequency components of the Fourier transform and spatial characteristics of an image [11]. On the contrary, contour edges in the gradient image is usually isolated with faster gray level changes against its surround, see the ear region of the elephant in Fig. 1(b), so they can be considered corresponding to high frequency components of the gradient image. To validate the above analysis, we use an example for illustration. As shown in Fig. 1: (a) is the original image, (b) is the gradient image computed using Canny operator with the standard deviation of Gaussian $\sigma = 1$, (c) and (d) are the filtered gradient images using Gaussian low-pass filter and Gaussian high-pass filter with cut-off frequency $D_0 = 5$ respectively. From the results, we can see that the contrast of contours against texture edges is increased when high-pass filter is applied but lowered when low-pass filter is applied, which implies that the contour edges and texture edges correspond to high-frequency and low-frequency components respectively. Therefore, we can differentiate the two types of edges in the frequency domain of gradient image. Since we aim at enhancing contour edges, a high-pass filtering technique should be adopted.

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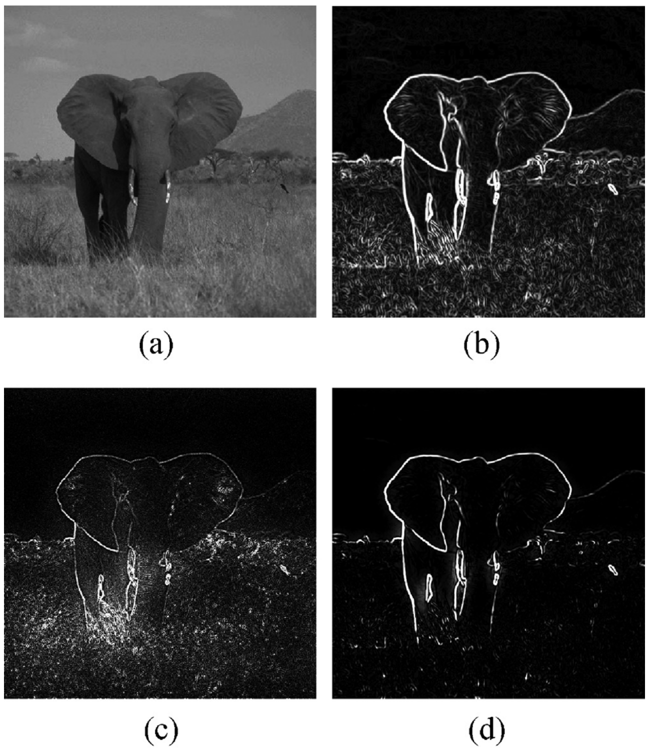

Fig. 1. Original image and its gradient images: (a) original image, (b) gradient image without filtering, (c) gradient image filtered by low-pass filtering and (d) gradient image filtered by high-pass filter.

In this paper, we propose a computational step, frequency domain filtering of gradient image using a high-pass filter, to suppress texture edges and thus improve detection of object contours in natural scenes. We add this step to the Canny edge detector [12] to illustrate its effect. The final contour detector is shown in Fig. 2, where $I(x,y)$ represents the original image, $M_\sigma(x,y)$ and $M_\sigma^f(x,y)$ are the scale-dependent gradient image before and after filtering respectively, $B(x,y)$ is the final edge map obtained by non-maxima suppression and hysteresis thresholding. The scale-dependent gradient computation, non-maxima suppression and hysteresis thresholding steps are all the same as the Canny edge detector, so we do not bother to introduce them again. Here, we mainly introduce the step of frequency domain filtering of the gradient image.

2. Frequency domain filtering of gradient image

Given the scale-dependent gradient image $M_\sigma(x,y)$, we apply Fourier transform on it to get its frequency domain representation $F(u,v)$:

$$F(u,v) = \Im[M_\sigma(x,y)] = A(u,v)\exp(j\phi(u,v)), \quad (1)$$

where $\Im[\cdot]$ denotes the Fourier transform of the argument, $A(u,v)$ and $\phi(u,v)$ denote the amplitude and phase spectrums of the gradient image.

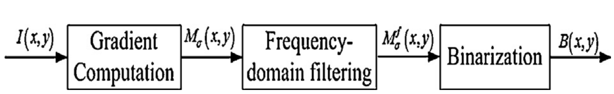

Fig. 2. Flowchart of the proposed contour detector.

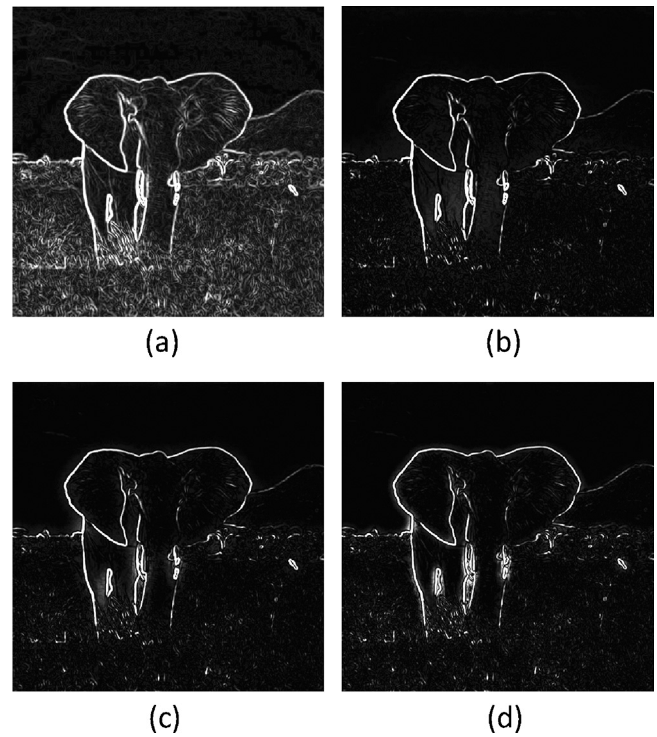

Fig. 3. Gradient images before and after filtering: (a) gradient image before filtering, (b) gradient image after filtering ($D_0 = 2$), (c) gradient image after filtering ($D_0 = 5$) and (d) gradient image after filtering ($D_0 = 10$).

To enhance contour edges and suppress texture edges, the spectrum of $A(u,v)$ is multiplied with a high-pass filter in the frequency domain:

$$A_f(u,v) = A(u,v)\cdot H(u,v), \quad (2)$$

where the Gaussian high-pass filter is adopted for $H(u,v)$:

$$H(u,v) = \exp\left[-\frac{D^2(u,v)}{2D_0^2}\right], \quad (3)$$

$$D(u,v) = \left[\left(\frac{u-N}{2}\right)^2 + \left(\frac{v-N}{2}\right)^2\right]^{1/2}, \quad (4)$$

D_0 is the cut-off frequency at a distance from the origin and will be estimated experimentally.

Finally, we can construct the filtered gradient image in spatial domain using Inverse Fourier Transform as follows:

$$M_\sigma^f(x,y) = |\Im^{-1}[A_f(u,v)\exp(j\phi(u,v))]|^2, \quad (5)$$

where $\Im^{-1}[\cdot]$ denotes the Inverse Fourier Transform and the square computation in Eq. (5) is for further contrast enhancement of contour edges over texture edges.

Fig. 3 gives an example of the gradient image before and after filtering. Contrast stretching is applied on the filtered gradient images for visual effect. It can be seen that, after filtering of the gradient image, the response to the texture edges is much lower than that to the contour edges because of the attenuation of low-frequency contents. As a result, the contrast of contour edges over texture edges is improved, which will facilitate the subsequent procedures such as thresholding and edge labeling. The parameter D_0 in the Gaussian high-pass filter controls the amount of frequency components to be discarded. Intuitively, the larger the value D_0, the more severe the filtering. From the point of removing texture edges, larger D_0 would be a good choice. However, as D_0 increases, it does not necessarily lead to more removal of texture edges but causes