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Image smoothing and sharpening based on nonlinear diffusion equation

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ABSTRACT

For the sake of the smoothing image and sharpening the edge features of the image, a nonlinear diffusion model for image smoothing and sharpening is proposed in this paper. The model consists of two terms. One is smoothing and preserving edge term, the other is sharpening term. The role of the smoothing and preserving edge term is to smooth the flat regions of the image, not smooth or less smooth the edge of image. The sharpening term can enhance the edge of the image. Smoothing diffusion coefficient and sharpening diffusion coefficient control the degree of smoothing and sharpening. The diffusion coefficients are functions of gradient magnitude and dynamic threshold of image, where the dynamic threshold function is driven by a Poisson equation. The experimental results show that the smoothing and sharpening model has better properties than the smoothing and preserving edge model or the sharpening model, and is more suitable for extracting the features of the image.

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1. Introduction

Nonlinear diffusion equation is a useful tool in image processing. Image processing based on nonlinear diffusion equation can not only smooth the image, but also keep some important features, such as edge and texture. The key point is that such an image processing can connect the solution of nonlinear diffusion equation with the image content, so the image-processing problem becomes solving partial differential equations, then we would use different processing method for intra-region and inter-region to keep the features of the image as much as possible.

Perona and Malik applied anisotropic diffusion equation to image smoothing firstly and proposed the famous P-M model [1]. The model can smooth the image and preserve the edge properties well, but the result of the denoising of isolated noise is not satisfactory. This is because the gray changes significantly for isolated noise, so that the isolated noise is regard as an edge and the smooth is not enough for it. In order to overcome the drawbacks of P-M model, Catte improved the model and proposed the selective smoothing model [2]. But he did not give a clear geometric interpretation on the model. Although Alvarez's degenerate diffusion model [3] gave a clear geometric interpretation and preserved the edge properties while smoothing the image, the model did not do well on the great-curvature and complicated-change edge such as regions near corners. Luo et al. presented an image selective smooth model by a coupled anisotropic diffusion equation [4], which can eliminate the Gaussian noise and preserve the edge features well. Gilboa et al. used a complex diffusion equation for image filter [5], when complex diffusion coefficient approaches the real axis, the imaginary part can serve as an edge detector (smoothed second derivative scaled by time). Mean curvature motion (MCM) equation [6] can be also used

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in image smoothing. MCM not only has profound physical background, but also is connected with median filter. However, it is a pity that the model also has some disadvantages in eliminating the noise, such as leading to shape distortion, etc.

The main purpose of above models is smoothing image and preserving edge, but it's not enough in the task of further image processing, such as extraction of image features and generation of image sketch, we also need to enhance the edge of the image. It means that we want to smooth the flat region of image and to enhance the edge of the image both. To realize the aim, we propose an image smoothing and sharpening model based on nonlinear diffusion equation. The proposed model takes the advantages of mean curvature motion equation to smooth the image and inverse heat diffusion equation to sharpen the image. Smoothing diffusion coefficient and sharpening diffusion coefficient control the degree of smoothing and sharpening, respectively. Diffusion coefficients are functions of gradient magnitude and dynamic threshold of image. Here, the dynamic threshold is decided by a Poisson equation.

The rest of this paper is organized as follows. Section 2 formulates an image smoothing and sharpening model based on nonlinear diffusion equation and discusses the relations among the proposed model, MCM equation, inverse heat diffusion and degenerate diffusion model. The choices of the smoothing diffusion coefficient and sharpening diffusion coefficient, the discrete forms of proposed model are also given in this section. Section 3 demonstrates some experimental results. Section 4 draws conclusions and points out the further work.

2. Image smoothing and sharpening model

2.1. Model description

$u(x, y, t)$ denotes the image at time t, t is an artificial time parameter. $u_0(x, y)$ denotes the original image. The nonlinear diffusion model is as follows:

$$\begin{cases} \dfrac{\partial u}{\partial t} = g(|\nabla u|, T(u))|\nabla u|\mathrm{curv}(u) - h(|\nabla u|, T(u))\Delta u \\ u(x,y,0) = u_0(x,y) \end{cases} \tag{1}$$

where, ∇ is the gradient operator, $\nabla u = (u_x, u_y)$, gradient magnitude $|\nabla u| = \sqrt{u_x^2 + u_y^2}$, curv is curvature, $\mathrm{curv}(u) = (u_y^2 u_{xx} - 2u_x u_y u_{xy} + u_x^2 u_{yy})/(u_x^2 + u_y^2)^{3/2}$, Δ is the Laplacian operator, $\Delta u = u_{xx} + u_{yy}$, the functions $g(\cdot,\cdot)$ and $h(\cdot,\cdot)$ are called diffusion coefficients, they control the degree of smoothing and sharpening, respectively. $T(u)$ denotes the dynamic threshold of the image, which is controlled by a partial differential equation.

The model (1) consists of two parts. The first part is the curvature flow term, which the coefficient is variable. The other part is inverse Laplace term of variable coefficient. The major effect of curvature flow term is to smooth the image, i.e. to median filter to the image. The inverse Laplace term is used to enhance the image, which can prominent image edge features. So the model can realize the image smoothing and sharpening.

Now, we shall discuss how to choose diffusion coefficient in model (1), the relations among the model (1), the MCM equation, the inverse heat diffusion and the degenerate diffusion equation.

(i) The choices of diffusion coefficients $g(\cdot,\cdot)$ and $h(\cdot,\cdot)$. We choose $g(\cdot,\cdot)$ as a monotone decreasing function for the first variable, and it is a monotone increasing function for the last variable. On the contrary, $h(\cdot,\cdot)$ is a monotone increasing function for the first variable, and it is a monotone decreasing function for the last variable. Here, $g(|\nabla u|, T(u)) = c/(a+k(|\nabla u|/T(u)))^p$, $h(|\nabla u|, T(u)) = 1/\left(1 + \mathrm{e}^{-(|\nabla u| - T(u))^q}\right)$, where c, a, k, p, q are constants and greater than zero. We can see from the selection of $g(\cdot,\cdot)$ and $h(\cdot,\cdot)$ that the two functions connect with the gradient magnitude and threshold of image. If $|\nabla u(x, y)| > T(u(x, y))$, (x, y) is the location where the image gray changes significantly, then the $g(|\nabla u|, T(u))$ is reduced and the $h(|\nabla u|, T(u))$ is increased, and the degree of image smoothing reduces and that of image sharpening increases. Thus, we can smooth the region with smaller gradient magnitude and sharpen the location with bigger gradient magnitude.

 The reason of choosing the different functions $g(\cdot,\cdot)$ and $h(\cdot,\cdot)$ is that we hope the model (1) can not only preserve the edge of image, but also enhance the edge of image while smoothing the image. Such choice of functions $g(\cdot,\cdot)$ and $h(\cdot,\cdot)$ can achieve this goal.

(ii) The relation between the model (1) and the MCM equation. The MCM equation can be described by the following equation [6]:

$$\begin{cases} \dfrac{\partial u}{\partial t} = |\nabla u|\mathrm{curv}(u) \\ u(x,y,0) = u_0(x,y) \end{cases} \tag{2}$$

 The model can filter image, with increasing of t, the details of the image will become less and less and the edge can be preserved well. MCM equation has a close relationship with median filtering. Let $u(x_0) = \mathrm{Med}\{u(y),\ y \in D(x_0, h)\}$, where Med means taking median value, $D(x_0, h)$ is a disk, here x_0 is the center and h is the radius. From the literature [7], we have the following equation:

$$\mathrm{curv}(u)(x_0) = \frac{u_y^2 u_{xx} - 2u_x u_y u_{xy} + u_x^2 u_{yy}}{(u_x^2 + u_y^2)^{3/2}} = 0.$$

 It is clear that strong relation exists between the $u(x_0)$ and the curvature of level line pass through x_0. In model (1), we maintain the advantages of the MCM equation (2) and add a diffusion coefficient $g(\cdot,\cdot)$ to control the degree of filtering to image. It means that the degree of filter to image is small in the regions of greater image magnitude and the degree of filter to image is greater in the regions of smaller image magnitude. So that the flat regions of image can be filter and the image edges can be preserved by using model (1).

(iii) The relation between the model (1) and the inverse heat diffusion equation. The inverse heat diffusion

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