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Wireless Capsule Endoscopy Images Enhancement by Tensor Based Diffusion

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***Abstract*—To enhance the contrast and the details of the wireless capsule endoscopy images, which are used to diagnose the status of the human gastrointestinal tracts, we propose a tensor based diffusion method in this paper. After analyzing the structure tensor of the image in RGB color space, we focus on the properties of the nonlinear anisotropic diffusion. Then we design two diffusion strength functions to determine the anisotropic diffusion according to the local characteristics of the wireless capsule endoscopy images. Experimental results on real wireless capsule endoscopy images indicate effective enhancement of details and contrast by our new approach.**

I. Introduction

GASTROINTESTINAL(GI) endoscopy has been widely applied for the diagnosis of diseases in the alimentary canal and small intestine. But there is a dead space in the middle part of the small intestines during diagnosis due to the limitations of the traditional GI endoscopy. Most recently, the wireless capsule endoscope system was invented and employed to record the whole GI tract images. With these images sent out to the recorder and downloaded into a personal computer, physicians could review the images and analyze potential sources of bleeding on the GI tracts [1]. However, the qualities of these images are not very good for some reasons such as low illumination and complex circumstances in the gastrointestinal tracts. To facilitate the diagnosis of the diseases, it is necessary to enhance these images. In fact, many methods [2-6] have been investigated for image enhancement. Among them, the nonlinear diffusion proposed by Perona and Malik [6] has drawn a lot of attention for its good behavior of preserving image edges while smoothing. In [7], the nonlinear diffusion was extended to multi-valued images. Weickert [8] proposed a multi-scale texture enhancement method to enhance flow-like pattern images.

In this paper, we develop a method to enhance the wireless capsule endoscopy images to make easier analysis and diagnosis of them. It is a tensor based anisotropic diffusion way with two diffusivity strength functions designed according to the characteristics of the wireless capsule endoscopy images. Experimental results show the effectiveness of this new method.

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II. Structure tensor in clolor space

The structure tensor has been successfully used to enhance gray images containing flow-like structures in [8]. As the wireless capsule endoscopy images are color images, so we firstly extend the structure tensor into color space. Given an image I , the structure tensor is

$$G=\begin{bmatrix} \tilde{I}_x^2 & \tilde{I}_x\tilde{I}_y \\ -\tilde{I}_x\tilde{I}_y & \tilde{I}_y^2 \end{bmatrix} \tag{1}$$

where the subscript denotes spatial derivatives and the ~ indicates the convolution with a Gaussian filter. For a multi-channel image $\mathbf{I}=(I_1, I_2,...I_m)^T$, the structure tensor is given by

$$\mathbf{G}=\begin{bmatrix} \tilde{\mathbf{I}}_\mathbf{x}^T\tilde{\mathbf{I}}_\mathbf{x} & \tilde{\mathbf{I}}_\mathbf{x}^T\tilde{\mathbf{I}}_\mathbf{y} \\ -\tilde{\mathbf{I}}_\mathbf{x}\tilde{\mathbf{I}}_y^T & \tilde{\mathbf{I}}_y^T\tilde{\mathbf{I}}_y \end{bmatrix} \tag{2}$$

where superscript T represents the transpose operation. For color images in RGB color space $\mathbf{I}=(R,G,B)^T$, this results in the color structure tensor

$$\mathbf{G}=\begin{bmatrix} \tilde{R}_\mathbf{x}^2+\tilde{G}_x^2+\tilde{B}_x^2 & \tilde{R}_x\tilde{R}_y+\tilde{G}_x\tilde{G}_y+\tilde{B}_x\tilde{B}_y \\ \tilde{R}_x\tilde{R}_y+\tilde{G}_x\tilde{G}_y+\tilde{B}_x\tilde{B}_y & \tilde{R}_y^2+\tilde{G}_y^2+\tilde{B}_y^2 \end{bmatrix} \tag{3}$$

The color structure tensor describes the $2D$ first order differential structure at one point in the image. Eigenvalue analysis of the tensor leads to two eigenvalues which are defined by

$$\lambda_1=\frac{1}{2}\left[g_{11}+g_{22}+\sqrt{(g_{11}-g_{22})^2+4g_{12}^2}\right] \tag{4}$$

$$\lambda_2=\frac{1}{2}\left[g_{11}+g_{22}-\sqrt{(g_{11}-g_{22})^2+4g_{12}^2}\right] \tag{5}$$

where

$$g_{11}=\tilde{R}_\mathbf{x}^2+\tilde{G}_x^2+\tilde{B}_x^2 \tag{6}$$

$$g_{22}=\tilde{R}_y^2+\tilde{G}_y^2+\tilde{B}_y^2 \tag{7}$$

$$g_{12}=\tilde{R}_x\tilde{R}_y+\tilde{G}_x\tilde{G}_y+\tilde{B}_x\tilde{B}_y \tag{8}$$

The larger eigenvalue λ_1 indicates the change rate along the gradient direction, and its eigenvector corresponds to the gradient direction. The smaller eigenvalue λ_2 denotes the

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variation rate in the edge direction and its eigenvector corresponds to the edge direction.

III. Tensor Based Diffusion for Wireless Capsule Endoscopy Images

To enhance an image $I_0(x, y)$, one of the widely used methods is to consider it as the initial state of a partial differential equation.

$$\frac{\partial I}{\partial t} = F(I(x, y, t)) \tag{9}$$

where $I(x, y, t)$ is an image at time t, $F: R \to R$ is a map corresponds to a specific algorithm, and the solution of (9) is the enhanced image. There are many different algorithms according to different F, such as linear diffusion, nonlinear diffusion [7], and nonlinear anisotropic diffusion [8]. The linear diffusion is defined as

$$\begin{cases} I_t = C\Delta I \\ I(x, y, 0) = I_0(x, y) \end{cases} \tag{10}$$

where C is a positive constant during the diffusion process. And the nonlinear diffusion is defined as follows

$$\begin{cases} I_t = div(C(|\nabla I|)\nabla I) \\ I(x, y, 0) = I_0(x, y) \end{cases} \tag{11}$$

Here the diffusivity C is a function of ∇I. And one of the functions proposed by Perona and Malik is:

$$C(|\nabla I|) = \frac{1}{1 + \left(|\nabla I|^2 \middle/ K^2 \right)} \tag{12}$$

This elaborated work triggered great focus afterwards in image processing and computer vision, and the review of its extensions and applications is beyond the scope of this paper. It must also be noted that the parameter K plays a very important role in the whole diffusion process. It determines the behavior of the diffusion, i.e, it determines whether the region in the image will be enhanced or smoothed. This leads into a high dependence of its choice in general.

Weickert [8] changed the above scalar-valued nonlinear diffusion into nonlinear anisotropic diffusion, taking into account the diffusion orientation. In nonlinear anisotropic diffusion, the diffusivity changes into a tensor D. And it is as below

$$\begin{cases} I_t = div(D\nabla I) \\ I(x, y, 0) = I_0(x, y) \end{cases} \tag{13}$$

where the diffusion tensor D is a matrix of size 2×2:

$$D = \begin{pmatrix} \omega_1 & \omega_2 \end{pmatrix} \begin{pmatrix} u_1 & 0 \\ 0 & u_2 \end{pmatrix} \begin{pmatrix} \omega_1^T \\ \omega_2^T \end{pmatrix} \tag{14}$$

where ω_1 ω_2 are the eigenvectors correspond to the two eigenvalues of D, i.e, u_1 and u_2.

The diffusion tensor steers the diffusion process in the following way: its eigenvalues determine the diffusivities along the directions of the eigenvectors. That is, u_1 represents the diffusion strength along the direction of ω_1, and u_2 indicates the diffusion strength along the direction of ω_2.

For a color image $\mathbf{I} = (R, G, B)^T$, the nonlinear anisotropic diffusion (13) changes correspondingly into

$$\begin{cases} I_t^i = div(D\nabla I^i) \\ I^i(x, y, 0) = I_0^i(x, y) \end{cases} \tag{15}$$

where $i = R, G, B$.

For different domains in a wireless capsule endoscopy image, we hope that an isotropic diffusion is done in homogenous region, while an anisotropic diffusion is performed in regions of edges and local details. This will result into efficient enhancement of the structured tissues and image textures that are rich of information about the status of the intestines while smoothing those flat regions without any details. From the point of view of gradient variation, the homogenous regions correspond to smaller gradient variation, and we need an isotropic diffusion along all directions, so we choose $u_1 \approx u_2$; while in the domains of edges and local details, which correspond to a larger gradient variation, we need an anisotropic diffusion along the direction of the edge and the gradient direction respectively in order to preserve edges or even enhance edges, i.e., we require $u_1 < u_2$ or sometimes $u_1 < 0$.

Furthermore, in order to process a color image efficiently, we should try to combine the different channels' information together to guide the diffusion. Employing the structure tensor of color images discussed in section II, we choose ω_1 and ω_2 the same as the eigenvectors of λ_1 and λ_2, and this ensures that the anisotropic diffusion will take place along the structure tensor's two directions. In other words, to efficiently enhance the contents in the wireless capsule endoscopy images, we need a smoothing diffusion which performs along the direction of ω_2 and a smoothing or even enhancing diffusion which implements along the direction of ω_1. This may be achieved in the following way by designing two diffusivity functions:

$$u_1 = \begin{cases} \exp\left(-\frac{(\lambda_1 - \lambda_2)^2}{K_1^2}\right) - \exp\left(-\frac{(\lambda_1 - \lambda_2)^2}{K_2^2}\right) & if\ (\lambda_1 - \lambda_2)^2 > T \\ \exp\left(-\frac{(\lambda_1 - \lambda_2)^2}{K_1^2}\right) & else \end{cases} \tag{16}$$

$$u_2 = \exp\left(-\frac{(\lambda_1 - \lambda_2)^2}{K_1^2}\right) \tag{17}$$

where λ_1 and λ_2 are the eigenvalues of the structure tensor mentioned in section II, and $(\lambda_1 - \lambda_2)^2$ indicates the local property of one point in the wireless capsule endoscopy image. K_1 and K_2 are the parameters to be set in the experiments.

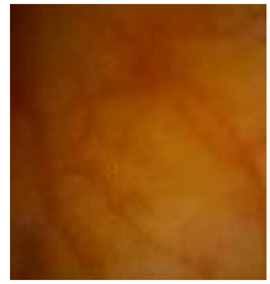
When $(\lambda_1 - \lambda_2)^2$ is small, the region corresponds to homogenous region, because in these regions $\lambda_1 \approx \lambda_2$. And when $(\lambda_1 - \lambda_2)^2$ is large, it indicates region of edges and local details since $\lambda_1 \gg \lambda_2$. From (16) and (17), we can see that $u_1 = u_2$ at domains of rather flat regions and $u_1 < u_2$ at other regions, and this is just what we need. To accomplish the desired diffusion along the gradient direction when $(\lambda_1 - \lambda_2)^2 > T$, we require $K_1 < K_2$. The unstable problem caused by the backward diffusion when $u_1 < 0$ is avoided because the value of u_1 tends to zero when $(\lambda_1 - \lambda_2)^2$ is sufficiently large.

Compared with the original nonlinear diffusion in [6], we design two new diffusion functions to determine the behavior of the diffusion according to the local properties of the wireless capsule endoscopy images, so it can control the whole diffusion process more efficiently. Moreover, these two functions also adaptively control the diffusion strength along the structure tensor's two directions. Finally, the parameters of our proposed method in (16) and (17) do not have the same role as that of (12), so the performance of our new proposed approach will be more stable.

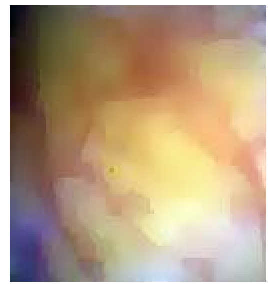
IV. EXPERIMENTAL RESULTS

To validate our new approach, we performed experiments on real wireless capsule endoscopy images containing vessels, which are in fact used to detect whether there is any blooding in the gastrointestinal tracts. The threshold T in the experiments is empirically chosen as $T = 0.1 \times \max(\lambda_1 - \lambda_2)^2$, and the Gaussian filter we used to obtain the structure tensor is a Gaussian filter with standard deviation being equal to 1 and a window size of 3×3.

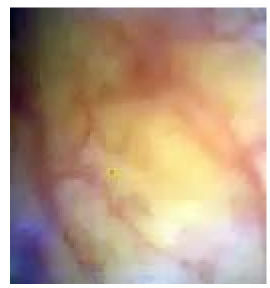
Fig.1 shows the results obtained for a ROI (128×138) of one image. Fig1. (a) is the ROI of the original wireless capsule endoscopy image. Fig1.(b) is the result of the standard nonlinear diffusion P-M method in [6] with $K = 2.8$, and 25 iterations, we implemented the diffusion in each channel and combined the results to get the color image result. Fig1. (c) is the result of our new tensor based anisotropic diffusion way with $K_1 = 2.4$, $K_2 = 5$ and the same iterations. With the new tensor based anisotropic diffusion, the contrast of the image has been enhanced better. Furthermore, we can see some small vessels clearly in Fig1.(c), but we can't see them in Fig.1(b) or Fig.1(a).



(a)



(b)



(c)

Fig.1 Enhancement of one ROI image (a) original ROI, (b) enhanced by P-M method, (c) enhanced by our new method

Fig.2 depicts another example that verifying our method's effectiveness. Fig2. (a) is the ROI (164×172) of the original wireless capsule endoscopy image. Fig2.(b) is the result of the P-M method in [6] with $K = 2$ and 30 iterations. Fig2.(c) is the result of our new tensor based anisotropic diffusion with $K_1 = 1.8$, $K_2 = 4$ and the same iterations. It can be also seen that the result of Fig2. (c) is better than that of Fig.2(b). As a matter of fact, we find that all the results in our experiments are not sensitive to the choices of parameters of our new proposal in our experiments.

Fig.2 Enhancement of another ROI image (a) original ROI, (b) enhanced by P-M method, (c) enhanced by our new method

V. Conclusion

We have put forward a new diffusion method for wireless capsule endoscopy images to overcome the problem of low contrast in these images in the present paper. Based on the structure tensor of the wireless capsule endoscopy images, this new approach exploited the nonlinear anisotropic diffusion to diffuse along the structure tensor's two directions with different forces respectively. Here, we designed two diffusivity functions to adaptively determine the diffusion force according to the characteristics of the wireless capsule endoscopy images. Experiments demonstrated the new method's usefulness for the wireless capsule endoscopy images enhancement.

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