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Regularized variational dynamic stochastic resonance method for enhancement of dark and low-contrast image

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A B S T R A C T

Dynamic stochastic resonance (DSR) is a distinctive technique for enhancement of dark and low-contrast image. Noise is necessary for DSR based image enhancement and the level of noise will be enlarged simultaneously with brightness, which reduces the perceptual quality of the enhanced image greatly and also increases the difficulty of subsequent denoising because removing high level of noise often leads to serious loss of image details. In this paper, instead of removing noise after the enhancement process is complete, we propose to suppress noise gradually and simultaneously in the process of enhancement. We rewrite the traditional partial differential equation (PDE) based DSR model in variational framework firstly, and then propose a novel total variation regularized (TV) DSR method for image enhancement. The existence and uniqueness of solution of the TV regularized DSR model is proved theoretically. Moreover, we generalize the TV regularized DSR model in variational framework and in PDE framework, respectively, and therefore we can incorporate more existing denoising methods into our approach. Numerical comparisons demonstrate that the proposed technique gives significant performance in terms of contrast and brightness enhancement as well as noise suppression, and therefore can obtain enhanced image with good perceptual quality.

1. Introduction

Nowadays, night-vision monitoring plays an increasingly important role in the field of public security, and medical imaging has become an important auxiliary technique of disease diagnosis. However, limited to hardware and imaging conditions, most of the night-vision images and the medical images produced from x-rays, computed tomography scans or magnetic resonance imaging often have low illumination and poor contrast, which leads to great difficulties in providing useful visual information for target identification and disease diagnosis. Hence, enhancement of dark and low-contrast image is urgently demanded in these application fields.

The literature survey of image enhancement reveals many well-known techniques. Traditional histogram equalization (HE) [1] is one of the most popular techniques due to its simplicity, which enhances the input image by modifying its histogram into desired shape. However, when there exist a small portion of the image which exhibits drastically different intensity distribution, the HE method will throw off the equalization for the rest of the image because it considers the histogram of the entire image in a global fashion. To remedy this, the contrast-limited adaptive histogram equalization (CLAHE) [2] computes several histograms with different parameters corresponding to various different parts of an image and can achieve better results, but the difficulty in parameter selection leads to high computational complexity in practice.

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Single-scale Retinex (SSR) [3] is a technique based on color formation that represents the image as a product of illumination and reflectance. To deal with the graying out, noise enlargement and halo effects existing in classical SSR method, Liu et al. [4] have proposed an adaptive single scale Retinex scheme (ASSR), which can eliminate noise but fails to preserve details of image.

As we all know, noise is inevitable in practice especially in night-vision and medical imaging. Most of the methods mentioned above will enlarge the level of noise simultaneously in the process of image enhancement. Conventionally, noise is undesirable because it reduces the perceptual quality of image greatly, while dynamic stochastic resonance (DSR) provides us a counter-intuitive understanding of noise. The DSR can maximize signal-to-noise ratio of an image by adding a proper amount of noise in an iterative manner, and this process increases the brightness and contrast of the image [5]. Recently, various DSR based methods for image enhancement have been proposed [6–9] and often perform better than traditional methods such as CLAHE and SSR. However, these DSR based methods also enlarge the level of noise in the enhanced image. On one hand, the existence of noise is necessary for the DSR based methods, and therefore we cannot remove the noise before we utilize these methods; on the other hand, removing enlarged high level of noise after the image enhancement process is complete often leads to serious loss of image details such as edges and textures. Thus, we propose to suppress noise gradually and simultaneously in the process of enhancement in this paper. Image denoising is an ill-posed problem and variational regularization is a typical technique utilized to remove noise while preserving image details such as edges and textures. The most widely used regularized variational denoising methods including total variation (TV) regularization [10], the non-local TV regularization [11], total generalized variation (TGV) regularization [12], high-order TV regularization [13] and fractional-order TV regularization [14] et al. All of these regularized denoising methods are proposed in the variational framework, but traditional DSR based methods are proposed in PDE form. In this paper, we rewrite the DSR based enhancement model in variational framework firstly, and then propose a TV regularized DSR method for image enhancement. Moreover, in order to incorporate more existing denoising methods into our approach, we generalize the TV regularized DSR model in variational framework and in PDE framework, respectively, and develop corresponding algorithms.

The rest of this paper is organized as follows: in Section 2, we introduce the new regularized variational DSR model coupled with TV regularization, and analyze the existence and uniqueness of the solution of the model in detail; in Section 3, we generalize the TV regularized model in variational framework and PDE framework, respectively, and develop corresponding algorithms to solve these new models; in Section 4, we demonstrate the efficiency of our method through experimental comparison and analysis; finally, discussion and conclusion are provided in Section 5.

2. Total variation regularized variational dynamic stochastic resonance

2.1. Dynamic stochastic resonance

Conventionally, noise degrades the quality of any system, but this assertion was proved wrong by Benzi et al. [5] through exploring the concept of dynamic stochastic resonance (DSR), which is a phenomenon where the weak signals of any nonlinear systems are amplified by adding noise to the input signal. In the context of image processing, DSR refers to the transition of pixel values while varying the intensity from low to high and vice versa. Such a change of state of the pixel under noise can be modeled by Brownian motion of a particle placed in a double-well-potential system. A classic 1D non-linear dynamic system that exhibits DSR is modeled with the help of Langevin equation of motion as follows [5]

$$\frac{dv\,(t)}{dt} = -\frac{dU(v)}{dv} + \sqrt{D}\xi\,(t)\,, \tag{1}$$

where ξ is the friction under which a particle of mass is moving in well. Additive stochastic force is applied with the intensity D and $U\,(v)$ is a bistable potential function defined by

$$U\,(v) = \frac{bv^4}{4} - \frac{av^2}{2}, \tag{2}$$

where a and b are positive bistable double-well parameters.

Adding a periodic input signal $B\sin(\omega t)$ into the bistable system (1), one can obtain

$$\frac{dv\,(t)}{dt} = -\frac{dU\,(v)}{dv} + B\sin(\omega t) + \sqrt{D}\xi\,(t)\,, \tag{3}$$

where B and ω are the amplitude and frequency of the signal, respectively. When the signal amplitude is small, the resonance caused by stochastic noise can force the particle to move from one well to another, which will lead to the enhancement of the weak signal.

The stochastic differential equation (3) can be solved by using the stochastic version of Euler–Maruyama's iterative method as follows

$$v_{n+1} = v_n + \Delta t \cdot \left(a\,v_n - b\,v_n^3 + Input\right), \tag{4}$$

where Δt is the step size and $Input = B\sin(\omega t) + \sqrt{D}\xi\,(t)$ denotes the input noisy signal.

In the context of two dimensional image enhancement, the $Input$ and v_n are the observed noisy low-contrast image and enhanced image in the iteration process in spatial domain [5], or wavelet transform domain [6,9] or DCT domain [7],

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