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The spatial correlation problem of noise in imaging deblurring and its solution ☆

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ABSTRACT

We describe the spatial correlation problem of noise in colour digital images and analyse its cause. Pixel-correlated image processing procedures, such as CFA colour interpolation and colour space transformation, mainly lead to this problem. Considering this problem, we propose a new noise model based on a joint Gaussian probability distribution. Furthermore, we present an algorithm that makes the revised noise model fit the existing image deconvolution well. The parameters of our algorithm depend only on the image processing procedures of the imaging system. Finally, we apply the proposed algorithm to revise two typical image deconvolution methods and perform simulations and real-world experiments. Both the quantitative indicators and visual performance of the image deblurring results show that the revised deconvolution methods based on our noise model behave better in reducing the noise and ringing artefacts, thus improving the image quality compared with the methods that use the original noise model.

1. Introduction

Image deblurring and noise reduction are important components of image quality improvement. One of the most significant problems in imaging processing is to remove motion blur due to camera motion. Using a short shutter speed can avoid the blur caused by hand shaking during the exposure to some extent. It could also product images with low noise level if there is a lack of illumination. How to remove the motion blur for images with noise has long been a difficult but fundamental research problem. When the blur function (point spread function, or PSF) that causes the blur is shift-invariant, the problem is solved by image deconvolution [1]. Currently, image deconvolution is also applied to the case of a shift-variant PSF after approximate treatment. When the blur kernel is known by certain approaches such as detection with motion sensors, it is non-blind deconvolution. When the blur kernel remains unknown, then it is a blind case that is more ill-posed. Usually, we should rely on certain priors [2] to address this problem.

Regardless of whether it is blind deconvolution or non-blind deconvolution, a widely used method [1,2,8–19] is to build and optimize a probabilistic model. In the framework of image deconvolution, noise is usually modelled as a certain probability distribution such as a Gaussian or Poisson distribution in terms of its intensity. Meanwhile, the previous deconvolution solutions suppose that the image noise is spatially uncorrelated. This hypothesis is controversial in some situations, according to our research. When the image processing system gains the RAW data from an imaging system, the noise in the RAW data remains spatially uncorrelated. However, when the processing system prepares to perform deconvolution after a series of pre-processing steps, the image noise is spatially correlated in some situations. Then, it is inappropriate to perform imaging deblurring and noise reduction with the previous incorrect models, which would lead to a decrease in image quality.

In this paper, we investigate the spatial correlation problem of noise in image deblurring and find that except for one-channel images, blurry colour images that are to be processed with pre-processing have spatially correlated noise. Among the image processing procedures, CFA (colour filter array) colour interpolation and colour space transformation are the main reasons for the spatial correlation of noise. We propose an amendment for the probability distribution model. Based on the new probability distribution model, we propose a fast algorithm to correct the previous deconvolution methods. We perform simulations and real-world experiments to compare our algorithm and the previous methods. Both the simulations and real-world experiments show good results. Compared with previous methods, ours reduces the image noise

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and restrains the ringing artefacts better with a limited increase in the time cost.

2. Related work

The image deblurring problem has been extensively studied in the image processing field for years. Classical non-blind deconvolution methods include Wiener filtering [3], Kalman filtering [4], constrained least squares filtering [5] and the Richardson-Lucy (R-L) algorithm [6,7]. The R-L algorithm, which solves a Maximum a Posteriori (MAP) method, assumes that the image noise follows a Poisson distribution. Several non-blind and blind deconvolution methods based on the R-L algorithm [8,9] have been proposed in recent years. The former improved the deconvolution with blurred/noised image pairs, and the latter implemented a prototype hybrid camera to compute the PSF before the deconvolution. Bar et al. [10] proposed an algorithm to handle impulsive noise such as salt & pepper noise, which is derived from the assumption of a Laplacian distribution for the noise. Further, many non-blind and blind deconvolution methods derived from a Gaussian noise model [11,12] have been proposed. In these methods, various image priors and regularization are used to estimate the blur kernel and perform noise reduction, such as total variation regularization [13], natural image statistics [14], sparse image prior [15–18] and colour prior [19]. Most of these methods work well in noise-free cases but behave poorly with an increase in the noise levels. To handle blurry images with noise Tai et al. [20] first apply an existing denoising package for the pre-processing. Zhong et al. [21] use directional filters to denoise before image deblurring. The pre-processing of low-pass filters causes the inputs to be deblurred to have spatially correlated noise. To handle the outliers in image deconvolution, such as saturated pixels and non-Gaussian noise, Cho et al. [22] separate them and correct the MAP method based on a Gaussian noise model. Whyte et al. [23] deblur the saturated pixels and normal pixels with the R-L algorithm.

The methods mentioned above do not account for the noise spatial correlation in the noise model of a Poisson or a Gaussian distribution. They simply assume that the image noise is spatially uncorrelated and multiply them directly in probability. Shan et al. [1] considered the spatial characteristic, assumed that the image noise is spatially uncorrelated and then proved that its several orders of difference follow the Gaussian distribution. The high-order partial derivatives of the image noise using forward differences are used to reflect the noise's spatial uncorrelation. If the image noise were spatially correlated in certain situations, then these methods would lead to lower quality results than expected.

3. The spatial correlation problem of noise

3.1. Spatially correlated noise

Image noise can be divided into Gaussian noise, salt-and-pepper noise, shot noise, quantization noise, anisotropic noise, film grain and periodic noise [24]. It is complex to model the image noise correctly. In imaging deblurring, we usually consider additive noise, which is unrelated to the input signals. In traditional deconvolution methods, noise is spatially uncorrelated. If this hypothesis holds, then a typical image with dark-current shot noise should be spatially independent, as shown in Fig. 1(a). However, we obtained images with dark-current shot noise from image systems with different data formats, as shown in Fig. 1(b), (c) and (d). Fig. 1(b) was taken by a smart phone and is in RAW format without any pre-operations. The spatial noise distribution in Fig. 1(b) is similar to these that we simulate with the spatially independent hypothesis. Fig. 1(c) was taken by the same phone and is in YUV format. Fig. 1

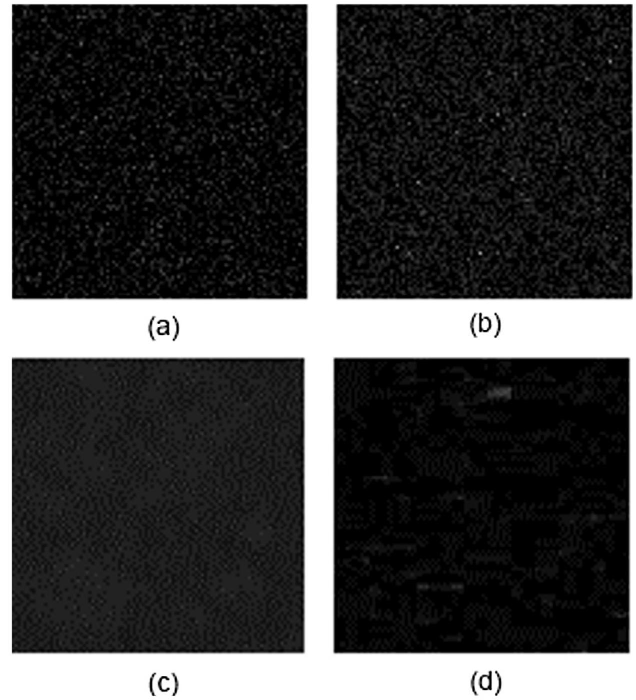

Fig. 1. Dark-current shot noise images of several image systems in several formats. (a) is the simulation with the spatially uncorrelated noise hypothesis. (b) is the image taken by a smart phone in RAW format without any preprocessing. (c) is taken by the same phone in YUV format. (d) is taken by an SLR camera in CR2 format.

(d) was taken by an SLR (Single Lens Reflex) camera and is in CR2 format. The latter two were given some image processing, such as white balance and colour interpolation. Compared with the former two images, the latter two have clumpier noise, which means that in a certain area, every pixel has a similar value. The noise in these two is obviously spatially relative. We calculated the spatial correlation coefficients of the noise in these images, and they show the same result. We express the dark-current noise image from the 2D matrix to 1D vector vertically or horizontally and obtain the vector $\vec{x}$. Then, we cyclically shift $\vec{x}$ with d pixels and obtain $\vec{x}'$. The Spatial Correlation Coefficient is defined as

$$\rho(d) = Cov(\vec{x}, \vec{x}')/\sigma(\vec{x})\sigma(\vec{x}') \tag{1}$$

By varying d, we obtain the $\rho - d$ curves, as shown in Fig. 2. The Spatial Correlation Coefficient of the image in the RAW format is similar to the simulated image, which tends to 0 when $d > 1$. The images with the pre-operation have $\rho(d) > 0$ when $d > 1$.

In image processing, imaging deblurring is always considered an advanced image processing procedure after the fundamental procedures, such as gamma correction, colour interpolation and colour space transformation, are completed. If we still assume that the noise in blurry images is spatially independent, then the deblurring result would be incorrect. We should account for the spatial correlation problem when modelling the noise probability distribution model.

3.2. Influence of spatially correlated noise on the image restoration quality

According to Shan et al. [1], the ringing artefacts are not Gibbs phenomena from an inability of the finite Fourier basis functions to model the type of step signals that are commonly found in natural images. Instead, the inaccurately modelled image noise and