The Hong Kong Polytechnic University

Department of Computing

External and Internal Nonlocal Self-Similarity based Models for Image Denoising

Jun Xu

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submitted in partial fulfilment of the requirements
for the degree of

Doctor of Philosophy

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CERTIFICATE OF ORIGINALITY

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______________________________ (Signed)

Jun Xu (Name of student)

Abstract

The nonlocal self-similarity (NSS) prior of natural images has been extensively studied in many image restoration methods. In this thesis, we exploit the NSS property of external natural images, external guided internal NSS property, and internal NSS property for image denoising tasks.

Acknowledgement

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Introduction 1

Nowadays, cameras are becoming more and more widely used in many aspects of human lifes such as taking pictures, medical analysis, security monitoring and control, etc. The camera imaging pipelines are of particular importance since it is the key step of transforming the real scenes into the pictures or videos. However, during the imaging process, the noise is unavoidable to be generated due to many reasons.

1.1 The Camera Imaging Pipeline

The cameras capture the images and store as raw image formats. During the camera imaging pipeline, the photons are transformed into electronics by the photodiode in the camera sensor. The original sensor arrat (also called color filter array, or CFA) contains red, green, and blue channels, and these incomplete channels are transformed into the final RGB files via the raw converter. The camera imaging pipeline includes multiple stages such as reading raw image, black light subtraction, lens correction, demosaicing, noise reduction, white balancing, gamma curve, final color space conversion, etc [**browneccv2016**]. Basically, a camera imaging pipeline includes demosaicing, white balancing and color space transform, gamut mapping, tone mapping, and JPEG compression [**crosschannel**]. However, different cameras have varying structures and camera parameters, and hence resulting different imaging effects. Recently, there also exists learning based imaging pipelines which directly learn the natural image priors from the RGB and raw images pairs.

1.2 The Image Noise

In image denoising community, the most commonly studied noise is the additive white Gaussian noise, which is used to model the independent noise in the raw images. The AWGN noise is described as a Gaussian distribution $\mathcal{N}(0, \sigma^2)$, which means that the noise is Gaussian distributed with 0 mean and σ standard deviation. Most of methods are focus on this type of noise since it is a good testing bed for many other image restoration problems such as super-resolution, deblurring, inpainting, etc.

However, the realistic noise in real-world natural images captured by cameras are much more complex than the synthetic AWGN noise being widely studied. The major reason is that, during the imaging pipeline, the noise will be generated. The key reason of noise generation is unstable measurement from the discrete nature of light and the thermal agitation. The major sources of noise generated during the imaging pipeline are the random noise , the spatial non-uniformity, and quantization noise. The random noise includes photon shot noise, dark current, and readout noise. The spatial non-uniformity noise includes the fixed pattern noise (PRNU, DCNU), CCD/CMOS specific noise.

A simplified model including various noise sources (for each pixel) can be approximately defined as follows:

$$\boldsymbol{P} = f((g_{cv}(\boldsymbol{C} + \boldsymbol{D}) + \boldsymbol{N}_{reset})g_{out} + \boldsymbol{N}_{out}) + \boldsymbol{Q}. \tag{1.1}$$

Now the above equation is explained in details. $\boldsymbol{P}$ is the raw pixel value, $\boldsymbol{C}$ is the number of absorbed electrons (charges) transformed from the photons via the photon-diodes in the camera sensor, $\boldsymbol{D}$ is the number of absorbed electrons generated by dark current, g_{cv} is the equivalent capacitance (EC) of the photo-diode, $\boldsymbol{N}_{reset}$ is the thermal noise generated by the readout circuitry (or reset noise related to reset voltage), g_{out} is the gain factor during voltage to pixel value conversion (readout), $\boldsymbol{N}_{out}$ is the readout noise, f is the camera response function, usually a linear function before attaining a saturation threshold, $\boldsymbol{Q}$ is the quantization error happened during rounding to interger values. The quantization noise is normally negligible compared to the readout noise.

Though can be approximated as Gaussian or Poisson distribution, these noise sources will be largely changed to be more complex during the in-camera imaging pipeline, which has been analyzed in [**crosschannel**]. Hence, the real-world noise is much more complex than the traditional additive white Gaussian noise, and should be paid more attention.

1.3 The Proposed Methods

To deal with the synthetic AWGN noise, and especially the realistic complex noise in the real-world images, we propose several methods exploiting the nonlocal self-simiarity priors of natural images. The first method is to utilize the external natural images to learn a NSS prior, which is then applied into the denoising task of input synthetic noisy image degraded by AWGN noise. The second method is to make use of power of external natural images, and then use the external NSS priors to guide the learning of the internal NSS priors of the input real noisy images. The third method is to fully utilize the internal NSS prior and make use of low rank models to exploit the NSS property of the input real noisy images. The fourth method is to use the sparse coding based method with additional weighting scheme to regard the local noise in real noisy images as a Gaussian and the prior is used to deal with the real noisy image. Finally, we construct a big real noisy images captured by widely used commercial cameras, on which we evaluate the existing image denoising methods as well as our proposed methods in this thesis. The structure of this thesis is organized as follows: in the 2nd chapter, we review the literatures in the image denoising area; in the 3rd chapter, we introduce the fully external method; in the 4th chapter, we introduce the external prior guided internal method; in the 5th chapter, we introduce the internal method based on low ran model; in the 6th chapter, we introduce the internal method based on sparse coding model; in the 7th chapter, we introduce the real noisy image dataset we construct, and finaly evaluate the proposed methods with the compared competing methods, both for synthetic AWGN or Poisson noise and real noise, including the commercial software designed especially for real noise.

1.4 Thesis Structure

Chapter 2: Literature Review

In this chapter, we review the related work and give a detailed introduction of the literature. We will first review the most representative work on additive white Gaussian noise removal. I review the detailed work on camera imaging pipeline and realistic noise generated in the camera sensors. I will also review the work on real noisy image denoising.

Chapter 3: External Nonlocal Self-Similarity Prior Learning for Synthetic Gaussian Noise Removal

In this chapter, I will introduce our work on external nonlocal self-similarity (NSS) prior learning for synthetic Gaussian noise removal. As far as we know, this work is the first to learn the NSS priors of natural clean images, while previous work only utilize the NSS priors of input noisy image for online denoising. The advantages of this offline learning is that it can preserve the details of natural images while being much faster then most online denoising methods.

Chapter 4: External Prior Guided Internal Prior Learning for Real Noisy Image Denoising

In this chapter, I will introduce our work on external prior guided internal prior learning method for real noisy image denoising. This work can maintain the advantages of both sides: from the external perspective, the method can preserve the structures of natural images better than the internal methods, while from the perspective of internal method, the proposed method can recover the details of the input noisy image better than the external methods.

Chapter 5: Multi-channel Weighted Nuclear Norm Minimization for Real Color Image Denoising

In this chapter, we introduce a multi-channel weighted nuclear norm minimization (MC-WNNM) method. This method regards different channels in RGB images differently to adaptively process the real color noisy images. While it is a new strategy to

Chapter 6: A Triple Weighted Sparse Coding Scheme for Realistic Noisy Image Denoising

Chapter 7: A Benchmark on Real Color Noisy Image, with Comprehensive Evaluation of State-of-the-art

2 Literature Review

> *"Mens cujusque is est Quisque" – "Mind Makes the Man"*
>
> — **Samuel Pepys**

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2.1 Synthetic Grayscale Image Denoising

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2.2 Realistic Color Image Denoising

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3 External Non-local Self-Similarity Prior for Additive White Gaussian Noise

> *Innovation distinguishes between a leader and a follower.*
>
> — **Steve Jobs**
> (CEO Apple Inc.)

3.1 Introduction

Fig. 3.1: Figure example: *(a)* example part one, *(c)* example part two; *(c)* example part three

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Fig. 3.2: Another Figure example: *(a)* example part one, *(c)* example part two; *(c)* example part three

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3.2 System Design

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3.3 Demo System

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3.4 Calibration

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3.5 Conclusion

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4 External Prior Guided Internal Prior Learning for Real Noisy Image Denoising

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> — **Steve Jobs**
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4.1 Learning External Nonlocal Self-Similarity Priors

Fig. 4.1: Figure example: *(a)* example part one, *(c)* example part two; *(c)* example part three

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5 Internal Nonlocal Self-Similarity Prior for Real Color Image Denoising: A Low Rank based Method

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>
> — **Jef Raskin**
> about Human Computer Interfaces

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5.2 Related Work

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5.3 Method

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5.4 Experimental Results

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5.5 Summary

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6 Internal Nonlocal Self-Similarity Prior for Real Color Image Denoising: A Sparse Coding based ethod

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6.2 Related Work

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7 A Large Real Noisy Image Dataset, with A Comprehensive Evaluation of State-of-the-arts

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8 Conclusions

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8.1 Section 1

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8.2 Section 2

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8.3 Future Work

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