

The Hong Kong Polytechnic University

Department of Computing

Thesis Title

Thesis Author

**A thesis
submitted in partial fulfilment of the requirements
for the degree of**

Doctor of Philosophy

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

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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

Nowadays, CCD or CMOS cameras are becoming more and more important in many aspects of human life such as photography, artificial intelligence, and security system. For each camera product, the camera imaging pipeline in the camera is of particular importance since it is the core part to transform the photons reflected by the real scene being captured in the camera sensor into the pixel values of an image, which can be displayed on a screen. During the camera imaging process, the noise is unavoidably generated due to many reasons. Two major reasons of noise generation are the discrete nature of light and the thermal agitation, which can cause the photon shot noise and the dark-current noise, respectively. Image denoising is the problem of recovering the latent clean image from the captured noise version.

Chapter abstract This chapter will introduce the image noise and its acquisition equation, the image denoising problem, the objective measures to evaluate the image denoising performance, the proposed denoising methods. Finally, I will summarize the structural of this thesis, and the contribution I made in this thesis.

1.1 The Image Noise

The realistic noise are very complex in real photography images captured by the camera sensors. One major reason is that the noise is unable to be explicitly modeled by some definitive probabilistic distributions. Often the sRGB images we look at the screen have been processed via the camera imaging pipeline, during which the noise will be much more complex than its initial status.

The noise are generated mainly due to the discrete nature of light and the thermal agitation, which will cause unstable measurement in camera sensors. The major types of noise generated during the imaging pipeline are the random noise, the spatial non-uniformity noise, 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.

To better describe the noise quantitatively, we provide a simplified signal acquisition model [] including various noise sources (for each pixel) as follows:

$$P = f((g_{cv}(C + D) + N_{reset})g_{out} + N_{out}) + Q. \quad (1.1)$$

The above equation is explained in details:

- P is the raw pixel value;
- f is the camera response function, usually a linear function before attaining a saturation threshold;
- C is the number of absorbed electrons (charges) transformed from the photons via the photon-diodes in the camera sensor, which can be modeled by a Poisson distribution;
- D is the number of absorbed electrons generated by dark current by thermal generation, which is often modeled by a Poisson distribution;
- N_{reset} is the thermal noise generated by the readout circuitry (or reset noise related to reset voltage), which can be well modeled by a Gaussian distribution;
- N_{out} is the readout noise, which is also modeled by a Gaussian distribution;
- Q is the quantization error happened during rounding to interger values, usually uniformly distributed and normally negligible compared to the readout noise;
- g_{cv} is the equivalent capacitance (EC) of the photo-diode and the gain factor during charge to voltage conversion;
- g_{out} is the gain factor during voltage to pixel value conversion (readout).

After some merging and simplifying, the acquisition model of the signal can be formulated as follows:

$$\begin{aligned} P &= f((g_{cv}(C + D) + N_{reset})g_{out} + N_{out}) + Q, \\ &= f(g_{cv}g_{out}(C + D) + g_{out}N_{reset} + N_{out}) + Q, \\ &= f(g\lambda + N_R) + Q, \end{aligned} \quad (1.2)$$

where $g = g_{cv}g_{out}$ is the overall camera gain factor, $\lambda = \mathbf{C} + \mathbf{D}$ is # of electrons in pixel capacitor and also Poisson distributed, since “Sum of Independent Poisson Random Variables is also Poisson”, and $N_R = g_{out}\mathbf{N}_{reset} + \mathbf{N}_{out}$ is the overall readout noise and also Gaussian distributed, since “Sum of Independent Gaussian Random Variables is also Gaussian”. In summary, the overall noise before the camera imaging pipeline can be modeled by a mixed Poisson and Gaussian distribution []. Unfortunately, the realistic noise will become very complex after being processed during the camera imaging pipeline [**crosschannel**]. This makes the image denoising an important and challenging task.

To make the problem easier, in image denoising community, the most common tested noise is additive white Gaussian noise (AWGN) [EA06]. In AWGN degraded image, each pixel is corrupted by a random value following Gaussian distribution with zero mean and a certain standard deviation (std). Note that for each pixel, the std of the Gaussian distribution is the same, and for all the pixels, the noise values are sampled independently. The AWGN noise is similar to the read-out noise in digital cameras.

In order to obtain images of good quality while still maintaining the structures and details of the captured scenes, image denoising is an essential step. In this thesis, I will present my work on image denoising, in which we focus on synthetic additive white Gaussian noise (AWGN) and the realistic noise in real-world 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 existing methods focus on processing AWGN noise since it is a perfect testing bed for evaluating the proposed methods as well as other image restoration problems such as image super-resolution, deblurring, inpainting, etc.

1.2 Image Denoising

In general, image denoising aims to recover the latent clean image \mathbf{x} from the observed noisy image $\mathbf{y} = \mathbf{x} + \mathbf{n}$, where \mathbf{n} is assumed to be the additive noise. \mathbf{n} is often assumed to be synthetic additive white Gaussian noise, or the realistic noise in real-world images. Image denoising can be viewed as a regression problem, in which a *plausible* clean image can be obtained from the infinite number of possible candidates. The word *plausible* means that

the denoised image should look like the noisy image but without the noise component.

Image denoising would be very hard if we do not employ any prior information on it. The reason is that we do not know what exactly the latent clean image is without the prior information of the clean image. Hence, it is meaningful to exploit the most *plausible* image under some prior information. The most commonly used prior information in image denoising community is the Bayesian rule, which is also known as maximum A-posterior (MAP) property. Under the MAP framework, the most *plausible* latent clean image is the one which has the maximum Bayesian probability given the given noisy version. The posterior probability can be measured by some existing evaluation methods which I will introduce in the following sections. In fact, the probability or measurements can measure the closeness of the latent clean image to the given noisy image. The closeness is usually measured by the ℓ_2 norm of the difference between the two images mentioned above. There are many latent clean images with the same ℓ_2 norm distance with the given noisy image. But some images in the circle are more *plausible* than the others due to the aspects of less artifacts, better structural preservation, and less remaining noise, etc.

1.3 Evaluating Denoising Performance

In order to achieve the maximum Bayesian probability, we need calculate the measurements of goodness for the denoised images. A natural problem is, how to measure the quality of the denoised image? It is very important to find better answer to this question. In fact, the research of image quality assessment is to find good algorithms to measure the quality of images under different situations and applications including image denoising.

A initial understanding is that the answer to the above question is largely depends on the situations we face when we perform image denoising experiments. When we perform synthetic experiments on additive white Gaussian noise (AWGN), we usually already have the original clean image, the noisy image is generated by adding synthetic AWGN noise to the clean image. Then we can directly measure the quality of the denoised image by some existing image quality assessment (IQA) metrics. When we do not have the clean image provided as “ground truth”, a possible and final solution is to measure

the image quality by relying on human subjective evaluation. The IQA metrics can be roughly divided into two major directions: 1) full reference IQA; and 2) no reference IQA. Full reference IQA metrics are based on the assumption that the true underlying image is available in order to compute a measure, while no reference IQA metrics perform quality assessments without the reference image since the true underlying image is not available.

RMSE and PSNR: We mentioned previously that it is corresponding to the ℓ_2 norm or equally mean square error (MSE) which is used to measure the distance between the denoised image and the given noisy image. In fact, the MSE measure is closely related to the famous peak signal to noise ratio (PSNR) metric. PSNR is the most commonly used full reference IQA metric for many image restoration tasks including denoising. The definition of PSNR can be formulated as follows (for 8-bit image):

$$\text{PSNR} = 20\log_{10}\left(\frac{2^8}{\text{RMSE}(\mathbf{x}, \mathbf{y})}\right), \quad (1.3)$$

where $\text{RMSE}(\mathbf{x}, \mathbf{y})$ refers to the root mean square error defined as $\text{RMSE} = \sqrt{\frac{1}{MN} \sum_{i=1}^M \sum_{j=1}^N (\mathbf{x}_{ij} - \mathbf{y}_{ij})^2}$ for images $\mathbf{x}, \mathbf{y} \in \mathcal{R}^{M \times N}$. As we can see, PSNR is closely related to the ℓ_2 norm distance between two images. The unit of PSNR is decibel (dB) and higher dB value indicates better image quality and lower RMSE. Even though PSNR is very simple and intuitive, higher PSNR does not indicate higher visual structural similarity. Hence, many researchers still make effort to find alternative and better IQA metrics.

SSIM [Wan+04]: Some researchers attempted to exploit the visual properties of the human visual system. One of the seminar work in this direction is the famous structural similarity index metric (SSIM), which is a full reference IQA metric. In SSIM, each image patch is separated into three different components indicating three core informative parts of the original patch. The three components are luminance (mean value of the pixels in the patch), contrast (the standard deviation of the patch), and structure (the mean subtracted patch). The major advantage of the SSIM is that it takes into account the fact that the human visual system is very sensitive to the relative changes in luminance, rather than the absolute changes in luminance. The value range of the SSIM is between 0 and 1, where higher value indicate higher similarity (SSIM of 1 indicates that the two images are exactly the same). Note that it does not indicate that higher SSIM indicate better image quality, since the reference image is not the image of the best quality.

Other IQA Metrics: Besides of the PSNR and SSIM, there are many other IQA metrics for full reference and no reference IQA. Some examples include the MS-SSIM [Wan+03], which is a multi-scale extension of the original SSIM. Some examples in no reference IQA include BLIINDS [Saa+12] and BIQI [MB10]. These IQA metrics capture the deviations from the expected statistics of the natural images. For example, BLIINDS measures the deviations from the expected histogram of certain features in DCT domain, while BIQI measures deviations from the expected distribution of wavelet coefficients in a multi-scale decomposition.

I have to mention that no IQA metric is perfect or best for image denoising task, both in full reference and no reference cases. The de facto standard metrics in image restoration community are PSNR and SSIM. In order to avoid these two metrics generate bad results, it is essential to demonstrate the image quality in the thesis for human subjective evaluation.

1.4 The Proposed Methods

This thesis is mainly consisted by the several work I have done during my PhD study, during which I focus on designing new and better image denoising algorithms.

Firstly, I propose a method for denoising synthetic AWGN noise, from which we can study the performance of the nonlocal self-similarity priors of natural images. In fact, we propose to learn the external NSS priors and apply the learned model on denoising AWGN noise. The proposed method achieves state-of-the-art performance on AWGN denoising on both effectiveness and efficiency.

Basing on the success on the synthetic noise removal, I propose to exploit the power of the NSS priors in natural images to deal with the complex realistic noise in real-world noisy images. Specifically, we propose three methods exploiting the NSS priors of natural images for real noisy image denoising, which can be introduced as follows.

In the first method, I propose to learn the NSS prior from the external natural images, and then apply the learned external prior to guide the learning of the internal NSS prior of the input real noisy image. The experiments on two commonly used datasets and a new one we constructed to implement

the shortage of existing datasets, demonstrate that the proposed method can achieve better performance than existing color image denoising methods such as CBM3D [Dab+07a], the state-of-the-art Gaussian noise removal methods [csr; Dab+07b; Bur+12], and the real noisy image denoising methods [] including a commercial software Neat Image [ABS], which is embedded into the famous PhotoShop CS for image processing tasks.

In the second method, I propose to employ the low rank model describe fully the the internal NSS prior, basing on the observed fact that the similar image patches can be contained as a matrix of low rank. Different from the previous work, I extend the WNNM model and apply it to multi-channel version to make it feasible for color image denoising.

In the third 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, to make my thesis more comprehensive, I construct a large benchmark of real noisy images captured by different types of famous commercial cameras, on which I also evaluate the image denoising methods mentioned above and the proposed methods in this thesis.

The structure of this thesis is organized as follows: in the chapter 2, we review the literatures in the image denoising area; in the chapter 3, we introduce the fully external method; in the chapter 4, we introduce the external prior guided internal method; in the chapter 5, we introduce the internal method based on low rank model; in the chapter 6, we introduce the internal method based on sparse coding model; in the chapter 7, we introduce the real noisy image dataset we construct, and finally 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.

1.5 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 than 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. Besides, this work also propose a new strategy for color image denoising. Experiments demonstrate that the proposed method can achieve better perfor-

mance on real color image denoising than existing state-of-the-art methods, including some commercial software.

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

In this chapter, I introduce a novel sparse coding based method for real color image denoising. In this method, I regard the noise in each of the local region in the real noisy image as a Gaussian, and propose a triplely weighted scheme to deal with the complex realistic noise in real color noisy images. Experiments show that the proposed method performs better and faster than the nuclear norm based method mentioned in previous chapter.

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

To fully boost the research of real color noisy image denoising, we construct a large benchmark on real color noisy images. This dataset is collected from several representative cameras with comprehensive settings on contents, lighting, ISO, shutter, and aperture, etc. Based on this newly established dataset, we fully evaluated existing denoising methods, including the methods designed for synthetic Gaussian noise and the methods designed especially for real color noise. We believe that this new dataset will largely boost the research of the image denoising especially the realistic image denoising problems.

Literature Review

In this chapter, I will review the methods related to denoising in literature during the past decades. These methods can be divided into three categories. Firstly, I will review the denoising methods designed for additive white Gaussian noise (AWGN) since AWGN is the mostly studied noise distribution in the literature. Though these methods are proposed to deal with the AWGN noise, the idea can be applied to the other image denoising tasks such as real color image denoising. Secondly, I will review the existing methods proposed for processing real noisy images. Though the methods in this domain is not that versatile than those methods for the AWGN noise, the real noisy image denoising is the current mainstream for the image denoising community. Due to the noise is not known beforehand, noise estimation should be performed for the real noisy image denoising task. Finally, I will also review the image noise estimation methods in the literature.

2.1 Synthetic Grayscale Image Denoising

As a classical problem in low level vision, image denoising has been extensively studied, yet it is still an active topic for that it provides an ideal test bed for image modeling techniques. In general, image denoising aims to recover the clean image x from its noisy observation $y = x + v$, where v is assumed to be additive white Gaussian noise. A variety of image denoising methods have been developed in past decades, including filtering based methods [TM98], diffusion based methods [PM90], total variation based methods [Rud+92; Osh+05], wavelet/curvelet based methods [Don95; Cha+00; Sta+02], sparse representation based methods [EA06; Mai+09a; Don+13], nonlocal self-similarity based methods [Bua+05a; Dab+07b; Ji+10a; Gu+14], etc.

Image modeling plays a central role in image denoising. By modeling the wavelet transform coefficients as Laplacian distributions, many wavelet shrinkage based denoising methods such as the classical soft-thresholding [Don95] have been proposed. Chang et al. modeled the wavelet transform coefficients as generalized Gaussian distribution, and proposed the BayesShrink [Cha+00] algorithm. By considering the correlation of wavelet coefficients

across scales, Portilla et al. [Por+03] proposed to use Gaussian Scale Mixtures for image modeling and achieved promising denoising performance. It is widely accepted that natural image gradients exhibit heavy-tailed distributions [WF07], and the total variation (TV) based methods [Rud+92; Osh+05] actually assume Laplacian distributions of image gradients for denoising. The Fields of Experts (FoE) [RB09] proposed by Roth and Black models the filtering responses with Student's t-distribution to learn filters through Markov Random Field (MRF) [Bis06]. Recently, Schmidt and Roth proposed the cascade of shrinkage fields (CSF) to perform denoising efficiently [SR14].

Instead of modeling the image statistics in some transformed domain (e.g., gradient domain, wavelet domain or filtering response domain), another popular approach is to model the image priors on patches. One representative is the sparse representation based scheme which encodes an image patch as a linear combination of a few atoms selected from a dictionary [OF96; OF97; EA06]. The dictionary can be chosen from the off-the-shelf dictionaries (e.g., wavelets and curvelets), or it can be learned from natural image patches. The seminal work of K-SVD [Aha+06; EA06] has demonstrated promising denoising performance by dictionary learning, which has yet been extended and successfully used in various image processing and computer vision applications [Mai+08a; Wri+10; Jia+13]. By viewing image patches as samples of a multivariate variable vector and considering that natural images are non-Gaussian, Zoran and Weiss [ZW11; ZW12] and Yu et al. [Yu+12] used Gaussian Mixture Model (GMM) to model image patches, and achieved state-of-the-art denoising and image restoration results, respectively.

2.2 Realistic Color Image Denoising

During the last decade, a few methods have been proposed for real color image denoising. Among them, the CBM3D method [Dab+07a] is a representative one, which first transforms the RGB image into a luminance-chrominance space (e.g., YCbCr) and then applies the benchmark BM3D method [Dab+07b] to each channel separately. The non-local similar patches are grouped by the luminance channel. In [Liu+08], Liu et al. proposed the “Noise Level Function” to estimate and remove the noise for each channel in natural images. However, processing each channel separately would often achieve inferior performance to processing the color channels jointly

[Mai+08b]. Therefore, the methods [Leb+15; Leb+; Zhu+16] perform real color image denoising by concatenating the patches of RGB channels into a long vector. However, the concatenation treats each channel equally and ignores the different noise statistics among these channels. The method in [Nam+16] models the cross-channel noise in real noisy images as multivariate Gaussian and the noise is removed by the Bayesian non-local means filter [Ker+07]. The commercial software Neat Image [ABS] estimates the noise parameters from a flat region of the given noisy image and filters the noise accordingly. The methods in [Nam+16; ABS] ignore the non-local self-similarity of natural images [Dab+07b; Gu+14].

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

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

3.3 Demo System

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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

“*Innovation distinguishes between a leader and a follower.*”

— Steve Jobs
(CEO Apple Inc.)

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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Fig. 4.2: Another Figure example: (a) example part one, (c) example part two; (c) example part three

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4.3 Demo System

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

4.4 Calibration

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4.5 Conclusion

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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

“Users do not care about what is inside the box, as long as the box does what they need done.

— Jef Raskin

about Human Computer Interfaces

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5.1 Introduction

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5.2 Related Work

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

5.3 Method

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5.4 Experimental Results

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5.5 Summary

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Internal Nonlocal Self-Similarity

Prior for Real Color Image

Denoising: A Sparse Coding based method

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— **Jef Raskin**

about Human Computer Interfaces

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6.1 Introduction

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6.2 Related Work

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

“Users do not care about what is inside the box, as long as the box does what they need done.

— Jef Raskin

about Human Computer Interfaces

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7.2 Related Work

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Conclusions

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

8.1 Section 1

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

8.2 Section 2

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language.

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8.3 Future Work

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

References

- [ABS] Neatlab ABSOft. *Neat Image*. <https://ni.neatvideo.com/home> (cit. on pp. 7, 13).
- [Aha+06] M. Aharon, M. Elad, and A. Bruckstein. „The K-SVD: An Algorithm for Designing Overcomplete Dictionaries for Sparse Representation“. In: *IEEE Transactions on Signal Processing* 54.11 (2006), pp. 4311–4322 (cit. on p. 12).
- [Ale+06] Milivoje Aleksic, Maxim Smirnov, and Sergio Goma. „Novel bilateral filter approach: Image noise reduction with sharpening“. In: *Electronic Imaging 2006* (2006), 60690F–60690F.
- [Arb+11] P. Arbelaez, M. Maire, C. Fowlkes, and J. Malik. „Contour Detection and Hierarchical Image Segmentation“. In: *IEEE Trans. Pattern Anal. Mach. Intell.* 33.5 (2011), pp. 898–916.
- [Ari+09] Tarik Arici, Salih Dikbas, and Yucel Altunbasak. „A histogram modification framework and its application for image contrast enhancement“. In: *IEEE Transactions on image processing* 18.9 (2009), pp. 1921–1935.
- [AW95] Volker Aurich and Jörg Weule. „Non-linear gaussian filters performing edge preserving diffusion“. In: *Mustererkennung 1995* (1995), pp. 538–545.
- [Bao+13] Chenglong Bao, Jian-Feng Cai, and Hui Ji. „Fast sparsity-based orthogonal dictionary learning for image restoration“. In: *IEEE International Conference on Computer Vision (ICCV)* (2013), pp. 3384–3391.
- [Bar09] Adrian Barbu. „Training an active random field for real-time image denoising“. In: *IEEE Transactions on Image Processing* 18.11 (2009), pp. 2451–2462.
- [Ben09] Yoshua Bengio. „Learning deep architectures for AI“. In: *Foundations and trends® in Machine Learning* 2.1 (2009), pp. 1–127.
- [Ber99] Dimitri P Bertsekas. „Nonlinear Programming“. In: (1999).

- [BI16] Y. Bahat and M. Irani. „Blind dehazing using internal patch recurrence“. In: *IEEE International Conference on Computational Photography (ICCP)* (2016), pp. 1–9.
- [Bis06] C. M. Bishop. *Pattern recognition and machine learning*. New York: Springer, 2006 (cit. on p. 12).
- [BM05] Eric P Bennett and Leonard McMillan. „Video enhancement using per-pixel virtual exposures“. In: *ACM Transactions on Graphics (TOG)* 24.3 (2005), pp. 845–852.
- [Boy+11] S. Boyd, N. Parikh, E. Chu, B. Peleato, and J. Eckstein. „Distributed Optimization and Statistical Learning via the Alternating Direction Method of Multipliers“. In: *Found. Trends Mach. Learn.* 3.1 (Jan. 2011), pp. 1–122.
- [Bua+05a] A. Buades, B. Coll, and J. M. Morel. „A non-local algorithm for image denoising“. In: *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2005), pp. 60–65 (cit. on p. 11).
- [Bua+05b] A. Buades, B. Coll, J. M. Morel, and Dpt Matemàtiques. „Denoising image sequences does not require motion estimation“. In: *Proc. of the IEEE Conf. on Advanced Video and Signal Based Surveillance September (AVSS)* (2005), pp. 70–74.
- [Bua+08] Antoni Buades, Bartomeu Coll, and Jean-Michel Morel. „Non-local image and movie denoising“. In: *International journal of computer vision* 76.2 (2008), pp. 123–139.
- [Bur+12] H. C. Burger, C. J. Schuler, and S. Harmeling. „Image denoising: Can plain neural networks compete with BM3D?“ In: *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2012), pp. 2392–2399 (cit. on p. 7).
- [Cai+10] J. Cai, E. J. Candès, and Z. Shen. „A singular value thresholding algorithm for matrix completion“. In: *SIAM Journal on Optimization* 20.4 (2010), pp. 1956–1982.
- [Can+11] E. J. Candès, X. Li, Y. Ma, and J. Wright. „Robust principal component analysis?“ In: *Journal of the ACM* 58.3 (2011), p. 11.
- [Cha+00] S. G. Chang, B. Yu, and M. Vetterli. „Adaptive wavelet thresholding for image denoising and compression“. In: *Image Processing, IEEE Transactions on* 9.9 (2000), pp. 1532–1546 (cit. on p. 11).
- [Cha+04] Hong Chang, Dit-Yan Yeung, and Yimin Xiong. „Super-resolution through neighbor embedding“. In: *Computer Vision and Pattern Recognition, 2004. CVPR 2004. Proceedings of the 2004 IEEE Computer Society Conference on* 1 (2004), pp. I–I.

- [Che+06a] ZhiYu Chen, Bisma R Abidi, David L Page, and Mongi A Abidi. „Gray-level grouping (GLG): an automatic method for optimized image contrast Enhancement-part I: the basic method“. In: *IEEE Transactions on image processing* 15.8 (2006), pp. 2290–2302.
- [Che+06b] ZhiYu Chen, Bisma R Abidi, David L Page, and Mongi A Abidi. „Gray-level grouping (GLG): an automatic method for optimized image contrast enhancement-part II: the variations“. In: *IEEE Transactions on Image Processing* 15.8 (2006), pp. 2303–2314.
- [Che+15a] G. Chen, F. Zhu, and A. H. Pheng. „An Efficient Statistical Method for Image Noise Level Estimation“. In: *IEEE International Conference on Computer Vision (ICCV)* (2015).
- [Che+15b] Y. Chen, W. Yu, and T. Pock. „On learning optimized reaction diffusion processes for effective image restoration“. In: *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2015), pp. 5261–5269.
- [Col+14] M. Colom, M. Lebrun, A. Buades, and J.-M. Morel. „A non-parametric approach for the estimation of intensity-frequency dependent noise“. In: *IEEE International Conference on Image Processing (ICIP)* (2014), pp. 4261–4265.
- [Con+14] David Connah, Mark Samuel Drew, and Graham David Finlayson. „Spectral edge image fusion: Theory and applications“. In: *European Conference on Computer Vision* (2014), pp. 65–80.
- [Cou43] R. Courant. „Variational methods for the solution of problems of equilibrium and vibrations“. In: *Bull. Amer. Math. Soc.* 49.1 (1943), pp. 1–23.
- [CP15] Yunjin Chen and Thomas Pock. „Trainable Nonlinear Reaction Diffusion: A Flexible Framework for Fast and Effective Image Restoration“. In: *arXiv preprint arXiv:1508.02848* (2015).
- [Cro84] F. C. Crow. „Summed-area Tables for Texture Mapping“. In: *SIGGRAPH Comput. Graph.* 18.3 (Jan. 1984), pp. 207–212.
- [Cui+14] Zhen Cui, Hong Chang, Shiguang Shan, Bineng Zhong, and Xilin Chen. „Deep network cascade for image super-resolution“. In: *European Conference on Computer Vision* (2014), pp. 49–64.
- [CW98] Tony F Chan and Chiu-Kwong Wong. „Total variation blind deconvolution“. In: *IEEE transactions on Image Processing* 7.3 (1998), pp. 370–375.
- [Dab+07a] K. Dabov, A. Foi, V. Katkovnik, and K. Egiazarian. „Color image denoising via sparse 3D collaborative filtering with grouping constraint in luminance-chrominance space“. In: *IEEE International Conference on Image Processing (ICIP)* (2007), pp. 313–316 (cit. on pp. 7, 12).

- [Dab+07b] K. Dabov, A. Foi, V. Katkovnik, and K. Egiazarian. „Image denoising by sparse 3-D transform-domain collaborative filtering“. In: *IEEE Transactions on Image Processing* 16.8 (2007), pp. 2080–2095 (cit. on pp. 7, 11–13).
- [Dan+12] Aram Danielyan, Vladimir Katkovnik, and Karen Egiazarian. „BM3D frames and variational image deblurring“. In: *IEEE Transactions on Image Processing* 21.4 (2012), pp. 1715–1728.
- [DD02] Frédo Durand and Julie Dorsey. „Fast bilateral filtering for the display of high-dynamic-range images“. In: *ACM transactions on graphics (TOG)* 21.3 (2002), pp. 257–266.
- [DE03] David L Donoho and Michael Elad. „Optimally sparse representation in general (nonorthogonal) dictionaries via l1 minimization“. In: *Proceedings of the National Academy of Sciences* 100.5 (2003), pp. 2197–2202.
- [Dem+77] A. P. Dempster, N. M. Laird, and D. B. Rubin. „Maximum likelihood from incomplete data via the EM algorithm“. In: *Journal of the Royal Statistical Society. Series B (methodological)* (1977), pp. 1–38.
- [DH01] D. L. Donoho and X. Huo. „Uncertainty principles and ideal atomic decomposition“. In: *IEEE Transactions on Information Theory* 47.7 (2001), pp. 2845–2862.
- [Don+13] W. Dong, L. Zhang, G. Shi, and X. Li. „Nonlocally centralized sparse representation for image restoration.“ In: *IEEE Transactions on Image Processing* 22.4 (2013), pp. 1620–1630 (cit. on p. 11).
- [Don+15] Chao Dong, Yubin Deng, Chen Change Loy, and Xiaoou Tang. „Compression artifacts reduction by a deep convolutional network“. In: *Proceedings of the IEEE International Conference on Computer Vision* (2015), pp. 576–584.
- [Don+16] Chao Dong, Chen Change Loy, Kaiming He, and Xiaoou Tang. „Image super-resolution using deep convolutional networks“. In: *IEEE transactions on pattern analysis and machine intelligence* 38.2 (2016), pp. 295–307.
- [Don95] D. L. Donoho. „De-noising by soft-thresholding“. In: *IEEE Trans. Inf. Theory* 41.3 (1995), pp. 613–627 (cit. on p. 11).
- [EA06] M. Elad and M. Aharon. „Image denoising via sparse and redundant representations over learned dictionaries“. In: *IEEE Transactions on Image Processing* 15.12 (2006), pp. 3736–3745 (cit. on pp. 3, 11, 12).
- [EB92] J. Eckstein and D. P. Bertsekas. „On the Douglas–Rachford splitting method and the proximal point algorithm for maximal monotone operators“. In: *Mathematical Programming* 55.1 (1992), pp. 293–318.

- [ED04] Elmar Eisemann and Frédo Durand. „Flash photography enhancement via intrinsic relighting“. In: *ACM transactions on graphics (TOG)* 23.3 (2004), pp. 673–678.
- [EY36] C. Eckart and G. Young. „The approximation of one matrix by another of lower rank“. In: *Psychometrika* 1.3 (1936), pp. 211–218.
- [Faz02] M. Fazel. „Matrix rank minimization with applications“. In: *PhD thesis, Stanford University* (2002).
- [Fin+11] Graham D Finlayson, David Connah, and Mark S Drew. „Lookup-table-based gradient field reconstruction“. In: *IEEE Transactions on Image Processing* 20.10 (2011), pp. 2827–2836.
- [Fre+00] William T Freeman, Egon C Pasztor, and Owen T Carmichael. „Learning low-level vision“. In: *International journal of computer vision* 40.1 (2000), pp. 25–47.
- [Gla+09] Daniel Glasner, Shai Bagon, and Michal Irani. „Super-Resolution from a Single Image“. In: *IEEE International Conference on Computer Vision (ICCV)* (2009).
- [Gon+14] Z. Gong, Z. Shen, and K.-C. Toh. „Image Restoration with Mixed or Unknown Noises“. In: *Multiscale Modeling & Simulation* 12.2 (2014), pp. 458–487.
- [Goo+05] Amy A Gooch, Sven C Olsen, Jack Tumblin, and Bruce Gooch. „Color2gray: salience-preserving color removal“. In: *ACM Transactions on Graphics (TOG)* 24.3 (2005), pp. 634–639.
- [Gu+14] S. Gu, L. Zhang, W. Zuo, and X. Feng. „Weighted nuclear norm minimization with application to image denoising“. In: *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2014), pp. 2862–2869 (cit. on pp. 11, 13).
- [Gu+16] S. Gu, Q. Xie, D. Meng, et al. „Weighted nuclear norm minimization and its applications to low level vision“. In: *International Journal of Computer Vision* (2016), pp. 1–26.
- [Gui+98] Sébastien Guillon, Pierre Baylou, Mohamed Najim, and Naamen Keskes. „Adaptive nonlinear filters for 2D and 3D image enhancement“. In: *Signal processing* 67.3 (1998), pp. 237–254.
- [GW08] Rafael C Gonzalez and Richard E Woods. „Digital image processing“. In: *Nueva Jersey* (2008).
- [Has+09] Trevor Hastie, Robert Tibshirani, Jerome Friedman, et al. *The elements of statistical learning*. Springer, 2009.
- [He+10] Kaiming He, Jian Sun, and Xiaoou Tang. „Guided image filtering“. In: *European conference on computer vision* (2010), pp. 1–14.

- [He+13a] Kaiming He, Jian Sun, and Xiaoou Tang. „Guided image filtering“. In: *IEEE transactions on pattern analysis and machine intelligence* 35.6 (2013), pp. 1397–1409.
- [He+13b] Li He, Hairong Qi, and Russell Zaretzki. „Beta Process Joint Dictionary Learning for Coupled Feature Spaces with Application to Single Image Super-Resolution“. In: *Proceedings of the 2013 IEEE Conference on Computer Vision and Pattern Recognition* (2013), pp. 345–352.
- [Hig02] N. J. Higham. „Computing the nearest correlation matrix: a problem from finance“. In: *IMA Journal of Numerical Analysis* 22.3 (2002), p. 329.
- [HK94] G. E Healey and R. Kondepudy. „Radiometric CCD camera calibration and noise estimation“. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 16.3 (1994), pp. 267–276.
- [Hu+13] Y. Hu, D. Zhang, J. Ye, X. Li, and X. He. „Fast and Accurate Matrix Completion via Truncated Nuclear Norm Regularization“. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 35.9 (2013), pp. 2117–2130.
- [Hub11] P. J. Huber. *Robust statistics*. Springer, 2011.
- [Ji+10a] H. Ji, C. Liu, Z. Shen, and Y. Xu. „Robust video denoising using low rank matrix completion“. In: *CVPR* (2010), pp. 1791–1798 (cit. on p. 11).
- [Ji+10b] H. Ji, C. Liu, Z. Shen, and Y. Xu. „Robust video denoising using low rank matrix completion.“ In: *CVPR* (2010), pp. 1791–1798.
- [Jia+13] Z. Jiang, Z. Lin, and L. S. Davis. „Label Consistent K-SVD: Learning a Discriminative Dictionary for Recognition“. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 35.11 (2013), pp. 2651–2664 (cit. on p. 12).
- [Job+97] Daniel J Jobson, Zia-ur Rahman, and Glenn A Woodell. „A multiscale retinex for bridging the gap between color images and the human observation of scenes“. In: *IEEE Transactions on Image processing* 6.7 (1997), pp. 965–976.
- [JS09] Viren Jain and Sebastian Seung. „Natural image denoising with convolutional networks“. In: *Advances in Neural Information Processing Systems* (2009), pp. 769–776.
- [Jür00] Manuela Jürgens. *LaTeX: eine Einführung und ein bisschen mehr*. FernUniversität Gesamthochschule in Hagen, 2000.
- [KB16] H. C. Karaimer and M. S. Brown. „A Software Platform for Manipulating the Camera Imaging Pipeline“. In: *European Conference on Computer Vision (ECCV)* (2016).

- [Ker+07] C. Kervrann, J. Boulanger, and P. Coupé. „Bayesian non-local means filter, image redundancy and adaptive dictionaries for noise removal“. In: *International Conference on Scale Space and Variational Methods in Computer Vision* (2007), pp. 520–532 (cit. on p. 13).
- [Key81] Robert Keys. „Cubic convolution interpolation for digital image processing“. In: *IEEE transactions on acoustics, speech, and signal processing* 29.6 (1981), pp. 1153–1160.
- [Kim+12] S. J. Kim, H. T. Lin, Z. Lu, et al. „A New In-Camera Imaging Model for Color Computer Vision and Its Application“. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 34.12 (2012), pp. 2289–2302.
- [Kim+15a] Jiwon Kim, Jung Kwon Lee, and Kyoung Mu Lee. „Accurate image super-resolution using very deep convolutional networks“. In: *Computer Vision and Pattern Recognition (CVPR), 2016 IEEE Conference on* (2015).
- [Kim+15b] Jiwon Kim, Jung Kwon Lee, and Kyoung Mu Lee. „Deeply-Recursive Convolutional Network for Image Super-Resolution“. In: *Computer Vision and Pattern Recognition (CVPR), 2016 IEEE Conference on* (2015).
- [Kim97] Yeong-Taeg Kim. „Contrast enhancement using brightness preserving bi-histogram equalization“. In: *IEEE transactions on Consumer Electronics* 43.1 (1997), pp. 1–8.
- [Laf+01] John Lafferty, Andrew McCallum, and Fernando Pereira. „Conditional random fields: Probabilistic models for segmenting and labeling sequence data“. In: *Proceedings of the eighteenth international conference on machine learning, ICML 1* (2001), pp. 282–289.
- [Leb+] M. Lebrun, M. Colom, and J. M. Morel. *The Noise Clinic: a Blind Image Denoising Algorithm*. <http://www.ipol.im/pub/art/2015/125/>. Accessed 01 28, 2015 (cit. on p. 13).
- [Leb+13] M. Lebrun, A. Buades, and J. M. Morel. „A Nonlocal Bayesian Image Denoising Algorithm“. In: *SIAM Journal on Imaging Sciences* 6.3 (2013), pp. 1665–1688.
- [Leb+15] M. Lebrun, M. Colom, and J.-M. Morel. „Multiscale Image Blind Denoising“. In: *IEEE Transactions on Image Processing* 24.10 (2015), pp. 3149–3161 (cit. on p. 13).
- [Leu+11] B. Leung, G. Jeon, and E. Dubois. „Least-Squares Luma-Chroma Demultiplexing Algorithm for Bayer Demosaicking“. In: *IEEE Transactions on Image Processing* 20.7 (2011), pp. 1885–1894.
- [Lev+04] Anat Levin, Dani Lischinski, and Yair Weiss. „Colorization using optimization“. In: *ACM Transactions on Graphics (TOG)* 23.3 (2004), pp. 689–694.

- [Lim90] Jae S Lim. „Two-dimensional signal and image processing“. In: *Englewood Cliffs, NJ, Prentice Hall, 1990, 710 p.* 1 (1990).
- [Lin+11a] Z. Lin, R. Liu, and Z. Su. „Linearized alternating direction method with adaptive penalty for low-rank representation“. In: *Advances in Neural Information Processing Systems (NIPS)* (2011), pp. 612–620.
- [Lin+11b] Zhouchen Lin, Risheng Liu, and Zhixun Su. „Linearized Alternating Direction Method with Adaptive Penalty for Low-Rank Representation“. In: *Advances in Neural Information Processing Systems 24* (2011). Ed. by J. Shawe-Taylor, R. S. Zemel, P. L. Bartlett, F. Pereira, and K. Q. Weinberger, pp. 612–620.
- [Liu+06] Ce Liu, William T Freeman, Richard Szeliski, and Sing Bing Kang. „Noise estimation from a single image“. In: *2006 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'06)* 1 (2006), pp. 901–908.
- [Liu+08] C. Liu, R. Szeliski, S. Bing Kang, C. L. Zitnick, and W. T. Freeman. „Automatic Estimation and Removal of Noise from a Single Image“. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 30.2 (2008), pp. 299–314 (cit. on p. 12).
- [Liu+13] X. Liu, M. Tanaka, and M. Okutomi. „Single-image noise level estimation for blind denoising“. In: *IEEE Transactions on Image Processing* 22.12 (2013), pp. 5226–5237.
- [LM71] Edwin H Land and John J McCann. „Lightness and retinex theory“. In: *JOSA* 61.1 (1971), pp. 1–11.
- [Lou+11] Yifei Lou, Andrea L Bertozzi, and Stefano Soatto. „Direct sparse deblurring“. In: *Journal of Mathematical Imaging and Vision* 39.1 (2011), pp. 1–12.
- [Lu+15] C. Lu, C. Zhu, C. Xu, S. Yan, and Z. Lin. „Generalized Singular Value Thresholding“. In: *AAAI* (2015).
- [Luo+15] Enming Luo, Stanley H Chan, and Truong Q Nguyen. „Adaptive image denoising by targeted databases“. In: *IEEE Transactions on Image Processing* 24.7 (2015), pp. 2167–2181.
- [Mag+12] Matteo Maggioni, Giacomo Boracchi, Alessandro Foi, and Karen Egiazarian. „Video denoising, deblocking, and enhancement through separable 4-d non-local spatiotemporal transforms“. In: *IEEE Transactions on image processing* 21.9 (2012), pp. 3952–3966.
- [Mai+08a] J. Mairal, M. Elad, and G. Sapiro. „Sparse Representation for Color Image Restoration“. In: *IEEE Transactions on Image Processing*, 17.1 (2008), pp. 53–69 (cit. on p. 12).

- [Mai+08b] J. Mairal, M. Elad, and G. Sapiro. „Sparse representation for color image restoration“. In: *IEEE Transactions on Image Processing* 17.1 (2008), pp. 53–69 (cit. on p. 13).
- [Mai+09a] J. Mairal, F. Bach, J. Ponce, G. Sapiro, and A. Zisserman. „Non-local sparse models for image restoration“. In: *IEEE International Conference on Computer Vision (ICCV)* (2009), pp. 2272–2279 (cit. on p. 11).
- [Mai+09b] J. Mairal, F. Bach, J. Ponce, G. Sapiro, and A. Zisserman. „Non-local sparse models for image restoration“. In: *2009 IEEE 12th International Conference on Computer Vision* (2009), pp. 2272–2279.
- [Mai+10] J. Mairal, F. Bach, J. Ponce, and G. Sapiro. „Online learning for matrix factorization and sparse coding“. In: *The Journal of Machine Learning Research* 11 (2010), pp. 19–60.
- [Mao+16] Xiao-Jiao Mao, Chunhua Shen, and Yu-Bin Yang. „Image Restoration Using Convolutional Auto-encoders with Symmetric Skip Connections“. In: *arXiv preprint arxiv:1606.08921v1* (2016).
- [MB10] Anush Krishna Moorthy and Alan Conrad Bovik. „A two-step framework for constructing blind image quality indices“. In: *IEEE Signal processing letters* 17.5 (2010), pp. 513–516 (cit. on p. 6).
- [MI14] Tomer Michaeli and Michal Irani. „Blind deblurring using internal patch recurrence“. In: *European Conference on Computer Vision* (2014), pp. 783–798.
- [Mie11] André Miede. *A Classic Thesis Style: An Homage to The Elements of Typographic Style*. 2011.
- [Mit+91] Sanjit K Mitra, Hui Li, I-S Lin, and T-H Yu. „A new class of nonlinear filters for image enhancement“. In: *Acoustics, Speech, and Signal Processing, 1991. ICASSP-91., 1991 International Conference on* (1991), pp. 2525–2528.
- [Moe+15] Michael Moeller, Julia Diebold, Guy Gilboa, and Daniel Cremers. „Learning nonlinear spectral filters for color image reconstruction“. In: *Proceedings of the IEEE International Conference on Computer Vision* (2015), pp. 289–297.
- [Nam+16] S. Nam, Y. Hwang, Y. Matsushita, and S. J. Kim. „A Holistic Approach to Cross-Channel Image Noise Modeling and its Application to Image Denoising“. In: *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2016), pp. 1683–1691 (cit. on p. 13).
- [OF96] B. A. Olshausen and D. J. Field. „Emergence of simple-cell receptive field properties by learning a sparse code for natural images“. In: *Nature* 381.6583 (1996), pp. 607–609 (cit. on p. 12).

- [OF97] B. A. Olshausen and D. J. Field. „Sparse coding with an overcomplete basis set: A strategy employed by V1?“ In: *Vision research* 37.23 (1997), pp. 3311–3325 (cit. on p. 12).
- [Oh+16] T. H. Oh, Y. W. Tai, J. C. Bazin, H. Kim, and I. S. Kweon. „Partial Sum Minimization of Singular Values in Robust PCA: Algorithm and Applications“. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 38.4 (2016), pp. 744–758.
- [OS14] Aäron van den Oord and Benjamin Schrauwen. „The Student-t Mixture as a Natural Image Patch Prior with Application to Image Compression“. In: *Journal of Machine Learning Research* 15 (2014), pp. 2061–2086.
- [Osh+05] S. Osher, M. Burger, D. Goldfarb, J. Xu, and W. Yin. „An iterative regularization method for total variation-based image restoration“. In: *Multiscale Modeling & Simulation* 4.2 (2005), pp. 460–489 (cit. on pp. 11, 12).
- [Pao82] Chia-Ven Pao. „On nonlinear reaction-diffusion systems“. In: *Journal of Mathematical Analysis and Applications* 87.1 (1982), pp. 165–198.
- [Pey+11] G. Peyré, S. Bougleux, and L. D. Cohen. „Non-local regularization of inverse problems“. In: *Inverse Problems and Imaging* 5.2 (2011), pp. 511–530.
- [PM90] P. Perona and J. Malik. „Scale-space and edge detection using anisotropic diffusion“. In: *Pattern Analysis and Machine Intelligence, IEEE Transactions on* 12.7 (1990), pp. 629–639 (cit. on p. 11).
- [Pol+00] Andrea Polesel, Giovanni Ramponi, V John Mathews, et al. „Image enhancement via adaptive unsharp masking“. In: *IEEE transactions on image processing* 9.3 (2000), pp. 505–510.
- [Por+03] J. Portilla, V. Strela, M.J. Wainwright, and E.P. Simoncelli. „Image denoising using scale mixtures of Gaussians in the wavelet domain“. In: *Image Processing, IEEE Transactions on* 12.11 (2003), pp. 1338–1351 (cit. on p. 12).
- [Por04] J. Portilla. „Full blind denoising through noise covariance estimation using Gaussian scale mixtures in the wavelet domain“. In: *IEEE International Conference on Image Processing (ICIP)* 2 (2004), pp. 1217–1220.
- [Pro+09] Matan Protter, Michael Elad, Hiroyuki Takeda, and Peyman Milanfar. „Generalizing the nonlocal-means to super-resolution reconstruction“. In: *IEEE Transactions on image processing* 18.1 (2009), pp. 36–51.
- [Rab05] T. Rabie. „Robust estimation approach for blind denoising“. In: *IEEE Transactions on Image Processing* 14.11 (2005), pp. 1755–1765.

- [Ram+96] Giovanni Ramponi, Norbert K Strobel, Sanjit K Mitra, and Tian-Hu Yu. „Nonlinear unsharp masking methods for image contrast enhancement“. In: *Journal of Electronic Imaging* 5.3 (1996), pp. 353–366.
- [Ram98] Giovanni Ramponi. „A cubic unsharp masking technique for contrast enhancement“. In: *Signal Processing* 67.2 (1998), pp. 211–222.
- [RB09] S. Roth and M. J. Black. „Fields of Experts“. In: *International Journal of Computer Vision* 82.2 (2009), pp. 205–229 (cit. on p. 12).
- [Rec+10] B. Recht, M. Fazel, and P. A. Parrilo. „Guaranteed Minimum-Rank Solutions of Linear Matrix Equations via Nuclear Norm Minimization“. In: *SIAM Review* 52.3 (2010), pp. 471–501.
- [Rie+15] Gernot Riegler, Samuel Schulter, Matthias Ruther, and Horst Bischof. „Conditioned Regression Models for Non-Blind Single Image Super-Resolution“. In: *Proceedings of the IEEE International Conference on Computer Vision* (2015), pp. 522–530.
- [RS03] Rajeev Ramanath and Wesley Snyder. „Adaptive Demosaicking“. In: *Journal of Electronic Imaging* 12 (2003), pp. 633–642.
- [RT16] Xuejian Rong and Yingli Tian. „Adaptive Shrinkage Cascades for Blind Image Deconvolution“. In: *2016 IEEE International Conference on Digital Signal Processing (DSP)* (2016).
- [Rud+92] L. I. Rudin, S. Osher, and E. Fatemi. „Nonlinear total variation based noise removal algorithms“. In: *Physica D: Nonlinear Phenomena* 60.1 (1992), pp. 259–268 (cit. on pp. 11, 12).
- [Rus92] John C. Russ. *The Image Processing Handbook*. Boca Raton, FL, USA: CRC Press, Inc., 1992.
- [Saa+12] Michele A Saad, Alan C Bovik, and Christophe Charrier. „Blind image quality assessment: A natural scene statistics approach in the DCT domain“. In: *IEEE transactions on Image Processing* 21.8 (2012), pp. 3339–3352 (cit. on p. 6).
- [SB97] Stephen M. Smith and J. Michael Brady. „SUSAN—A New Approach to Low Level Image Processing“. In: *International Journal of Computer Vision* 23.1 (1997), pp. 45–78.
- [Sch+10] Uwe Schmidt, Qi Gao, and Stefan Roth. „A generative perspective on mrfs in low-level vision“. In: *Computer Vision and Pattern Recognition (CVPR), 2010 IEEE Conference on* (2010), pp. 1751–1758.
- [Sch+13] Uwe Schmidt, Carsten Rother, Sebastian Nowozin, Jeremy Jancsary, and Stefan Roth. „Discriminative non-blind deblurring“. In: *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (2013), pp. 604–611.

- [SD93] K Sivakumar and Uday B Desai. „Image restoration using a multilayer perceptron with a multilevel sigmoidal function“. In: *IEEE transactions on signal processing* 41.5 (1993), pp. 2018–2022.
- [SJ03] N. Srebro and T. Jaakkola. „Weighted low-rank approximations“. In: *ICML* 3.2003 (2003), pp. 720–727.
- [SR14] U. Schmidt and S. Roth. „Shrinkage Fields for Effective Image Restoration“. In: *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2014), pp. 2774–2781 (cit. on p. 12).
- [Sta+02] J. L. Starck, E. J. Candès, and D. L. Donoho. „The curvelet transform for image denoising“. In: *IEEE Transactions on Image Processing* 11.6 (2002), pp. 670–684 (cit. on p. 11).
- [Sta00] J Alex Stark. „Adaptive image contrast enhancement using generalizations of histogram equalization“. In: *IEEE Transactions on image processing* 9.5 (2000), pp. 889–896.
- [Sun+05] Jian Sun, Lu Yuan, Jiaya Jia, and Heung-Yeung Shum. „Image completion with structure propagation“. In: *ACM Transactions on Graphics (ToG)* 24.3 (2005), pp. 861–868.
- [Sun+08] Jian Sun, Zongben Xu, and Heung-Yeung Shum. „Image super-resolution using gradient profile prior“. In: *Computer Vision and Pattern Recognition, 2008. CVPR 2008. IEEE Conference on* (2008), pp. 1–8.
- [Tim+13] Radu Timofte, Vincent De Smet, and Luc Van Gool. „Anchored neighborhood regression for fast example-based super-resolution“. In: *Proceedings of the IEEE International Conference on Computer Vision* (2013), pp. 1920–1927.
- [TM98] C. Tomasi and R. Manduchi. „Bilateral filtering for gray and color images“. In: *IEEE International Conference on Computer Vision (ICCV)* (1998), pp. 839–846 (cit. on p. 11).
- [Tsi+01] Y. Tsin, Visvanathan Ramesh, and Takeo Kanade. „Statistical calibration of CCD imaging process“. In: *IEEE International Conference on Computer Vision (ICCV)* 1 (2001), pp. 480–487.
- [Vin+08] Pascal Vincent, Hugo Larochelle, Yoshua Bengio, and Pierre-Antoine Manzagol. „Extracting and composing robust features with denoising autoencoders“. In: *Proceedings of the 25th international conference on Machine learning* (2008), pp. 1096–1103.
- [Vin+10] Pascal Vincent, Hugo Larochelle, Isabelle Lajoie, Yoshua Bengio, and Pierre-Antoine Manzagol. „Stacked denoising autoencoders: Learning useful representations in a deep network with a local denoising criterion“. In: *Journal of Machine Learning Research* 11.Dec (2010), pp. 3371–3408.

- [VJ04] Paul Viola and Michael J Jones. „Robust real-time face detection“. In: *International Journal of Computer Vision* 57.2 (2004), pp. 137–154.
- [Wan+03] Zhou Wang, Eero P Simoncelli, and Alan C Bovik. „Multiscale structural similarity for image quality assessment“. In: *Signals, Systems and Computers, 2004. Conference Record of the Thirty-Seventh Asilomar Conference on*. Vol. 2. IEEE. 2003, pp. 1398–1402 (cit. on p. 6).
- [Wan+04] Z. Wang, A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli. „Image quality assessment: from error visibility to structural similarity“. In: *IEEE Transactions on Image Processing* 13.4 (2004), pp. 600–612 (cit. on p. 5).
- [Wan+12] S. Wang, L. Zhang, Y. Liang, and Q. Pan. „Semi-coupled dictionary learning with applications to image super-resolution and photo-sketch synthesis“. In: *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2012), pp. 2216–2223.
- [Wan+13] S. Wang, L. Zhang, and Y. Liang. „Non-local spectral prior model for low-level vision“. In: *ACCV* (2013), pp. 231–244.
- [Wan+15] Zhaowen Wang, Ding Liu, Jianchao Yang, Wei Han, and Thomas Huang. „Deep networks for image super-resolution with sparse prior“. In: *Proceedings of the IEEE International Conference on Computer Vision* (2015), pp. 370–378.
- [WF07] Y. Weiss and W. T. Freeman. „What makes a good model of natural images?“ In: *CVPR* (2007), pp. 1–8 (cit. on p. 12).
- [Wri+10] J. Wright, Y. Ma, J. Mairal, et al. „Sparse representation for computer vision and pattern recognition“. In: *Proceedings of the IEEE* 98.6 (2010), pp. 1031–1044 (cit. on p. 12).
- [Wu83] C. F. Wu. „On the convergence properties of the EM algorithm“. In: *The Annals of Statistics* (1983), pp. 95–103.
- [Xie+12] Junyuan Xie, Linli Xu, and Enhong Chen. „Image denoising and inpainting with deep neural networks“. In: *Advances in Neural Information Processing Systems* (2012), pp. 341–349.
- [Xu+14] Li Xu, Jimmy SJ Ren, Ce Liu, and Jiaya Jia. „Deep convolutional neural network for image deconvolution“. In: *Advances in Neural Information Processing Systems* (2014), pp. 1790–1798.
- [Xu+15] J. Xu, L. Zhang, W. Zuo, D. Zhang, and X. Feng. „Patch Group Based Nonlocal Self-Similarity Prior Learning for Image Denoising“. In: *IEEE International Conference on Computer Vision (ICCV)* (2015), pp. 244–252.

- [Yan+10] Jianchao Yang, John Wright, Thomas S Huang, and Yi Ma. „Image super-resolution via sparse representation“. In: *IEEE transactions on image processing* 19.11 (2010), pp. 2861–2873.
- [YK98] Yu-Li You and M Kaveh. „Image enhancement using fourth order partial differential equations“. In: *Signals, Systems & Computers, 1998. Conference Record of the Thirty-Second Asilomar Conference on* 2 (1998), pp. 1677–1681.
- [Yu+12] G. Yu, G. Sapiro, and S. Mallat. „Solving Inverse Problems With Piecewise Linear Estimators: From Gaussian Mixture Models to Structured Sparsity“. In: *IEEE Transactions on Image Processing* 21.5 (2012), pp. 2481–2499 (cit. on p. 12).
- [Yu+15] Wei Yu, Stefan Heber, and Thomas Pock. „Learning Reaction-Diffusion Models for Image Inpainting“. In: *Pattern Recognition: 37th German Conference, GCPR 2015, Aachen, Germany, October 7-10, 2015, Proceedings* (2015). Ed. by Juergen Gall, Peter Gehler, and Bastian Leibe, pp. 356–367.
- [Zen+15] Kun Zeng, Jun Yu, Ruxin Wang, Cuihua Li, and Dacheng Tao. „Coupled deep autoencoder for single image super-resolution“. In: (2015).
- [Zey+10] Roman Zeyde, Michael Elad, and Matan Protter. „On single image scale-up using sparse-representations“. In: *International conference on curves and surfaces* (2010), pp. 711–730.
- [Zha+12] Kaibing Zhang, Xinbo Gao, Dacheng Tao, and Xuelong Li. „Single image super-resolution with non-local means and steering kernel regression“. In: *IEEE Transactions on Image Processing* 21.11 (2012), pp. 4544–4556.
- [Zha+17] K. Zhang, W. Zuo, Y. Chen, D. Meng, and L. Zhang. „Beyond a gaussian denoiser: Residual learning of deep cnn for image denoising“. In: *IEEE Transactions on Image Processing* (2017).
- [Zho+13] Lin Zhong, Sunghyun Cho, Dimitris Metaxas, Sylvain Paris, and Jue Wang. „Handling noise in single image deblurring using directional filters“. In: *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (2013), pp. 612–619.
- [Zhu+16] F. Zhu, G. Chen, and P.-A. Heng. „From Noise Modeling to Blind Image Denoising“. In: *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2016) (cit. on p. 13).
- [ZI11] M. Zontak and M. Irani. „Internal statistics of a single natural image“. In: *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2011), pp. 977–984.

- [Zon+13] Maria Zontak, Inbar Mosseri, and Michal Irani. „Separating signal from noise using patch recurrence across scales“. In: *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (2013), pp. 1195–1202.
- [Zou+06] H. Zou, T. Hastie, and R. Tibshirani. „Sparse principal component analysis“. In: *Journal of Computational and Graphical Statistics* 15.2 (2006), pp. 265–286.
- [ZW11] D. Zoran and Y. Weiss. „From learning models of natural image patches to whole image restoration“. In: *IEEE International Conference on Computer Vision (ICCV)* (2011), pp. 479–486 (cit. on p. 12).
- [ZW12] D. Zoran and Y. Weiss. „Natural images, Gaussian mixtures and dead leaves“. In: *NIPS* (2012), pp. 1736–1744 (cit. on p. 12).

Websites

- [@Fre10] Free Software Foundation, Inc. *GNU General Public License*. 2010. URL: <http://www.gnu.org/licenses/gpl.html> (visited on May 27, 2011).

