

000
001
002054
055
056003 **External Patch Group Prior Guided Internal Prior Learning for Real Image
004 Denoising**057
058
059005
006
007060
061
062008
009
010063
064
065011
012
013066
067
068

014

069

Abstract

For image denoising problem, the external and internal priors are playing key roles in many different methods. External priors learn from external images to restore noisy images while internal ones exploit priors of given images for denoising. The external priors are more generative and efficient on recovering structures existing in most images while the internal priors are more adaptive on recovering details existed in given noisy images. In this paper, we propose to employ the external patch group prior of images to guide the clustering of internal patch groups, and develop an external dictionary guided internal orthogonal dictionary learning algorithm for real image denoising. The internal orthogonal dictionary learning process has closed-form solutions and hence very efficient for online denoising. The experiments on standard datasets demonstrate that, that the proposed method achieves better performance than other state-of-the-art methods on real image denoising.

1. Introduction

Most vision systems, such as medical imaging and surveillance, need accurate feature extraction from high-quality images. The camera sensors and outdoor low light conditions will unavoidably bring noise to the captured images. The impact is that the image details will be lost or hardly visible. As a result, image denoising is an essential procedure for the reliability of these vision systems. In the research area, image denoising is also an ideal platform for testing natural image models and provides high-quality images for other computer vision tasks such as image registration, segmentation, and pattern recognition, etc.

For several decades, there emerge numerous image denoising methods [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11], and all of them focus mainly on dealing with additive white Gaussian noise (AWGN). In real world, the cameras will undertake high ISO settings for high-speed shots on actions, long exposure for low light on night shots, etc. Under these

situations, the noise is generated in a complex form and also been changed during the in-camera imaging pipeline [12, 13]. Therefore, the noise in real images are much more complex than Gaussian [13, 14]. It depends on camera series, brands, as well as the settings (ISO, shutter speed, and aperture, etc). The models designed for AWGN would become much less effective on real noisy images.

In the last decade, the methods of [15, 16, 17, 18, 19, 20, 13] are developed to deal with real noisy images. Almost all these methods employ a two-stage framework: estimating the parameters of the assumed noise model (usually Gaussian) and performing denoising with the help of the noise modeling and estimation in the first stage. However, the Gaussian assumption is inflexible in describing the complex noise on real noisy images [17]. Although the mixture of Gaussians (MoG) model is possible to approximate any noise distribution [21], estimating its parameters is time consuming via nonparametric Bayesian techniques [20]. To evaluate the performance of these methods on dealing with complex real noise, we apply these methods, with corresponding default parameters, on a real noisy image provided in [13]. The testing image is captured by a Nikon D800 camera when ISO is 3200. The "ground truth" image is also provided with which we can calculate objective measurements such as PSNR and SSIM [22]. The denoised images are listed in Figure 1, from which we can see that these methods either remove the noise or oversmooth the complex details in real noisy image.

The above mentioned methods can be categorized into external methods which learn priors from external images to recover noisy images, and internal ones which exploit priors of given images for denoising. The external priors in natural images are free of the high correlation between noise and signals in real noisy images, while the internal prior is adaptive to the image and can recover better the latent clean image. Combining the priors of external clean images and adaptively of internal testing images can naturally improve the performance of denoising methods, especially on real noisy images. Based on these observations, in this paper, we propose to employ the external patch group prior [10]

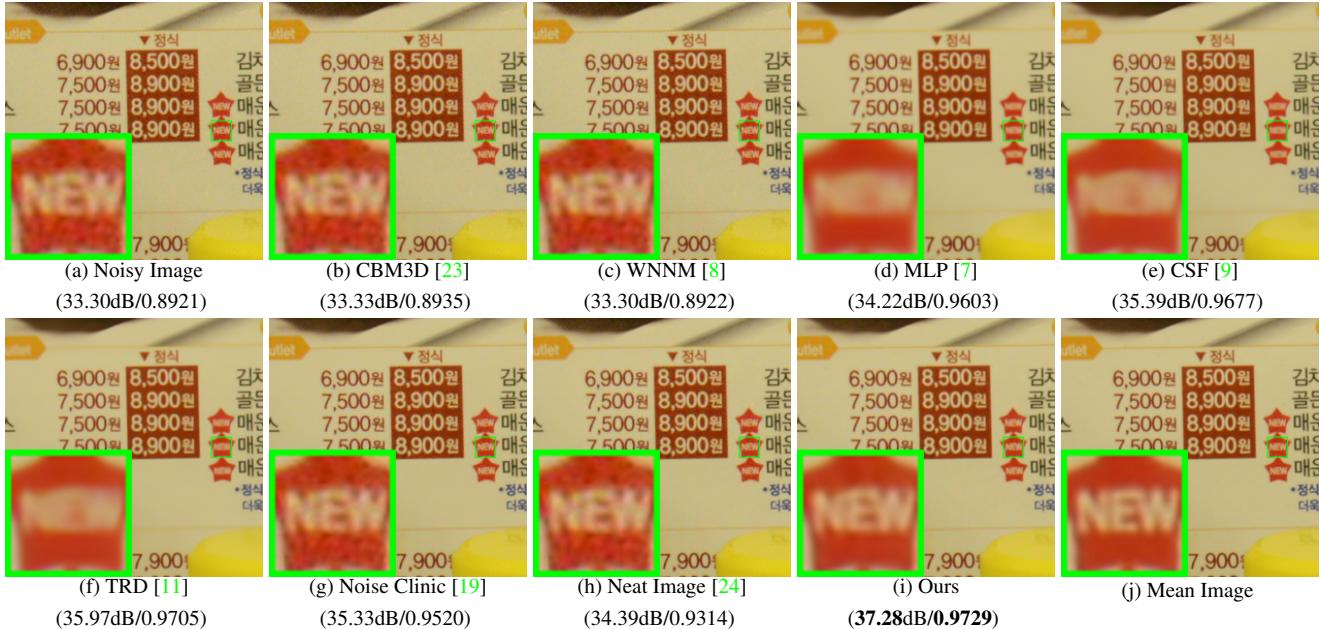


Figure 1. Denoised images of the real noisy image "Nikon D800 ISO 3200 A3" from [13] by different methods. The images are better viewed by zooming in on screen.

of natural clean images to guide the clustering of internal patch groups in given noisy image, and develop an external prior guided internal orthogonal dictionary learning (DL) algorithm for real image denoising. The internal orthogonal DL process includes two alternating stages: updating sparse coefficients and updating orthogonal dictionary. Both of the two stages have closed-form solutions. Hence, our internal DL process is very efficient for online internal denoising. Through comprehensive experiments on real noisy images captured by different cameras and settings, we demonstrate that the proposed method achieves better performance on real image denoising

1.1. Our Contributions

The contributions of this paper are summarized as follows:

- We propose a novel model to learn internal priors adaptive to given images. This model employs the external patch group (PG) prior learned from clean images to guide the internal PG prior learning of given images. The external prior benefits the internal learning on subspace selection and orthogonal dictionary learning.
- The proposed guided internal prior learning method is very efficient. The reason is that both the subspace selection and orthogonal dictionary learning have explicit solutions.
- For real image denoising problem, the proposed method achieves much better performance than other competing methods.

The rest of this paper will be summarized as follows: in Section 2, we briefly introduce the related work; in Section 3, we develop the proposed external prior guided internal prior learning model; in Section 4, we formulate the overall image denoising algorithm; in Section 4, we demonstrate extensive experiments on real image denoising probelm; in Section 5, we conclude our paper and give future work.

2. Related Work

2.1. Patch Group Prior of Natural Images

The Patch Group (PG) prior [10] is proposed to directly model the non-local self similar (NSS) property of natural images. The NSS property is commonly used in image restoration tasks [1, 4, 5, 8, 10]. The PG prior largely reduces the space of images to be modeled when compared to the patch prior [6]. In [10], only the PGs of clean natural images is utilized, while the PGs of noisy input images are ignored. In this paper, we make use of PGs both from external clean images and internal given real noisy image for better denoising performance.

2.2. Internal v.s. External Prior Learning

Learning priors to represent images has been successfully used in image modeling [3, 6, 10, 25, 33]. There are mainly two categories of prior learning methods: 1) External methods pre-learned priors (e.g., dictionaries) from a set of clean images, and the learned priors are used to recover the noisy images [6, 10]. 2) Internal methods directly learned priors from the given noisy image, and the image denoising is simultaneously done with the learning process

108 162
109 163
110 164
111 165
112 166
113 167
114 168
115 169
116 170
117 171
118 172
119 173
120 174
121 175
122 176
123 177
124 178
125 179
126 180
127 181
128 182
129 183
130 184
131 185
132 186
133 187
134 188
135 189
136 190
137 191
138 192
139 193
140 194
141 195
142 196
143 197
144 198
145 199
146 200
147 201
148 202
149 203
150 204
151 205
152 206
153 207
154 208
155 209
156 210
157 211
158 212
159 213
160 214
161 215

[3, 25, 33]. Both the two categories of methods have limitations. The external methods is not adaptive to the noisy image, while the internal methods ignores the information hidden in clean images. In this paper, our goal is to employ the external prior to guide the internal prior learning.

2.3. Real Image Denoising

In the last decade, there are many methods [15, 16, 17, 18, 19, 20, 13] proposed for real image denoising problem. In the seminar work of BLS-GSM [30] for real image denoising, Portilla et al. proposed to use scale mixture of Gaussian in overcomplete oriented pyramids to estimate the latent clean images. In [15], Portilla proposed to use a correlated Gaussian model for noise estimation of each wavelet subband. The work of Rabie [16] modeled the noisy pixels as outliers which are removed via Lorentzian robust estimator [31]. Liu et al. [17] proposed to use ‘noise level function’ to estimate the noise and then use Gaussian conditional random field to obtain the latent clean image. Gong et al. [18] models the noise by mixed ℓ_1 and ℓ_2 norms and remove the noise by sparsity prior in the wavelet transform domain. Later, Lebrun el al. proposed a multiscale denoising algorithm called ‘Noise Clinic’ [19]. This method generalizes the NL-Bayes model [32] to deal with blind noise and achieves state-of-the-art performance. Recently, Zhu et al. proposed a Bayesian model [20] which approximates and removes the noise via Low-Rank Mixture of Gaussians.

3. External Patch Group Prior Guided Internal Prior Learning

In this section, we formulate the framework of external patch group (PG) prior guided internal orthogonal dictionary learning. We first introduce the patch PG leaning on clean natural RGB images. Then we propose to employ the external PG prior to guide the internal clustering and orthogonal dictionary learning (DL). The orthogonal DL has alternative closed-form solutions in term of updating sparse coefficients and dictionary. Finally, we discuss the advantages of our proposed external PG prior guided internal orthogonal dictionary learning algorithm.

3.1. External Patch Group Prior Learning

Natural images often demonstrate repetitive local patterns, this nonlocal self-similarity (NSS) property is a key successful factor for many image denoising methods [1, 4, 5, 33, 8, 10]. In this section, we formulate the Patch Group prior learned on natural color images. Similar to [10], the patch group (PG) is defined as a group of similar patches to the local patch. The patch group mean is destracted, and hence different groups patches can share similar PGs. In this way, the space natural image patches to be modeled is largely reduced.

In this work, each local patch extracted from RGB images is of size $p \times p \times 3$. Then we search the M most similar patches $\{\mathbf{x}_m\}_{m=1}^M$ around each local patch through Euclidean distance, in a local window of size $W \times W$. The $\mathbf{x}_m \in \mathbb{R}^{3p^2 \times 1}$ is a patch vector formed by combining the 3 patch vectors (of size $p^2 \times 1$) in R, G, B channels. The mean vector of this PG is $\boldsymbol{\mu} = \frac{1}{M} \sum_{m=1}^M \mathbf{x}_m$, and the group mean subtracted PG is defined as $\bar{\mathbf{X}} \triangleq \{\bar{\mathbf{x}}_m = \mathbf{x}_m - \boldsymbol{\mu}\}, m = 1, \dots, M$. Assume we have extracted N PGs from a set of external natural images, and the n -th PG is defined as $\bar{\mathbf{X}}_n \triangleq \{\bar{\mathbf{x}}_{n,m}\}_{m=1}^M, n = 1, \dots, N$. We employ the Gaussian Mixture Model (GMM) to learn the external patch group based NSS prior. In this model, the likelihood of the n -th PG $\{\bar{\mathbf{X}}_n\}$ can be calculated as

$$P(\bar{\mathbf{X}}_n) = \sum_{k=1}^K \pi_k \prod_{m=1}^M \mathcal{N}(\bar{\mathbf{x}}_{n,m} | \boldsymbol{\mu}_k, \Sigma_k), \quad (1)$$

where K is the number of Gaussians and the parameters π_k , $\boldsymbol{\mu}_k$, Σ_k are mixture weight, mean vector, and covariance matrix of the k -th Gaussian, respectively. By assuming that all the PGs are independently sampled, the overall objective log-likelihood function is

$$\ln \mathcal{L} = \sum_{n=1}^N \ln \left(\sum_{k=1}^K \pi_k \prod_{m=1}^M \mathcal{N}(\bar{\mathbf{x}}_{n,m} | \boldsymbol{\mu}_k, \Sigma_k) \right). \quad (2)$$

We maximize the above objective function via EM algorithm [35] and finally obtain the GMM model with learned parameters. Similar to [10], the mean vector of each cluster is natural zeros, i.e., $\boldsymbol{\mu}_k = \mathbf{0}$.

Now, we have clustered the PGs extracted from external clean images into K Gaussians or subspaces. For notation simplicity, we ignore the index of subspace k . To better characterize each subspace, we perform singular value decomposition (SVD) on the covariance matrix:

$$\boldsymbol{\Sigma} = \mathbf{U}_e \mathbf{S}_e \mathbf{V}_e^T. \quad (3)$$

The singular vectors in \mathbf{U}_e are employed as the external orthogonal dictionary to guide the internal orthogonal dictionary learning (the singular values are employed as prior weights for sparse coding which will be discussed in Section 4). For a dictionary \mathbf{D} , its *mutual incoherence* $\mu(\mathbf{D})$ [36] defined by

$$\mu(\mathbf{D}) = \max_{i=j} \frac{|\mathbf{d}_i^T \mathbf{d}_j|}{\|\mathbf{d}_i\|_2 \|\mathbf{d}_j\|_2} \quad (4)$$

is a measure of quality of dictionary (lower is better). The dictionary \mathbf{U}_e always has 0 *mutual incoherence* and hence better quality than non-orthogonal dictionaries.

3.2. External Prior Guided Internal Prior Learning

After the external patch group (PG) prior is learned, we can employ it to guide the internal PG prior learning for the given testing (real noisy) image. The guidance mainly comes from two aspects. One aspect is that the external prior can guide the internal noisy PGs to be assigned to most

324 suitable Gaussians or subspaces. And for each subspace, the
 325 other aspect is to guide the orthogonal dictionary learning of
 326 internal noisy PGs.
 327

328 3.2.1 Guided Internal Subspace Selection

329 Given a real noisy image, we extract the noisy PGs and
 330 corresponding mean vectors. Each mean substracted PG is defined
 331 as $\bar{\mathbf{Y}} \triangleq \{\bar{\mathbf{x}}_m\}_{m=1}^M$. Noted that, different from the external
 332 PGs, the mean vectors of the internal noisy PGs are saved for recovering.
 333 For adaptivity, we project the PG $\bar{\mathbf{Y}}$ into its most suitable Gaussian component (subspace) of the
 334 GMM learned on external PGs. The subspace most suitable for $\bar{\mathbf{Y}}$ is selected by firstly calculating the posterior probability
 335 of " $\bar{\mathbf{Y}}$ belonging to the k th Gaussian component":
 336

$$P(k|\bar{\mathbf{Y}}) = \frac{\prod_{m=1}^M \mathcal{N}(\bar{\mathbf{y}}_m|\mathbf{0}, \Sigma_k)}{\sum_{l=1}^K \prod_{m=1}^M \mathcal{N}(\bar{\mathbf{y}}_m|\mathbf{0}, \Sigma_l)}, \quad (5)$$

337 and then choosing the component with the maximum A-
 338 posteriori (MAP) probability $\ln P(k|\bar{\mathbf{Y}})$.
 339

340 3.2.2 Guided Internal Orthogonal Dictionary Learning

341 Assume we have assigned all internal noisy PGs to their
 342 corresponding most suitable Gaussians or subspaces in
 343 $\{\mathcal{N}(\mathbf{0}, \Sigma_k)\}_{k=1}^K$. For each subspace, we consider to utilize the external orthogonal dictionary to guide the learning
 344 of an orthogonal dictionary $\mathbf{D} := [\mathbf{D}_e \mathbf{D}_i] \in \mathbb{R}^{3p^2 \times 3p^2}$.
 345 This dictionary has two parts: the external part $\mathbf{D}_e \in \mathbb{R}^{3p^2 \times (3p^2 - r)}$ is consisted of the first $(3p^2 - r)$ columns of
 346 the singular vector matrix \mathbf{U}_e obtained from the external prior by Equ. (3), and the internal part \mathbf{D}_i is consisted of
 347 adaptive dictionary atoms learned from the internal noisy
 348 PGs. The learning is performed under the sparse coding
 349 framework (along with which the denoising of real noisy
 350 image is simultaneously done) as follows:
 351

$$\begin{aligned} & \min_{\mathbf{D}_i \in \mathbb{R}^{3p^2 \times r}, \mathbf{A} \in \mathbb{R}^{3p^2 \times MN}} \|\mathbf{Y} - [\mathbf{D}_e \mathbf{D}_i]\mathbf{A}\|_F^2 + \lambda \|\mathbf{A}\|_1 \\ & \text{s.t. } \mathbf{D}_i^T \mathbf{D}_i = \mathbf{I}_r, \mathbf{D}_e^T \mathbf{D}_i = \mathbf{0}, \end{aligned} \quad (6)$$

352 Noted that $\mathbf{D}_e = \emptyset$ if $r = 3p^2$ and $\mathbf{D}_e = \mathbf{U}_e$ if $r = 0$. The
 353 dictionary $\mathbf{D} = [\mathbf{D}_e \mathbf{D}_i]$ is orthogonal by checking that:
 354

$$\mathbf{D}^T \mathbf{D} = \begin{bmatrix} \mathbf{D}_e^T \\ \mathbf{D}_i^T \end{bmatrix} [\mathbf{D}_e \mathbf{D}_i] = \begin{bmatrix} \mathbf{D}_e^T \mathbf{D}_e & \mathbf{D}_e^T \mathbf{D}_i \\ \mathbf{D}_i^T \mathbf{D}_e & \mathbf{D}_i^T \mathbf{D}_i \end{bmatrix} = \mathbf{I} \quad (7)$$

355 Similar to K-SVD [3], we employ an alternating iterative
 356 framework to solve the optimization problem (6). Specifically,
 357 we initialize the orthogonal dictionary as $\mathbf{D}^{(0)} = \mathbf{U}_e$
 358 and for $t = 0, 1, \dots, T - 1$, alternatively do:
 359

360 **Updating Sparse Coefficients:** given the orthogonal dic-
 361 tioanry $\mathbf{D}_i^{(t)}$, we update the sparse coefficients via solving
 362

$$\mathbf{A}^{(t)} := \arg \min_{\mathbf{A} \in \mathbb{R}^{3p^2 \times MN}} \|\mathbf{Y} - [\mathbf{D}_e \mathbf{D}_i^{(t)}]\mathbf{A}\|_F^2 + \lambda \|\mathbf{A}\|_1. \quad (8)$$

363 Since dictionary $\mathbf{D}_t = [\mathbf{D}_e \mathbf{D}_i^{(t)}]$ is orthogonal, the prob-
 364 lem (8) has closed-form solution $\mathbf{A}^{(t)} = T_\lambda(\mathbf{D}_t^T \mathbf{Y})$, where
 365

366 $T_\lambda(\bullet) = \text{sgn}(\bullet) \odot \max(\bullet, \lambda)$ is soft-thresholding function
 367 and \odot is element-wise product.
 368

369 **Updating Orthogonal Dictionary:** given the sparse coeffi-
 370 cients $\mathbf{A}^{(t)}$, we update the orthogonal dictionary via solving
 371

$$\begin{aligned} \mathbf{D}_i^{(t+1)} &:= \arg \min_{\mathbf{D}_i \in \mathbb{R}^{3p^2 \times r}} \|\mathbf{Y} - [\mathbf{D}_e \mathbf{D}_i]\mathbf{A}^{(t)}\|_F^2 \\ &\text{s.t. } \mathbf{D}_i^T \mathbf{D}_i = \mathbf{I}_r, \mathbf{D}_e^T \mathbf{D}_i = \mathbf{0}, \end{aligned} \quad (9)$$

372 Here we ignore the index (t) for notation simplicity. The
 373 sparse coefficient matrix $\mathbf{A} = [\mathbf{A}_e^T \mathbf{A}_i^T]^T$ also has two
 374 parts: the external part \mathbf{A}_e and the internal part \mathbf{A}_i denote the
 375 coefficients over external dictionary \mathbf{D}_e and internal
 376 dictionary \mathbf{D}_i , respectively. According to the Proposition
 377 2.2 in [34], the problem (9) has a closed-form solution
 378 $\mathbf{D}_i^* = \mathbf{U}_i \mathbf{V}_i^T$, where \mathbf{U}_i and \mathbf{V}_i are the orthogonal matrices
 379 obtained by the following SVD
 380

$$(\mathbf{I} - \mathbf{D}_e \mathbf{D}_e^T) \mathbf{Y} \mathbf{A}_i^T = \mathbf{U}_i \mathbf{S}_i \mathbf{V}_i^T \quad (10)$$

381 3.3. Discussions

382 Here we take a detailed analysis on the guiance of the
 383 external patch group (PG) prior for the internal noisy PGs
 384 of given real noisy images. The guidance comes from at
 385 least three aspects: 1) the external prior guides the internal
 386 PGs to be clustered into suitable subspaces through MAP in
 387 Equ. (5). The guided subspace clustering is more efficient
 388 than directly clustering the internal noisy PGs via k-means
 389 or Gaussian Mixture Model (GMM). The reason is, by guid-
 390 ance we only need calculate the probabilities via Equ. (5)
 391 for all noisy PGs while by internal clustering via GMM we
 392 need perform EM algorithm [35]. 2) under the guidance
 393 of external orthogonal dictionary, the learned internal dic-
 394 tioary are also orthogonal and more adaptive to the given
 395 noisy images. This makes the learning process very effi-
 396 cient. Besides, the learned orthogonal dictionary can also
 397 makes the denoising process very efficient. 3) the singular
 398 values obtained by SVD in Equ. (3) reflect the prior im-
 399 portance of the atoms in learned dictionary and hence can
 400 be used as adaptive parameters in the sparse coding frame-
 401 work for real image denoising.
 402

4. The Denoising Algorithm

4.1. Fast Patch Group Searching by Integral Image

422 The searching of patch groups in images is inefficient
 423 if we search non-local similar patches to each local patch.
 424 To speed up the searching process and make our proposed
 425 method faster, we employ the technique of 'Summed Area
 426 Table' [37] for efficient PG searching. The SAT permits
 427 to evaluate the sum of pixel values in rectangular regions
 428 of the image with four operations, regardless of the region
 429 size. That is to say, we do not need do distance measure for
 430 each patch. It was first proposed under the name of summed
 431 area table[38]

432 **4.2. Prior Weights for Sparse Coding** 486

433 To remove the real noise, we employ the sparse coding 486
 434 framework. And in order to be adaptive to the input image 487
 435 we employ the internal learned \mathbf{U} of each cluster as 488
 436 an adaptive dictionary to represent the structural variations 489
 437 of the PGs in that cluster. Since the \mathbf{U} is orthonormal, its 490
 438 *mutual incoherence* is naturally 0 and therefore better than 491
 439 other redundant dictionaries. 492
 440

$$\min_{\boldsymbol{\alpha}} \|\bar{\mathbf{y}}_m - \mathbf{U}\boldsymbol{\alpha}\|_2^2 + \sum_{i=1}^{3p^2} \lambda_i |\alpha_i|. \quad (11)$$

441 The i th entry of the regularization parameter λ_i 493

$$\lambda_i = \lambda / (\mathbf{S}_i + \varepsilon), \quad (12)$$

442 where ε is a small positive number to avoid dividing by zero. 494
 443 Since the dictionary \mathbf{U} is orthonormal, it is not difficult to 495
 444 find out that (4) has a closed-form solution (detailed derivation 496
 445 can be found in the supplementary material): 497

$$\hat{\boldsymbol{\alpha}} = \text{sgn}(\mathbf{U}^T \bar{\mathbf{y}}_m) \odot \max(|\mathbf{U}^T \bar{\mathbf{y}}_m| - \Lambda, 0), \quad (13)$$

446 where $\Lambda = [\lambda_1, \lambda_2, \dots, \lambda_{3p^2}]$ is the vector of regularization 500
 447 parameter and $\text{sgn}(\bullet)$ is the sign function, \odot means 501
 448 element-wise multiplication, and $|\mathbf{U}^T \bar{\mathbf{y}}_m|$ is the absolute 502
 449 value of each entry of vector $|\mathbf{U}^T \bar{\mathbf{y}}_m|$. The closed-form 503
 450 solution makes our weighted sparse coding process very 504
 451 efficient. 505

452 **4.3. The Overall Algorithm** 506

453 With the solution $\hat{\boldsymbol{\alpha}}$ in (7), the clean patch in a PG can 507
 454 be estimated as $\hat{\mathbf{x}}_m = \mathbf{D}\hat{\boldsymbol{\alpha}} + \mu_y$. Then the clean image $\hat{\mathbf{x}}$ 508
 455 can be reconstructed by aggregating all the estimated PGs. 509
 456 In practice, we could perform the above denoising 510
 457 procedures for several iterations for better denoising outputs. 511
 458 In iteration t , we use the iterative regularization strategy [39] 512
 459 to add back to the recovered image $\hat{\mathbf{x}}^{(t-1)}$ some estimation 513
 460 residual in iteration $t-1$. The proposed denoising algorithm 514
 461 is summarized in Algorithm 1 (Alg. 1). 515

462 **5. Experiments** 516

463 In this section, we perform real image denoising experiments 517
 464 on three standard datasets. The first dataset is real noisy 518
 465 images with mean images as ground truths provided 519
 466 by [13], some samples are shown in Figure 3. The second 520
 467 dataset is provided by the website of Noise Clinic [19]. The 521
 468 third dataset is provided by the Commercial software 522
 469 Neat Image [24]. The second and third dataset do not have 523
 470 ground truth images. 524

471 **5.1. Implementation Details** 525

472 Our proposed method contains two stages, the external 526
 473 prior guided internal subspace learning stage and the adap- 527

474 **Alg. 1: External Prior Guided Internal Orthogonal 528**
 475 Dictionary Learning for Denoising 529

476 **Input:** Noisy image \mathbf{y} , PG-GMM model 530

477 1. Initialization: $\hat{\mathbf{x}}^{(0)} = \mathbf{y}, \mathbf{y}^{(0)} = \mathbf{y}$; 531

478 **for** $t = 1 : IteNum$ **do** 532

479 **for** each PG \mathbf{Y} **do** 533

480 2. Calculate group mean μ_y and form PG $\bar{\mathbf{Y}}$; 534

481 3. Gaussian component selection via (3); 535

482 **end for** 536

483 **for** each Internal Subspace **do** 537

484 4. Internal Subspace Learning by (4); 538

485 5. Recover each patch in all PGs via $\hat{\mathbf{x}}_m = \mathbf{D}\hat{\boldsymbol{\alpha}} + \mu_y$; 539

486 **end for** 540

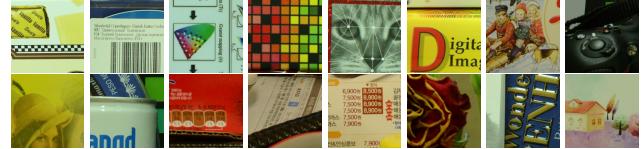
487 6. Aggregate the recovered PGs of all subspaces to form 541
 488 the recovered image $\hat{\mathbf{x}}^{(t)}$; 542

489 **end for** 543

490 **Output:** The recovered image $\hat{\mathbf{x}}^{(IteNum)}$. 544



491 Figure 2. Some testing images in the dataset [13]. 515



516 Figure 3. Some cropped images of the dataset [13]. 520

521 In the learning stage, there are 4 parameters: the patch size p , the number of patches in a PG 522
 523 M , the window size W for PG searching and the number of 524
 525 clusters K . We set $p = 6$ (hence the patch size is $6 \times 6 \times 3$), 526
 526 $M = 10$, $W = 31$, $K = 32$. We extracted about 3.6 million 527
 527 PGs from the Kodak PhotoCD Dataset, which includes 528
 528 24 high quality color images, to train the external prior via 529
 529 PG-GMM. In the denoising stage, the parameter $\lambda = 0.002$ 530
 530 is used to regularize the sparse term. The δ in iterative 531
 531 regularization is set as $\delta = 0.09$. 532

533 **5.2. Comparison on External and Internal methods** 534

535 In this subsection, we compared the proposed external 536
 536 prior guided internal subspace learning model on real image 537
 537 denoising. The three methods are evaluated on the dataset 538
 538 provided in [13]. We calculate the PSNR, SSIM [22] and 539
 539 visual quality of these three methods. We also compare the 540

540 Table 1. Average PSNR(dB)/SSIM results of external, internal,
 541 and guided methods on 60 cropped real noisy images in [13].
 542

	Noisy	Offline	Online	Guided
PSNR	34.51	38.19	38.07	38.55
SSIM	0.8718	0.9663	0.9625	0.9675

543 speed. The PSNR and SSIM results on 60 cropped images
 544 from [13] are listed in Table 1. The images are cropped into
 545 size of 500×500 for better illustration. We also compare
 546 the three methods on visual quality in Figure 5.2. Compare
 547 the denoised images listed in Figure 5.2 and Figure 5.2, we
 548 can see that the Offline method is better at edges, smooth
 549 regions while the Online method is good at complex textures.
 550 The reason is two folds. Firstly, the Offline method is
 551 learned on clean images and hence is better at representing
 552 edges, structuals, and smooth area. The online method is
 553 influenced by the noise and hence some noise cannot be
 554 removed. Secondly, the Online method is better at recovering
 555 complex area sicne they could learn adaptive dictionaries
 556 for the specific area. The Offline method cannot recover the
 557 complex area since they did not learn the similar structures
 558 from the external natural clean images.

559 5.3. Comparison With other Competing Methods

560 We compare with previous state-of-the-art Gaussian
 561 noise removal methods such as BM3D [4], WNNM [8],
 562 MLP [7], CSF [9], and the recently proposed TRD [11].
 563 We also compare with three competing real image denoising
 564 methods such as Noise Clinic, Neat Image, and the CC-
 565 Noise method proposed recently. The commercial software
 566 Neat Image [24] first estimates the parameters of noise via
 567 a large flat area and then filters the noise accordingly. All
 568 these methods need noise estimation which is vary hard to
 569 perform if there is no uniform regions are available in the
 570 testing image. The NeatImage will fail to perform automatical
 571 parameters settings if there is no uniform regions. ¹

572 We the competing denoising methods from various
 573 research directions on two datasets. Both the two datasets
 574 comes from the [13]. The first dataset contains 17 images
 575 of size over 7000×5000 . Since this dataset contains repeti-
 576 tive contents across different images, we crop 60 small im-
 577 ages of size 500×500 from these 17 images in [13]. The
 578 PSNR and SSIM resluts are listed in Table 3. The number
 579 in red color and blue color means the best and second best
 580 results, respectively. From the Table 3, we can see that the
 581 external based method can already surpass largely the pre-
 582 vious denoising methods. The improvement on PSNR over
 583 the second best method, i.e., TRD, is 0.44dB. The

584 ¹To compare with CCNoise, we first transform the denoised images
 585 into double format.

586 5.4. Discussion on Parameter λ

587 The proposed method only has a key parameter, namely
 588 the regularization paramters λ . To demonstrate that the pro-
 589 posed method is robust to the variance of λ , we vary the
 590 parameter λ across a wide range and obtain the PSNR and
 591 SSIM results as a function of the parameter λ . The re-
 592 sults is shown in Figure 8, from which we can see that the
 593 proposed method can achieve a PSNR (SSIM) over 38.5dB
 594 (0.9660) when λ varies from 0.0015 to 0.0025. This shows
 595 that the proposed method is indeed robust to the chosen of
 596 the paramter λ .

597 6. Conclusion and Future Work

598 In the future, we will evaluate the proposed method on
 599 other computer vision tasks such as single image super-
 600 resolution, photo-sketch synthesis, and cross-domain im-
 601 age recognition. Our proposed method can be improved
 602 if we use better training images, fine tune the parameters
 603 via cross-validation. We believe that our framework can
 604 be useful not just for real image denoising, but for image
 605 super-resolution, image cross-style synthesis, and recogni-
 606 tion tasks. This will be our line of future work.

607 7. References

- [1] A. Buades, B. Coll, and J. M. Morel. A non-local algorithm for image denoising. *CVPR*, pages 60–65, 2005. [1](#), [2](#), [3](#)
- [2] S. Roth and M. J. Black. Fields of Experts. *International Journal of Computer Vision*, 82(2):205–229, 2009. [1](#)
- [3] M. Elad and M. Aharon. Image denoising via sparse and redundant representations over learned dictionaries. *Image Processing, IEEE Transactions on*, 15(12):3736–3745, 2006. [1](#), [2](#), [3](#), [4](#)
- [4] K. Dabov, A. Foi, V. Katkovnik, and K. Egiazarian. Image denoising by sparse 3-D transform-domain collaborative filtering. *Image Processing, IEEE Transactions on*, 16(8):2080–2095, 2007. [1](#), [2](#), [3](#), [6](#)
- [5] J. Mairal, F. Bach, J. Ponce, G. Sapiro, and A. Zisserman. Non-local sparse models for image restoration. *ICCV*, pages 2272–2279, 2009. [1](#), [2](#), [3](#)
- [6] D. Zoran and Y. Weiss. From learning models of natural image patches to whole image restoration. *ICCV*, pages 479–486, 2011. [1](#), [2](#)
- [7] Harold C Burger, Christian J Schuler, and Stefan Harmeling. Image denoising: Can plain neural networks compete with bm3d? *Computer Vision and Pattern Recognition (CVPR), 2012 IEEE Conference on*, pages 2392–2399, 2012. [1](#), [2](#), [6](#)
- [8] S. Gu, L. Zhang, W. Zuo, and X. Feng. Weighted nuclear norm minimization with application to image denoising. *CVPR*, pages 2862–2869, 2014. [1](#), [2](#), [3](#), [6](#)
- [9] U. Schmidt and S. Roth. Shrinkage fields for effective im-
 age restoration. *Computer Vision and Pattern Recognition (CVPR), 2014 IEEE Conference on*, pages 2774–2781, June 2014. [1](#), [2](#), [6](#)

648

649

650

651

652

653

654

655

656

657

658

659

660

661

662

663

664

665

666

667

668

669

670

671

672

673

674

675

676

677

678

679

680

681

682

683

684

685

686

687

688

689

690

691

692

693

694

695

696

697

698

699

700

701

702

703

704

705

706

707

708

709

710

711

712

713

714

715

716

717

718

719

720

721

722

723

724

725

726

727

728

729

730

731

732

733

734

735

736

737

738

739

740

741

742

743

744

745

746

747

748

749

750

751

752

753

754

755



Figure 4. Denoised images of the image "Nikon D600 ISO 3200 C1" by different methods. The images are better to be zoomed in on screen.

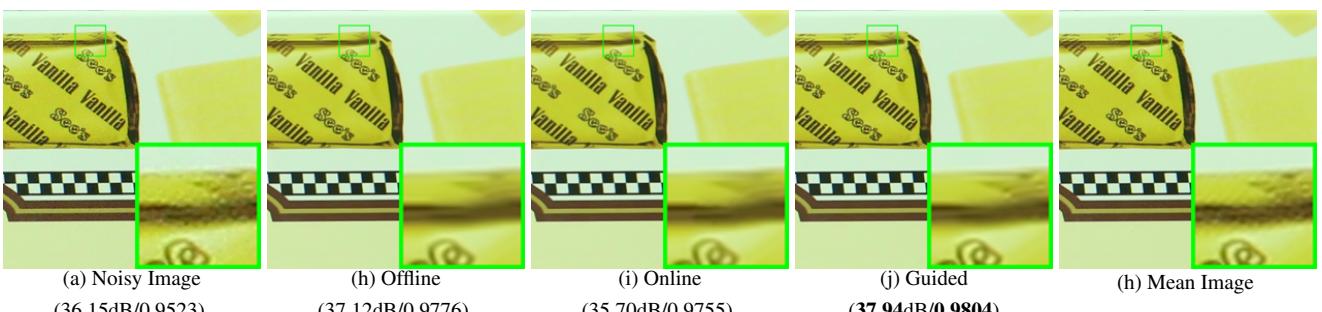


Figure 5. Denoised images of the image "Canon EOS 5D Mark3 ISO 3200 C1" by different methods. The images are better to be zoomed in on screen.

- [10] J. Xu, L. Zhang, W. Zuo, D. Zhang, and X. Feng. Patch group based nonlocal self-similarity prior learning for image denoising. *2015 IEEE International Conference on Computer Vision (ICCV)*, pages 244–252, 2015. [1](#), [2](#), [3](#)
- [11] Yunjin Chen, Wei Yu, and Thomas Pock. On learning optimized reaction diffusion processes for effective image restoration. *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 5261–5269, 2015. [1](#), [2](#), [6](#)
- [12] S. J. Kim, H. T. Lin, Z. Lu, S. Ssstrunk, S. Lin, and M. S. Brown. A new in-camera imaging model for color computer vision and its application. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 34(12):2289–2302, Dec 2012. [1](#)
- [13] Seonghyeon Nam, Youngbae Hwang, Yasuyuki Matsushita, and Seon Joo Kim. A holistic approach to cross-channel image noise modeling and its application to image denoising. *Proc. Computer Vision and Pattern Recognition (CVPR)*, pages 1683–1691, 2016. [1](#), [2](#), [3](#), [5](#), [6](#), [8](#)
- [14] Glenn E Healey and Raghava Kondepudy. Radiometric ccd camera calibration and noise estimation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 16(3):267–276, 1994. [1](#)
- [15] J. Portilla. Full blind denoising through noise covariance estimation using gaussian scale mixtures in the wavelet domain. *Image Processing, 2004. ICIP '04. 2004 International Conference on*, 2:1217–1220, 2004. [1](#), [3](#)

- [16] Tamer Rabie. Robust estimation approach for blind denoising. *Image Processing, IEEE Transactions on*, 14(11):1755–1765, 2005. [1](#), [3](#)
- [17] C. Liu, R. Szeliski, S. Bing Kang, C. L. Zitnick, and W. T. Freeman. Automatic estimation and removal of noise from a single image. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 30(2):299–314, 2008. [1](#), [3](#)
- [18] Zheng Gong, Zuowei Shen, and Kim-Chuan Toh. Image restoration with mixed or unknown noises. *Multiscale Modeling & Simulation*, 12(2):458–487, 2014. [1](#), [3](#)
- [19] M. Lebrun, M. Colom, and J.-M. Morel. Multiscale image blind denoising. *Image Processing, IEEE Transactions on*, 24(10):3149–3161, 2015. [1](#), [2](#), [3](#), [5](#)
- [20] Fengyuan Zhu, Guangyong Chen, and Pheng-Ann Heng. From noise modeling to blind image denoising. *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2016. [1](#), [3](#)
- [21] C. M. Bishop. *Pattern recognition and machine learning*. New York: Springer, 2006. [1](#)
- [22] Z. Wang, A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli. Image quality assessment: from error visibility to structural similarity. *IEEE Transactions on Image Processing*, 13(4):600–612, 2004. [1](#), [5](#)
- [23] K. Dabov, A. Foi, V. Katkovnik, and K. Egiazarian. Color image denoising via sparse 3d collaborative filtering with grouping constraint in luminance-chrominance space. *IEEE International Conference on Image Processing*, 1, 2007. [1](#)

756 Table 2. Average PSNR(dB) results of different methods on 60 cropped real noisy images captured in [13].
757

	Noisy	CBM3D	WNNM	MLP	CSF	TRD	NI	NC	Guided	Guided2
PSNR	34.51	34.58	34.52	36.19	37.40	37.75	36.53	37.57	38.72	38.90
SSIM	0.8718	0.8748	0.8743	0.9470	0.9598	0.9617	0.9241	0.9514	0.9694	0.9702

761 Table 3. Average PSNR(dB) results of different methods on 15 cropped real noisy images used in [13].
762

Camera Settings	Noisy	CBM3D	WNNM	MLP	CSF	TRD	NI	NC	CC	Guided2
Canon 5D Mark III ISO = 3200	37.00	37.08	37.09	33.92	35.68	36.20	37.68	38.76	38.37	40.50
	33.88	33.94	33.93	33.24	34.03	34.35	34.87	35.69	35.37	37.22
	33.83	33.88	33.90	32.37	32.63	33.10	34.77	35.54	34.91	37.13
Nikon D600 ISO = 3200	33.28	33.33	33.34	31.93	31.78	32.28	34.12	35.57	34.98	35.34
	33.77	33.85	33.79	34.15	35.16	35.34	35.36	36.70	35.95	36.69
	34.93	35.02	34.95	37.89	39.98	40.51	38.68	39.28	41.15	39.17
Nikon D800 ISO = 1600	35.47	35.54	35.57	33.77	34.84	35.09	37.34	38.01	37.99	38.82
	35.71	35.79	35.77	35.89	38.42	38.65	38.57	39.05	40.36	40.98
	34.81	34.92	34.95	34.25	35.79	35.85	37.87	38.20	38.30	38.90
Nikon D800 ISO = 3200	33.26	33.34	33.31	37.42	38.36	38.56	36.95	38.07	39.01	38.69
	32.89	32.95	32.96	34.88	35.53	35.76	35.09	35.72	36.75	36.82
	32.91	32.98	32.96	38.54	40.05	40.59	36.91	36.76	39.06	38.80
Nikon D800 ISO = 6400	29.63	29.66	29.71	33.59	34.08	34.25	31.28	33.49	34.61	33.31
	29.97	30.01	29.98	31.55	32.13	32.38	31.38	32.79	33.21	33.18
	29.87	29.90	29.95	31.42	31.52	31.76	31.40	32.86	33.22	33.35
Average PSNR	33.41	33.48	33.48	34.32	35.33	35.65	35.49	36.43	36.88	37.26
Average SSIM	0.8483	0.8511	0.8512	0.9113	0.9250	0.9280	0.9126	0.9364	0.9481	0.9505

782 [24] Neatlab ABSoft. Neat image. <https://ni.neatvideo.com/home>. 2, 5, 6783 [25] G. Yu, G. Sapiro, and S. Mallat. Solving inverse problems
784 with piecewise linear estimators: From Gaussian mixture
785 models to structured sparsity. *IEEE Transactions on Image
786 Processing*, 21(5):2481–2499, 2012. 2, 3787 [26] Daniel Glasner, Shai Bagon, and Michal Irani. Super-
788 resolution from a single image. *ICCV*, 2009.789 [27] Maria Zontak, Inbar Mosseri, and Michal Irani. Separating
790 signal from noise using patch recurrence across scales. *Proceedings of the IEEE Conference on Computer Vision and
791 Pattern Recognition*, pages 1195–1202, 2013.792 [28] Tomer Michaeli and Michal Irani. Blind deblurring using internal patch recurrence. *European Conference on Computer
793 Vision*, pages 783–798, 2014.794 [29] Y. Bahat and M. Irani. Blind dehazing using internal patch
795 recurrence. *IEEE International Conference on Computational Photography (ICCP)*, pages 1–9, May 2016.796 [30] J. Portilla, V. Strela, M.J. Wainwright, and E.P. Simoncelli.
797 Image denoising using scale mixtures of Gaussians in the
798 wavelet domain. *Image Processing, IEEE Transactions on*,
799 12(11):1338–1351, 2003. 3800 [31] Peter J Huber. *Robust statistics*. Springer, 2011. 3801 [32] M. Lebrun, A. Buades, and J. M. Morel. A nonlocal bayesian
802 image denoising algorithm. *SIAM Journal on Imaging Sciences*,
803 6(3):1665–1688, 2013. 3804 [33] W. Dong, L. Zhang, G. Shi, and X. Li. Nonlocally centralized
805 sparse representation for image restoration. *Image Processing, IEEE Transactions on*, 22(4):1620–1630, 2013. 2,
806 3807 [34] Chenglong Bao, Jian-Feng Cai, and Hui Ji. Fast sparsity-
808 based orthogonal dictionary learning for image restoration.
809 *Proceedings of the IEEE International Conference on Computer Vision*, pages 3384–3391, 2013. 4810 [35] A. P. Dempster, N. M. Laird, and D. B. Rubin. Maximum
811 likelihood from incomplete data via the EM algorithm. *Journal of the Royal Statistical Society. Series B (methodological)*,
812 pages 1–38, 1977. 3, 4813 [36] David L Donoho and Michael Elad. Optimally sparse representation in general (nonorthogonal) dictionaries via 1 minimization.
814 *Proceedings of the National Academy of Sciences*, 100(5):2197–2202, 2003. 3815 [37] Franklin C. Crow. Summed-area tables for texture mapping.
816 *SIGGRAPH Comput. Graph.*, 18(3):207–212, January 1984.
817 4818 [38] Paul Viola and Michael J Jones. Robust real-time face detection.
819 *International journal of computer vision*, 57(2):137–154, 2004. 4820 [39] S. Osher, M. Burger, D. Goldfarb, J. Xu, and W. Yin. An iterative
821 regularization method for total variation-based image
822 restoration. *Multiscale Modeling & Simulation*, 4(2):460–
823 489, 2005. 5

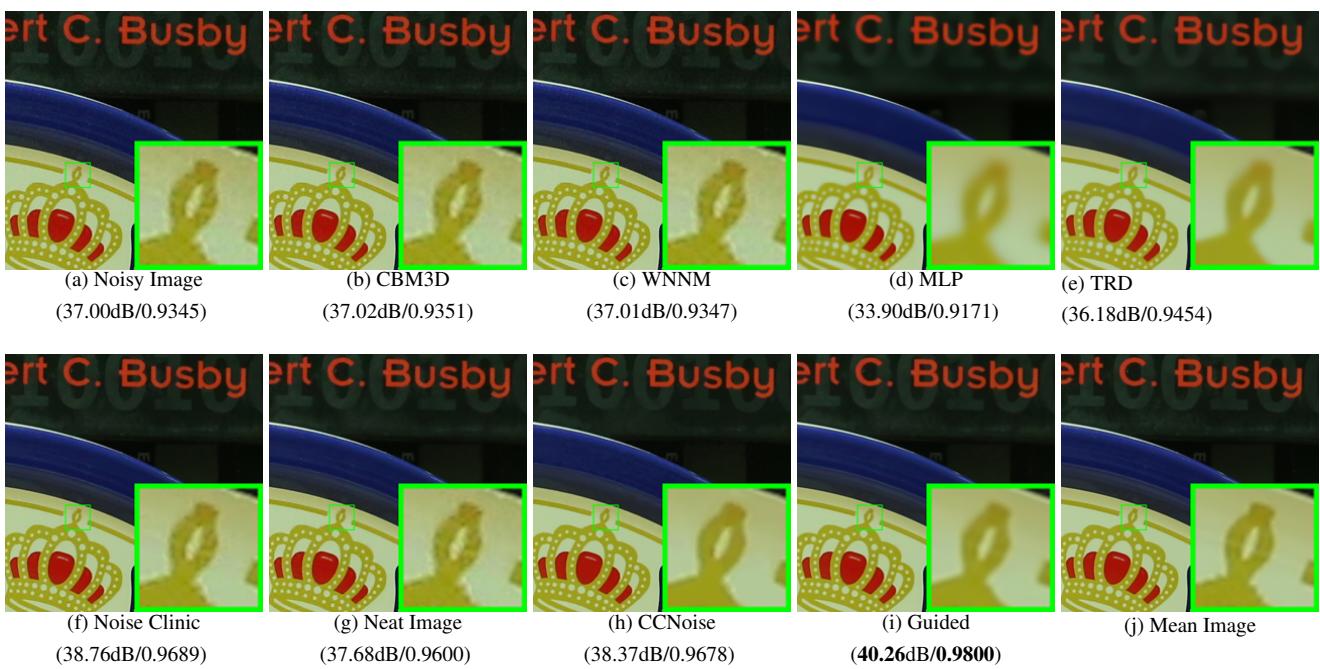


Figure 6. Denoised images of the image "Canon 5D Mark 3 ISO 3200 1" by different methods. The images are better to be zoomed in on screen.

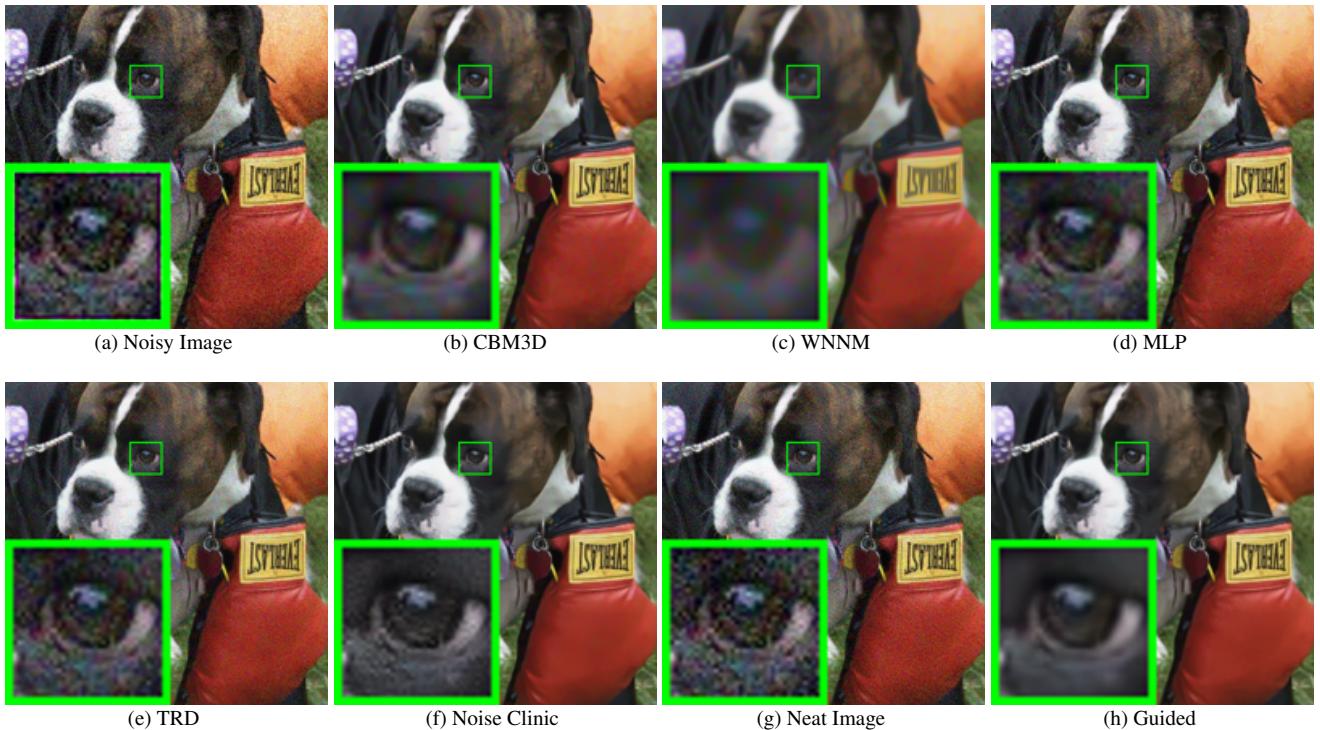


Figure 7. Denoised images of the image "5dmark3iso32003" by different methods. The images are better to be zoomed in on screen.

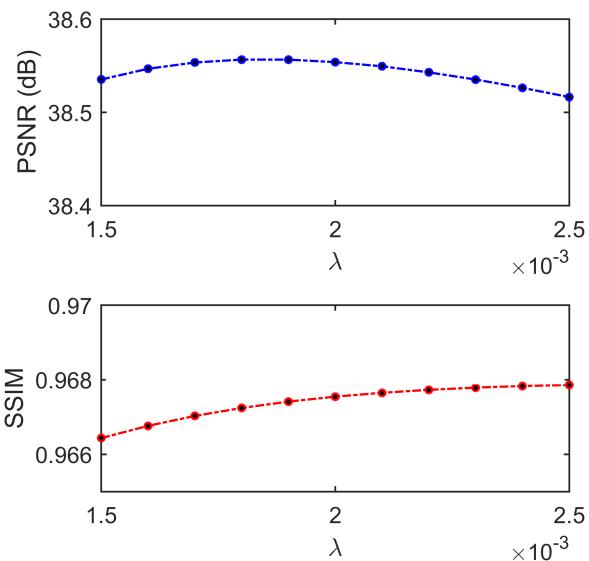


Figure 8. The PSNR/SSIM results as a function of the parameter λ .