

000 054
 001 055
 002 056
 003 057
 004 058
 005 059
 006 060
 007 061
 008 062
 009 063
 010 064
 011 065
 012 066
 013 067
 014 068
 015 069
 016 070
 017 071
 018 072
 019 073
 020 074
 021 075
 022 076
 023 077
 024 078
 025 079
 026 080
 027 081
 028 082
 029 083
 030 084
 031 085
 032 086
 033 087
 034 088
 035 089
 036 090
 037 091
 038 092
 039 093
 040 094
 041 095
 042 096
 043 097
 044 098
 045 099
 046 100
 047 101
 048 102
 049 103
 050 104
 051 105
 052 106
 053 107

Supplementary File to “Multi-channel Weighted Nuclear Norm Minimization for Real Color Image Denoising”

Anonymous ICCV submission

Paper ID 572

In this supplementary file, we provide:

1. The proof of the Theorem 1 in the main paper.
2. More denoising results on the 24 high quality images from the Kodak PhotoCD dataset.
3. More visual comparisons of denoised images by different methods on the real noisy images of the dataset [1].
4. More visual comparisons of denoised images by different methods on the real noisy images of the dataset [2].

1. Proof of Theorem 1.

Theorem 1. Assume that the weights in w are in a non-descending order, the sequence $\{\mathbf{X}_k\}$, $\{\mathbf{Z}_k\}$, and $\{\mathbf{A}_k\}$ generated in Algorithm 1 satisfy:

$$(a) \lim_{k \rightarrow \infty} \|\mathbf{X}_{k+1} - \mathbf{Z}_{k+1}\|_F = 0; \quad (b) \lim_{k \rightarrow \infty} \|\mathbf{X}_{k+1} - \mathbf{X}_k\|_F = 0; \quad (c) \lim_{k \rightarrow \infty} \|\mathbf{Z}_{k+1} - \mathbf{Z}_k\|_F = 0. \quad (1)$$

Proof. 1. Firstly, we prove that the sequence $\{\mathbf{A}_k\}$ generated by Algorithm 1 is upper bounded. Let $\mathbf{X}_{k+1} + \rho_k^{-1} \mathbf{A}_k = \mathbf{U}_k \Sigma_k \mathbf{V}_k^\top$ be its singular value decomposition (SVD) [3] in the $(k+1)$ -th iteration. According to Corollary 1 of [4], we can have the SVD of \mathbf{Z}_{k+1} as $\mathbf{Z}_{k+1} = \mathbf{U}_k \hat{\Sigma}_k \mathbf{V}_k^\top = \mathbf{U}_k \mathcal{S}_{\frac{w}{\rho_k}}(\Sigma_k) \mathbf{V}_k^\top$. Then we have

$$\|\mathbf{A}_{k+1}\|_F = \|\mathbf{A}_k + \rho_k (\mathbf{X}_{k+1} - \mathbf{Z}_{k+1})\|_F = \rho_k \|\rho_k^{-1} \mathbf{A}_k + \mathbf{X}_{k+1} - \mathbf{Z}_{k+1}\|_F \quad (2)$$

$$= \rho_k \|\mathbf{U}_k \Sigma_k \mathbf{V}_k^\top - \mathbf{U}_k \mathcal{S}_{\frac{w}{\rho_k}}(\Sigma_k) \mathbf{V}_k^\top\|_F = \rho_k \|\Sigma_k - \mathcal{S}_{\frac{w}{\rho_k}}(\Sigma_k)\|_F \quad (3)$$

$$= \rho_k \sqrt{\sum_i (\Sigma_k^{ii} - \mathcal{S}_{\frac{w}{\rho_k}}(\Sigma_k^{ii}))^2} \leq \rho_k \sqrt{\sum_i \left(\frac{w_i}{\rho_k}\right)^2} = \sqrt{\sum_i w_i^2}. \quad (4)$$

The inequality in the second last step can be proved as follows: given the diagonal matrix Σ_k , we define Σ_k^{ii} as the i -th element of Σ_k^{ii} . If $\Sigma_k^{ii} \geq \frac{w_i}{\rho_k}$, we have $\mathcal{S}_{\frac{w}{\rho_k}}(\Sigma_k^{ii}) = \Sigma_k^{ii} - \frac{w_i}{\rho_k} \geq 0$. If $\Sigma_k^{ii} < \frac{w_i}{\rho_k}$, we have $\mathcal{S}_{\frac{w}{\rho_k}}(\Sigma_k^{ii}) = 0 < \Sigma_k^{ii} + \frac{w_i}{\rho_k}$. After all, we have $|\Sigma_k^{ii} - \mathcal{S}_{\frac{w}{\rho_k}}(\Sigma_k^{ii})| \leq \frac{w_i}{\rho_k}$ and hence the inequality holds true. Hence, the sequence $\{\mathbf{A}_k\}$ is upper bounded.

2. Secondly, we prove that the sequence of Lagrangian function $\{\mathcal{L}(\mathbf{X}_{k+1}, \mathbf{Z}_{k+1}, \mathbf{A}_k, \rho_k)\}$ is also upper bounded. Since the global optimal solution of \mathbf{X} and \mathbf{Z} in corresponding subproblems, we always have $\mathcal{L}(\mathbf{X}_{k+1}, \mathbf{Z}_{k+1}, \mathbf{A}_k, \rho_k) \leq \mathcal{L}(\mathbf{X}_k, \mathbf{Z}_k, \mathbf{A}_k, \rho_k)$. Based on the updating rule that $\mathbf{A}_{k+1} = \mathbf{A}_k + \rho_k (\mathbf{X}_{k+1} - \mathbf{Z}_{k+1})$, we have $\mathcal{L}(\mathbf{X}_{k+1}, \mathbf{Z}_{k+1}, \mathbf{A}_{k+1}, \rho_{k+1}) = \mathcal{L}(\mathbf{X}_{k+1}, \mathbf{Z}_{k+1}, \mathbf{A}_k, \rho_k) + \langle \mathbf{A}_{k+1} - \mathbf{A}_k, \mathbf{X}_{k+1} - \mathbf{Z}_{k+1} \rangle + \frac{\rho_{k+1} - \rho_k}{2} \|\mathbf{X}_{k+1} - \mathbf{Z}_{k+1}\|_F^2 = \mathcal{L}(\mathbf{X}_{k+1}, \mathbf{Z}_{k+1}, \mathbf{A}_k, \rho_k) + \frac{\rho_{k+1} + \rho_k}{2\rho_k^2} \|\mathbf{A}_{k+1} - \mathbf{A}_k\|_F^2$. Since the sequence $\{\|\mathbf{A}_k\|_F\}$ is upper bounded, the sequence $\{\|\mathbf{A}_{k+1} - \mathbf{A}_k\|_F\}$ is also upper bounded. Denote by a the upper bound of $\{\|\mathbf{A}_{k+1} - \mathbf{A}_k\|_F\}$, we have $\mathcal{L}(\mathbf{X}_{k+1}, \mathbf{Z}_{k+1}, \mathbf{A}_{k+1}, \rho_{k+1}) \leq \mathcal{L}(\mathbf{X}_1, \mathbf{Z}_1, \mathbf{A}_0, \rho_0) + a \sum_{k=0}^{\infty} \frac{\rho_{k+1} + \rho_k}{2\rho_k^2} = \mathcal{L}(\mathbf{X}_1, \mathbf{Z}_1, \mathbf{A}_0, \rho_0) + a \sum_{k=0}^{\infty} \frac{\mu+1}{2\mu^k \rho_0} \leq \mathcal{L}(\mathbf{X}_1, \mathbf{Z}_1, \mathbf{A}_0, \rho_0) + \frac{a}{\rho_0} \sum_{k=0}^{\infty} \frac{1}{\mu^{k-1}}$. The last inequality holds since $\mu+1 < 2\mu$. Since $\sum_{k=0}^{\infty} \frac{1}{\mu^{k-1}} < \infty$, the sequence of Lagrangian function $\mathcal{L}(\mathbf{X}_{k+1}, \mathbf{Z}_{k+1}, \mathbf{A}_{k+1}, \rho_{k+1})$ is upper bound.

3. Thirdly, we prove that the sequences of $\{\mathbf{X}_k\}$ and $\{\mathbf{Z}_k\}$ are upper bounded. Since $\|\mathbf{W}(\mathbf{Y} - \mathbf{X})\|_F^2 + \|\mathbf{Z}\|_{w,*} = \mathcal{L}(\mathbf{X}_k, \mathbf{Z}_k, \mathbf{A}_{k-1}, \rho_{k-1}) - \langle \mathbf{A}_k, \mathbf{X}_k - \mathbf{Z}_k \rangle - \frac{\rho_k}{2} \|\mathbf{X}_k - \mathbf{Z}_k\|_F^2 = \mathcal{L}(\mathbf{X}_k, \mathbf{Z}_k, \mathbf{A}_{k-1}, \rho_{k-1}) + \frac{1}{2\rho_k} (\|\mathbf{A}_{k-1}\|_F^2 - \|\mathbf{A}_k\|_F^2)$. Thus $\{\mathbf{W}(\mathbf{Y} - \mathbf{X}_k)\}$ and $\{\mathbf{Z}_k\}$ are upper bounded, and hence the sequence $\{\mathbf{X}_k\}$ is bounded by the Cauchy-Schwarz inequality

Table 1. PSNR(dB) results of different denoising methods on 24 natural images.

Image#	$\sigma_r = 5, \sigma_g = 30, \sigma_b = 15$								
	CBM3D	MLP	TNRD	NI	NC	WNNM-1	WNNM-2	WNNM-3	MC-WNNM
1	27.25	28.06	28.62	25.00	29.55	28.91	27.95	28.15	
2	29.70	31.30	32.70	27.80	29.69	33.23	31.60	31.73	
3	30.34	31.98	34.07	28.02	31.93	34.60	33.68	33.52	
4	29.47	31.10	32.56	27.70	32.56	33.23	31.85	31.90	
5	27.31	28.59	29.35	26.14	30.00	29.70	29.00	28.91	
6	28.20	29.10	29.90	26.15	28.81	30.38	29.46	29.62	
7	29.73	31.60	33.46	27.22	31.63	33.85	33.29	32.86	
8	27.47	28.16	28.91	25.34	30.16	29.89	29.24	29.03	
9	30.07	31.63	33.55	27.86	31.54	33.88	33.20	32.95	
10	29.96	31.37	33.20	27.74	33.44	33.74	33.02	32.74	
11	28.73	29.85	30.87	26.98	30.16	31.22	30.14	30.21	
12	30.20	31.50	33.31	27.97	31.69	33.80	32.71	32.65	
13	26.18	26.69	26.98	25.14	27.97	27.27	26.42	26.62	
14	27.86	29.07	29.87	26.67	29.21	30.17	29.14	29.30	
15	29.91	31.58	33.13	28.04	31.17	33.71	32.34	32.36	
16	29.29	30.35	31.54	27.46	32.18	32.12	31.05	31.21	
17	29.50	31.09	32.52	27.81	32.80	32.77	32.00	31.85	
18	27.72	28.74	29.36	26.57	28.63	29.73	28.76	28.89	
19	28.98	30.18	31.35	27.25	29.79	31.98	30.77	30.95	
20	30.63	31.78	33.27	27.89	29.52	33.62	32.55	32.58	
21	28.50	29.58	30.54	26.86	31.71	30.80	30.03	30.03	
22	28.61	29.78	30.82	27.19	30.50	31.19	29.82	30.10	
23	30.60	32.66	35.06	28.17	32.82	35.23	34.37	33.94	
24	27.97	28.81	29.61	26.01	30.75	30.25	29.35	29.39	
Average	28.92	30.19	31.44	27.04	30.76	31.89	30.91	30.89	32.70

and triangle inequality. We can obtain that $\lim_{k \rightarrow \infty} \|\mathbf{X}_{k+1} - \mathbf{Z}_{k+1}\|_F = \lim_{k \rightarrow \infty} \rho_k^{-1} \|\mathbf{A}_{k+1} - \mathbf{A}_k\|_F = 0$ and the equation (a) is proved.

4. Then we can prove that $\lim_{k \rightarrow \infty} \|\mathbf{X}_{k+1} - \mathbf{X}_k\|_F = \lim_{k \rightarrow \infty} \|(\mathbf{W}^\top \mathbf{W} + \frac{\rho_k}{2} \mathbf{I})^{-1} (\mathbf{W}^\top \mathbf{W} \mathbf{Y} - \mathbf{W}^\top \mathbf{W} \mathbf{Z}_k - \frac{1}{2} \mathbf{A}_k) - \rho_k^{-1} (\mathbf{A}_k - \mathbf{A}_{k-1})\|_F \leq \lim_{k \rightarrow \infty} \|(\mathbf{W}^\top \mathbf{W} + \frac{\rho_k}{2} \mathbf{I})^{-1} (\mathbf{W}^\top \mathbf{W} \mathbf{Y} - \mathbf{W}^\top \mathbf{W} \mathbf{Z}_k - \frac{1}{2} \mathbf{A}_k)\|_F + \rho_k^{-1} \|\mathbf{A}_k - \mathbf{A}_{k-1}\|_F = 0$ and hence (b) is proved.

5. Finally, (c) can be proved by checking that $\lim_{k \rightarrow \infty} \|\mathbf{Z}_{k+1} - \mathbf{Z}_k\|_F = \lim_{k \rightarrow \infty} \|\mathbf{X}_k + \rho_k^{-1} \mathbf{A}_{k-1} - \mathbf{Z}_k + \mathbf{X}_{k+1} - \mathbf{X}_k + \rho_k^{-1} \mathbf{A}_{k-1} + \rho_k^{-1} \mathbf{A}_k - \rho_k^{-1} \mathbf{A}_{k+1}\|_F \leq \lim_{k \rightarrow \infty} \|\Sigma_{k-1} - \mathcal{S}_{w/\rho_{k-1}}(\Sigma_{k-1})\|_F + \|\mathbf{X}_{k+1} - \mathbf{X}_k\|_F + \rho_k^{-1} \|\mathbf{A}_{k-1} + \mathbf{A}_{k+1} - \mathbf{A}_k\|_F = 0$, where $\mathbf{U}_{k-1} \Sigma_{k-1} \mathbf{V}_{k-1}^\top$ is the SVD of the matrix $\mathbf{X}_k + \rho_{k-1} \mathbf{A}_{k-1}$. \square

2. More denoising results on the 24 high quality images from the Kodak PhotoCD dataset

In the main paper, we have given the PSNR results of the competing methods on the 24 high quality images from the Kodak PhotoCD dataset when the noise standard deviations are $\sigma_r = 40, \sigma_g = 20, \sigma_b = 30$. Here we provide more denoising results on this dataset. In Tables ??-??, we give more PSNR results on these images when the noise standard deviations are $\sigma_r = 5, \sigma_g = 30, \sigma_b = 15$ in Table 1 and $\sigma_r = 30, \sigma_g = 10, \sigma_b = 50$ in Table 2, respectively. In Figures 1-??, we give the visual comparisons of the denoised images by different methods.

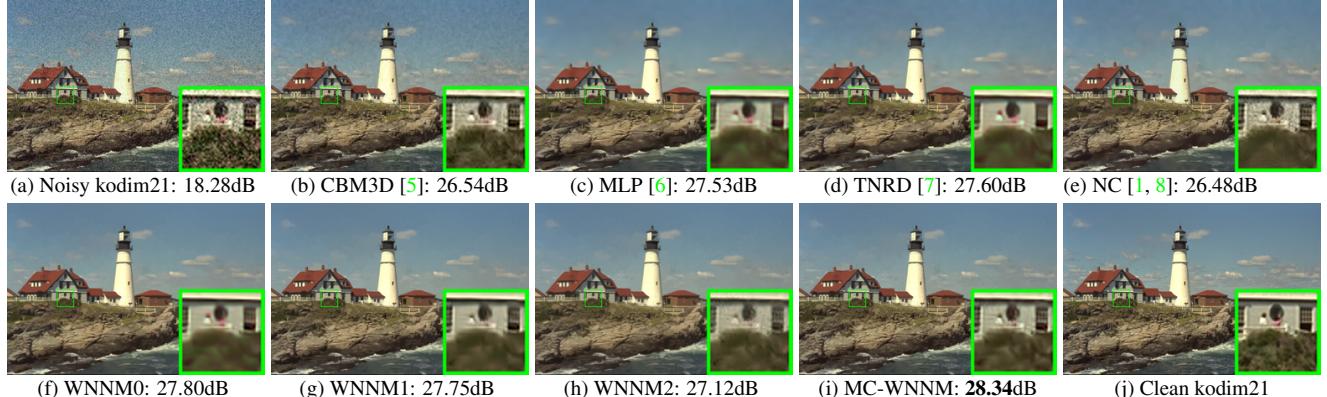
Fig. 1 shows a scene denoised by the compared methods. We can see that the methods of CBM3D and NC would remain some noise on the recovered images. The methods of MLP, TNRD, and “WNNM0”, which process separately the channels of color images, would over-smooth the images and generate false colors or artifacts. The method “WNNM1”, which process jointly the channels of color images, would not generate false colors, but still over-smooth the image. The “WNNM2”, which is the WNNM model solved by ADMM algorithm, would remain some noise on the image. By employing the proposed MC-WNNM model, our method preserves the structures (e.g., textures in windows and grass) better across the R, G, B channels and generate less artifacts than other denoising methods, leading to visually pleasant outputs.

3. More visual comparisons of denoised images by different methods on the real noisy images of the dataset [1]

In this section, we give more comparisons of the state-of-the-art denoising methods on the dataset [1]. The real noisy images in dataset [1] have no “ground truth” images and hence we only compare the visual quality of the denoised images by

Table 2. PSNR(dB) results of different denoising methods on 24 natural images.

Image#	CBM3D	MLP	TNRD	NI	NC	WNNM-1	WNNM-2	WNNM-3	MC-WNNM
1	23.38	26.49	26.50	24.82	23.59	26.40	25.60		
2	25.19	30.94	30.90	26.82	27.79	30.89	29.75		
3	25.39	32.03	32.09	27.52	27.41	32.20	31.17		
4	24.96	30.55	30.47	27.34	27.00	30.74	29.71		
5	23.29	26.65	26.73	25.72	26.67	26.74	25.98		
6	24.09	27.76	27.70	26.10	26.12	27.85	26.96		
7	24.89	30.70	30.72	27.17	28.07	30.91	29.94		
8	23.30	26.12	26.27	25.59	26.11	26.87	26.33		
9	25.20	31.35	31.31	27.74	28.33	31.30	30.45		
10	25.13	31.01	31.05	27.60	28.53	31.12	30.17		
11	24.54	28.79	28.82	26.72	24.40	28.73	27.79		
12	25.43	31.60	31.60	27.82	29.01	31.59	30.62		
13	22.50	24.71	24.73	24.96	23.36	24.70	23.85		
14	23.91	27.69	27.72	26.26	23.08	27.62	26.81		
15	25.45	31.09	31.05	27.36	28.49	31.29	30.21		
16	24.89	29.79	29.73	27.35	27.10	29.84	28.85		
17	25.12	30.26	30.24	27.15	27.54	30.11	29.35		
18	23.83	27.26	27.26	26.05	26.15	27.32	26.18		
19	24.63	29.40	29.39	27.06	27.41	29.78	28.87		
20	26.43	31.16	31.27	26.43	26.92	31.25	30.43		
21	24.24	28.26	28.27	26.66	27.18	28.22	27.45		
22	24.51	29.03	29.06	26.83	27.64	29.02	27.81		
23	25.55	32.87	32.75	27.60	23.75	32.58	31.46		
24	23.85	27.06	27.13	25.86	27.05	27.50	26.63		
Average	24.57	29.27	29.28	26.69	26.61	29.36	28.43		29.90

Figure 1. Denoised images of different methods on the image “kodim21” degraded by AWGN with different standard derivations of $\sigma_r = 40, \sigma_g = 20, \sigma_b = 30$ on R, G, B channels, respectively. The images are better to be zoomed in on screen.

different methods. As can be seen from Figures ??-??, our proposed method performs better than the competing methods.

4. More visual comparisons of denoised images by different methods on the real noisy images of the dataset [2]

In this section, we provide more comparisons of the proposed method with the state-of-the-art denoising methods on the 15 cropped real noisy images used in [2]. In this dataset, each scene was shot 500 times under the same camera and camera setting. The mean image of the 500 shots is roughly taken as the “ground truth”, with which the PSNR can be computed. As can be seen from Figures 8-10, in most cases, our proposed method achieves better performance than the the competing methods. This validates the effectiveness of our proposed external prior guided internal prior learning framework for real noisy image denoising.

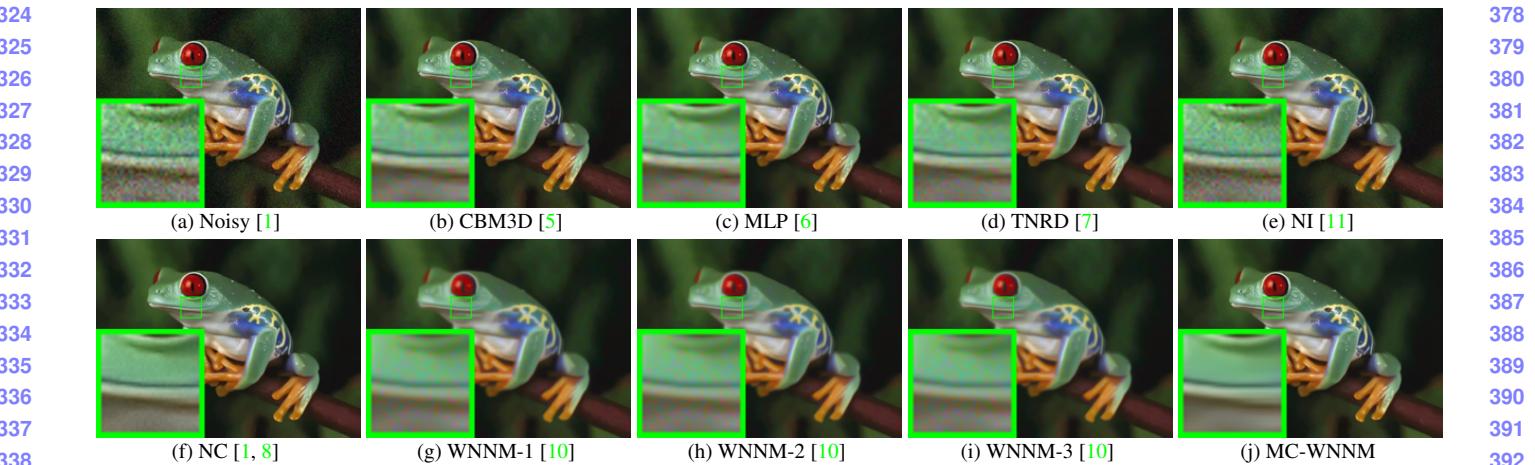


Figure 2. Denoised images of the real noisy image “Frog” [1] by different methods. The images are better to be zoomed in on screen.

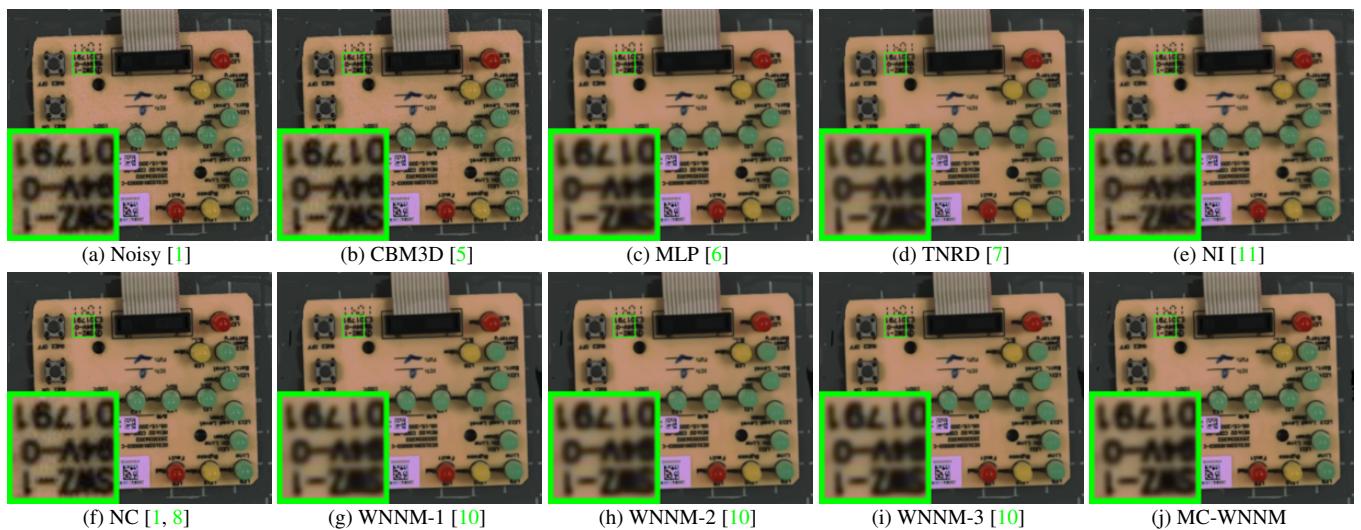


Figure 3. Denoised images of the real noisy image “Circuit” [1] by different methods. The images are better to be zoomed in on screen.

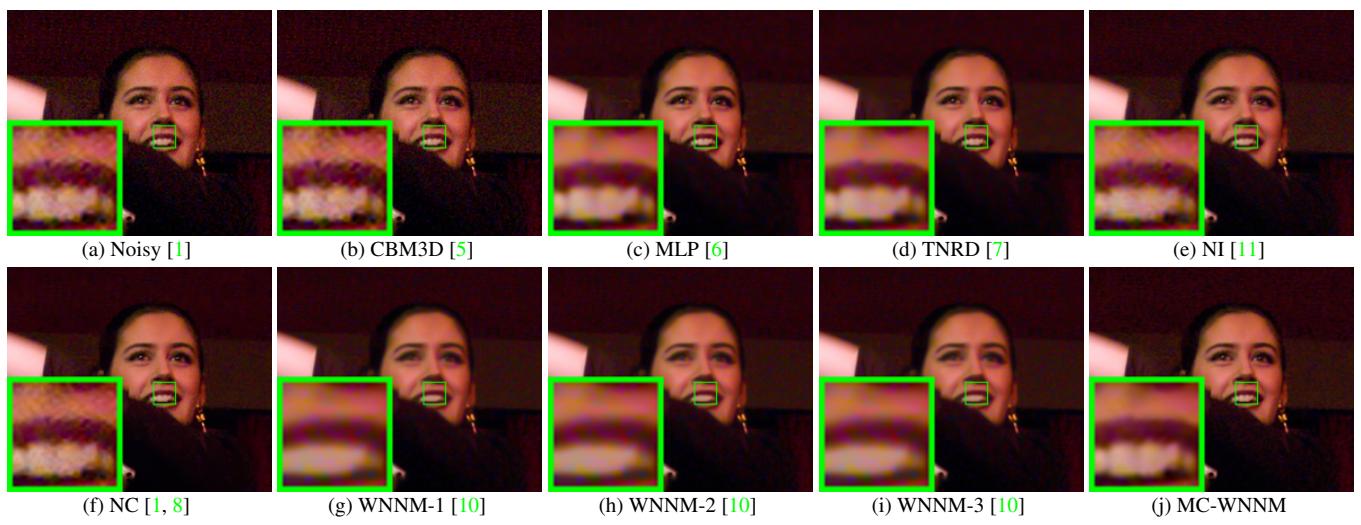


Figure 4. Denoised images of the real noisy image “Woman” [1] by different methods. The images are better to be zoomed in on screen.

432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501

(a) Noisy [1] (b) CBM3D [5] (c) MLP [6] (d) TNRD [7] (e) NI [11]
(f) NC [1, 8] (g) WNNM-1 [10] (h) WNNM-2 [10] (i) WNNM-3 [10] (j) MC-WNNM

Figure 5. Denoised images of the real noisy image ‘‘Vehicle’’ [1] by different methods. The images are better to be zoomed in on screen.

449
450
451
452
453
454
455
456
457
458 (a) Noisy [2]: 33.88dB (b) CBM3D [5, 9]: 33.91dB (c) TNRD [7]: 34.33dB (d) NI [11]: 34.87dB (e) NC [1, 8]: 35.69dB
459
460
461
462
463
464
465
466
467 (f) CC [2]: 35.37dB (g) WNNM-2 [10]: 33.88dB (h) WNNM-3 [10]: 33.88dB (i) Ours: 37.05dB (j) Mean Image [2]

Figure 6. Denoised images of a region cropped from the real noisy image “Canon 5D Mark 3 ISO 3200 2” [2] by different methods. The images are better to be zoomed in on screen.

References

- [1] 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. 1, 2, 3, 4, 5, 6, 7
 - [2] 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. *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pages 1683–1691, 2016. 1, 3, 5, 6, 7
 - [3] C. Eckart and G. Young. The approximation of one matrix by another of lower rank. *Psychometrika*, 1(3):211–218, 1936. 1
 - [4] S. Gu, Q. Xie, D. Meng, W. Zuo, X. Feng, and L. Zhang. Weighted nuclear norm minimization and its applications to low level vision. *International Journal of Computer Vision*, pages 1–26, 2016. 1
 - [5] 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 (ICIP)*, pages 313–316, 2007. 3, 4, 5, 6, 7

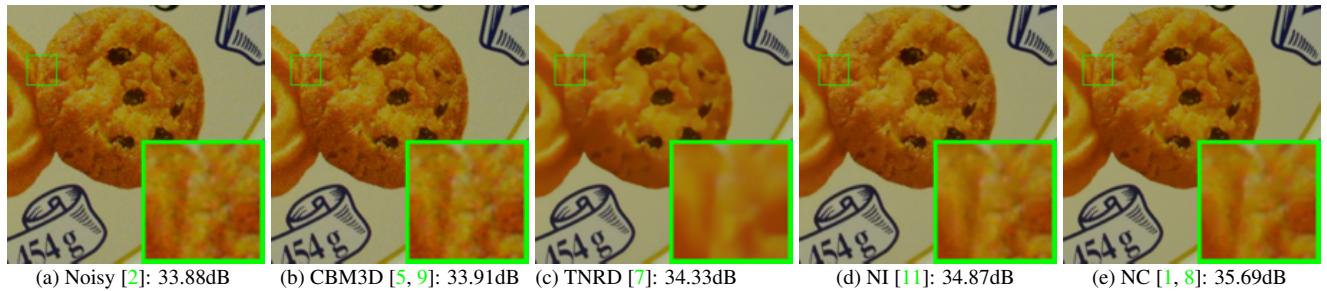
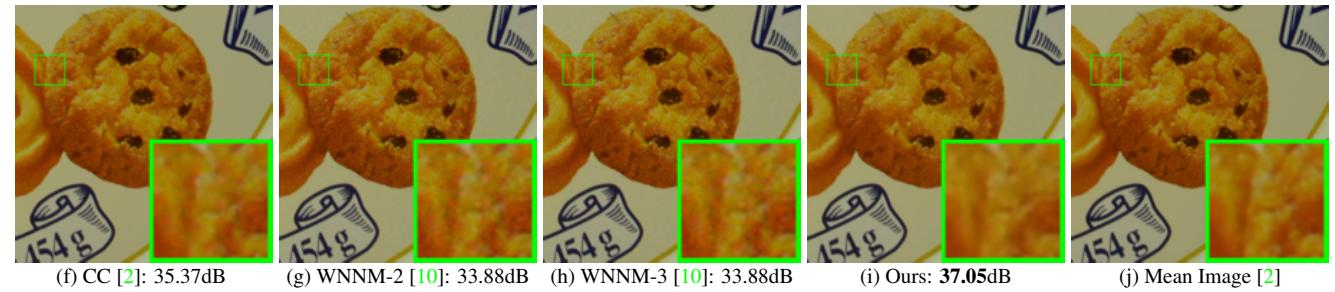
540
541
542
543
544
545
546
547
548
549594
595
596
597
598
599
600
601
602
603550
551
552
553
554
555
556
557
558
559
560
561604
605
606
607
608
609
610
611
612
613
614

Figure 7. Denoised images of a region cropped from the real noisy image “Nikon D600 ISO 1600 2” [2] by different methods. The images are better to be zoomed in on screen.

562

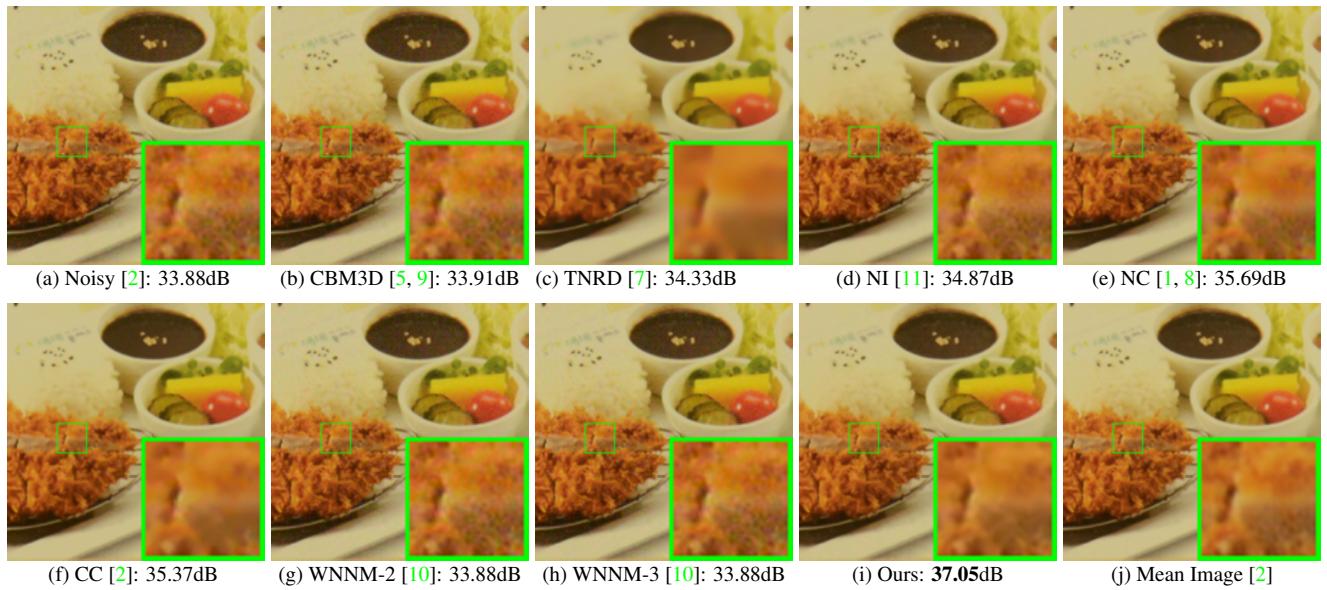
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640

Figure 8. Denoised images of a region cropped from the real noisy image “Nikon D800 ISO 1600 2” [2] by different methods. The images are better to be zoomed in on screen.

583

584
585
586

- [6] H. C. Burger, C. J. Schuler, and S. Harmeling. Image denoising: Can plain neural networks compete with BM3D? *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pages 2392–2399, 2012. 3, 4, 5, 7

587
588
589

- [7] Y. Chen, W. Yu, and T. Pock. On learning optimized reaction diffusion processes for effective image restoration. *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pages 5261–5269, 2015. 3, 4, 5, 6, 7

590
591
592

- [8] M. Lebrun, M. Colom, and J.-M. Morel. Multiscale image blind denoising. *IEEE Transactions on Image Processing*, 24(10):3149–3161, 2015. 3, 4, 5, 6, 7

593

- [9] K. Dabov, A. Foi, V. Katkovnik, and K. Egiazarian. Image denoising by sparse 3-D transform-domain collaborative filtering. *IEEE Transactions on Image Processing*, 16(8):2080–2095, 2007. 5, 6, 7

641
642
643
644
645
646
647

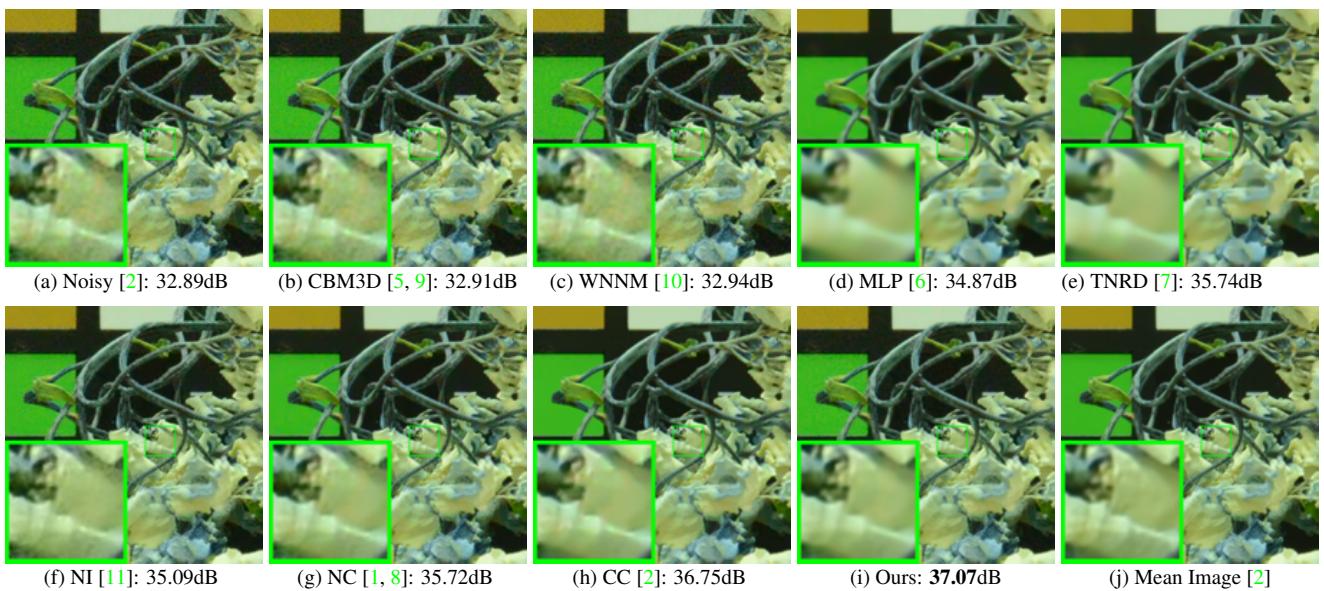


Figure 9. Denoised images of a region cropped from the real noisy image “Nikon D800 ISO 6400 2” [2] by different methods. The images are better to be zoomed in on screen.

[10] S. Gu, L. Zhang, W. Zuo, and X. Feng. Weighted nuclear norm minimization with application to image denoising. *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pages 2862–2869, 2014. 4, 5, 6, 7

[11] Neatlab ABSoft. Neat Image. <https://ni.neatvideo.com/home>. 4, 5, 6, 7