Supplementary File to "Unfolded Deep Kernel Estimation for Blind Image Super-resolution"

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In this supplementary file, we provide the following materials:

- Network architectures of $\text{Net}_{\mathbf{X}}$, $\text{Net}_{\mathbf{K}}$ and HypaNet (referring to Section 3.3 and Section 3.4 in the main paper).
- The $\times 3$ BISR results with DEPD-evaluation pool (referring to Section 4.2 in the main paper).
- The BISR results on several selected kernels from the DEPD-evaluation pool (referring to Section 4.2 in the main paper).
- More visualization of kernels estimated by UDKE and other kernel estimation methods (referring to Section 4.2 in the main paper).
- The BISR Results with isotropic Gaussian kernels (referring to Section 4.2 in the main paper).
- Visualization of the outputs in each stage of UDKE (referring to Section 4.2 in the main paper).
- More visualization results of BISR with DEPD kernel pool (referring to Section 4.2 in the main paper).
- More visualization results of BISR on real-world low-resolution images (referring to Section 4.2 in the main paper).

1 Network Architectures of $\text{Net}_{\mathbf{X}}$, $\text{Net}_{\mathbf{K}}$ and HypaNet

Fig. 1 shows the network architectures of $\text{Net}_{\mathbf{X}}$, $\text{Net}_{\mathbf{K}}$ and HypaNet.

2 $\times 3$ BISR Results with DEPD-evaluation Pool

Table 1 shows the experimental results of $\times 3$ BISR results with DEPD-evaluation pool. Table 2 shows the kernel estimation results. Note that some methods cannot be applied to $3\times$ SR and thus they are omitted. It can be seen that UDKE based BISR method achieves the highest BISR and kernel estimation performance.

3 BISR Results on Selected DEPD-evaluation Kernels

Table 3 shows the BISR results on some distinct kernels selected from the DEPD-evaluation pool. The experiment is done on BSD100 images with s=2 and σ= 7.65. It can be seen that UDKE based BISR framework consistently shows the SOTA performance on different testing blur kernels.

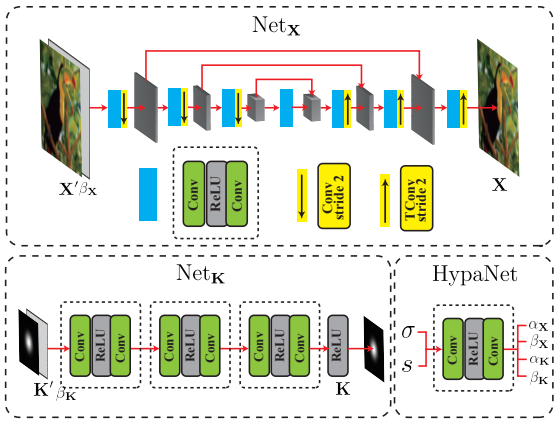


Fig. 1: Network architectures of Net$_{\mathbf{X}}$, Net$_{\mathbf{K}}$ and HypaNet.

Datasets	Set5			BSD100			Urban100		
σ	0	2.55	7.65	0	2.55	7.65	0	2.55	7.65
Bicubic	24.56/.7570	24.51/.7463	24.12/.6819	23.61/.6329	23.56/.6243	23.23/.5684	20.80/.6258	20.76/.6163	20.62/.5601
RCAN	25.26/.7911	25.13/.7582	23.94/.6680	23.90/.7209	23.73/.6826	21.43/.5088	21.89/.6791	21.65/.6788	20.01/.5020
ZSSR	25.22/.7810	24.71/.7419	23.47/.6213	24.10/.7464	23.91/.7098	21.29/.4971	22.66/.7043	22.34/.6921	21.09/.5179
DASR	25.97/.8110	25.37/.7833	23.91/.6452	24.62/.7552	24.55/.7254	21.65/.5149	22.71/.7350	22.37/.7152	20.94/.5016
DFKP	25.51/.7825	25.03/.7512	22.32/.5917	23.79/.7343	23.62/.7043	20.03/.4543	20.31/.7040	19.98/.6949	19.02/.4654
IKC	24.98/.7656	24.81/.7413	24.01/.6690	24.21/.7460	24.07/.7154	21.87/.5029	22.05/.7032	21.68/.7010	20.77/.5025
DAN	25.80/.8012	25.22/.7637	23.88/.6170	24.42/.7554	24.31/.7213	21.65/.5289	22.71/.7335	22.48/.7227	20.65/.5230
Ours	29.12/.8617	28.92/.8478	27.86/.8161	26.19/.7768	26.04/.7426	25.43/.6999	24.02/.7715	23.92/.7630	23.56/.7416
UBound	32.61/.9004	32.23/.8711	31.10/.8537	29.22/.8313	29.02/.7870	28.45/.7636	27.99/.8010	26.89/.7862	26.42/.7260

Table 1: 3× BISR results (PSNR/SSIM). Best results are in red.

Scale	Datasets	Set5			BSD100			Urban100		
	σ	0	2.55	7.65	0	2.55	7.65	0	2.55	7.65
×3	DFKP	39.2	39.0	37.8	38.7	38.2	37.5	37.2	37.2	37.0
	Ours	46.8	47.0	45.5	47.1	46.7	45.1	47.3	47.0	46.1

Table 2: Kernel estimation results (PSNR). Best results are in red.

4 More Visualization of Estimated Kernels

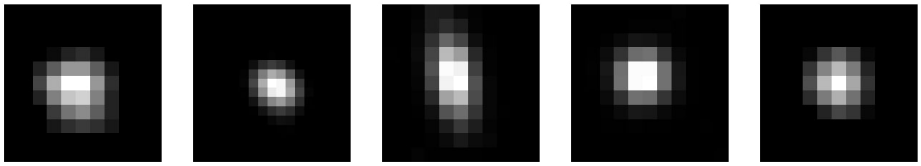
Figs. 2∼3 show more visualization of kernels estimated by UDKE and other kernel estimation methods. It can be seen that UDKE produces more reliable estimation of unseen blur kernels during inference.

5 BISR Results with Isotropic Gaussian Kernels

Table 4 shows the BISR results with isotropic Gaussian kernels. It can be seen that UDKE achieves competitive results with those BISR methods specifically

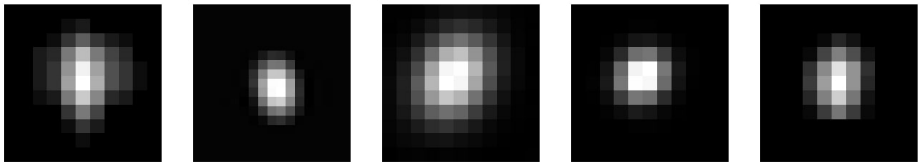
									
Bicubic	24.52/.6411	24.58/.6025	24.02/.6123	24.04/.6433	24.85/.6768	24.44/.6328	24.52/.6470	24.03/.5979	24.68/.6708
RCAN	23.72/.5365	23.23/.5165	23.47/.5359	23.01/.5011	23.67/.5235	23.43/.5109	23.73/.5498	23.13/.5298	23.86/.5525
ZSSR	24.71/.6834	25.02/.7043	25.24/.7323	24.83/.7233	24.89/.7310	25.20/.7321	24.99/.7432	25.45/.7236	25.20/.7235
DASR	24.01/.5632	23.92/.5594	23.45/.5293	23.77/.5695	23.99/.5860	23.04/.5202	23.57/.5905	23.77/.5342	23.12/.5231
KGAN	18.45/.3928	18.14/.3948	18.83/.3485	18.10/.3101	18.62/.3290	18.54/.3123	18.65/.3483	18.04/.2982	18.55/.3342
KFKP	16.32/.2985	16.10/.2583	16.75/.2685	16.12/.2950	16.01/.2409	16.47/.2938	16.73/.2192	16.95/.2940	15.94/.2394
DFKP	20.18/.3711	19.57/.3634	19.85/.3621	20.01/.3582	20.13/.3364	19.03/.3531	19.85/.3651	20.10/.3427	19.57/.3922
IKC	25.10/.7343	25.12/.7256	25.01/.7074	25.32/.7368	25.03/.7266	24.98/.6950	25.23/.7654	25.09/.7079	25.20/.7354
DAN	23.62/.5543	23.15/.5125	23.54/.5540	23.92/.5783	23.11/.5089	23.62/.5798	23.35/.5610	23.80/.5910	23.88/.5910
Ours	26.56/.7636	26.54/.7591	26.19/.7397	25.41/.7052	26.56/.7607	26.61/.7635	26.67/.7702	25.14/.7046	26.66/.7673
UBound	28.01/.8409	27.96/.8520	27.85/.8254	27.67/.8175	28.00/.8508	27.77/.8243	27.91/.8378	27.53/.8165	28.12/.8680

Table 3: BISR results (PSNR/SSIM) on different kernels. Best results are in red.



(a) Ground truth (b) KGAN (42.3dB) (c) KFKP (38.1dB) (d) DFKP (41.0dB) (e) UDKE (46.4dB)

Fig. 2: Kernel estimation results by different methods on "baby" in Set5 with s=3 and σ=2.55.



(a) Ground truth (b) KGAN (43.9dB) (c) KFKP (38.4dB) (d) DFKP (42.8dB) (e) UDKE (47.5dB)

Fig. 3: Kernel estimation results by different methods on "img051" in Urban100 with s=4 and σ=7.65.

designed for Gaussian kernels but without hardcoding any Gaussian priors, and it achieves the best performance when the noise increases.

6 Outputs in Each Stage of UDKE

Fig. 4 shows the outputs in each stage of UDKE. It can be seen that UDKE progressively improves the estimations of BISR kernel and super-resolution results, which validates the motivation and effectiveness of our architecture design.

s		σ=0	σ=2.55	σ=7.65
2	DAN	29.78/.8531/-	29.25/.8358/-	28.31/.7510/-
	KGAN	29.76/.8420/47.9	29.13/.7378/46.5	28.10/.7026/45.8
	KFKP	29.79/.8530/49.4	29.27/.8429/47.1	28.24/.7450/46.2
	DFKP	30.12/.8940/49.8	29.40/.8611/47.4	28.45/.7570/46.2
	Ours	29.80/.8522/48.8	29.24/.8435/47.0	28.57/.7700/46.4
4	DAN	26.34/.7849/-	25.92/.7320/-	25.42/.5820/-
	KGAN	26.21/.7810/46.2	25.73/.7243/44.2	25.30/.5575/41.9
	KFKP	26.48/.7911/46.3	25.94/.7310/44.9	25.43/.5801/42.4
	DFKP	26.53/.8012/47.5	26.10/.7592/45.3	25.68/.6013/44.4
	Ours	26.43/.7834/46.2	25.98/.7324/44.8	25.72/.6187/44.5

Table 4: BISR results (PSNR/SSIM/Kernel-PSNR) on isotropic Gaussian kernels.

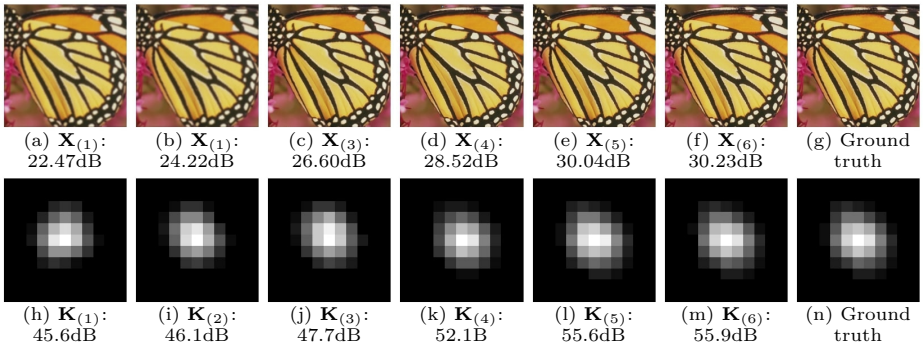


Fig. 4: Outputs in each stage of UDKE on "butterfly" in Set5 with s=2 and σ=0.

7 More Visualization Results of BISR with DEPD Kernel Pool

Figs. 5∼12 visualize the BISR results with DEPD kernel pool. It can be seen that UDKE generally recovers richer and clearer textures (see Figs. 7 and 12) and it is more robust to noisy images (see Figs. 5, 9, 10).

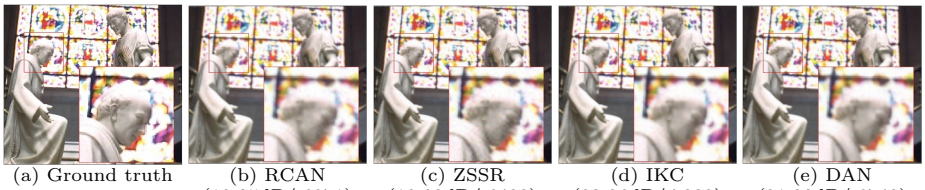
8 More Visualization Results of BISR on Real-world Images

Figs. 13∼18 visualizes the BISR results on real-world images. Note that KGAN, KGAN-FKP, BSRGAN, and RESRGAN cannot be applied to 3× super-resolution so that their results are not shown for 3× BISR. One can see that UDKE can reproduce much sharper edges and clearer textures without falsely changing their original patterns.

(a) Ground truth (b) RCAN (19.05dB/.6661) (c) ZSSR (18.92dB/.6489) (d) IKC (24.11dB/.7717) (e) DAN (23.62dB/.7476)

(f) DASR (22.97dB/.7267) (g) KGAN (18.74dB/.4677) (h) KFKP (8.26dB/.1274) (i) DFKP (19.80dB/.5118) (j) UDKE (25.28dB/.8421)

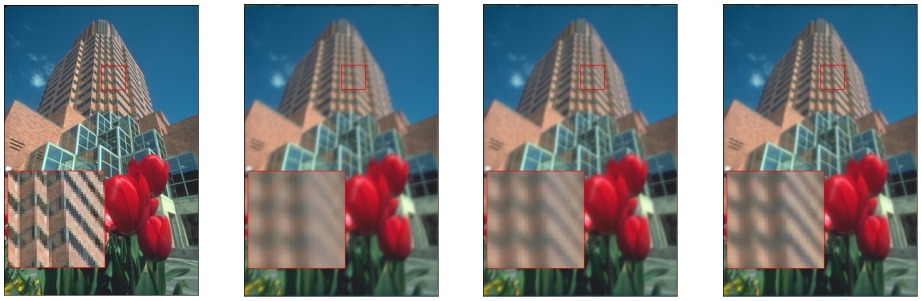
Fig. 5: BISR results (PSNR/SSIM) on "butterfly" in Set5 with s=2 and σ=7.65.



(a) Ground truth (b) RCAN (19.05dB/.6871) (c) ZSSR (18.92dB/.6489) (d) IKC (20.06dB/.7339) (e) DAN (21.90dB/.6748)

(f) DASR (22.05dB/.7166) (g) KGAN (17.74dB/.5301) (h) KFKP (21.82dB/.7122) (i) DFKP (22.70dB/.8120) (j) UDKE (23.82dB/.8471)

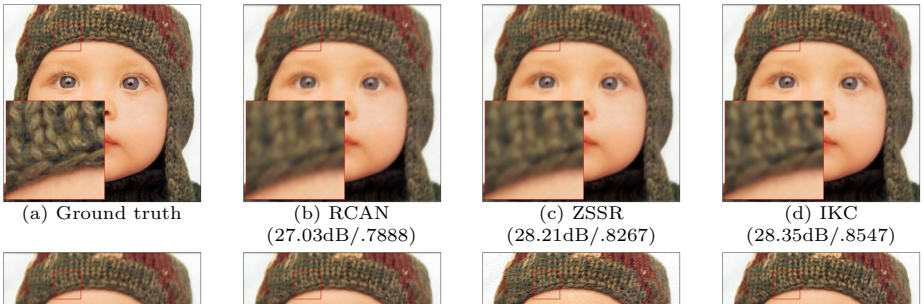
Fig. 6: BISR results (PSNR/SSIM) on "24077" in BSD100 with s=2 and σ=2.55.



(a) Ground truth (b) RCAN (19.29dB/.5469) (c) ZSSR (19.86/.6137) (d) IKC (20.56dB/.6967)

(e) DAN (20.49dB/.6903) (f) DASR (20.30dB/.6178) (g) DFKP (18.31dB/.5529) (h) UDKE (22.38dB/.7540)

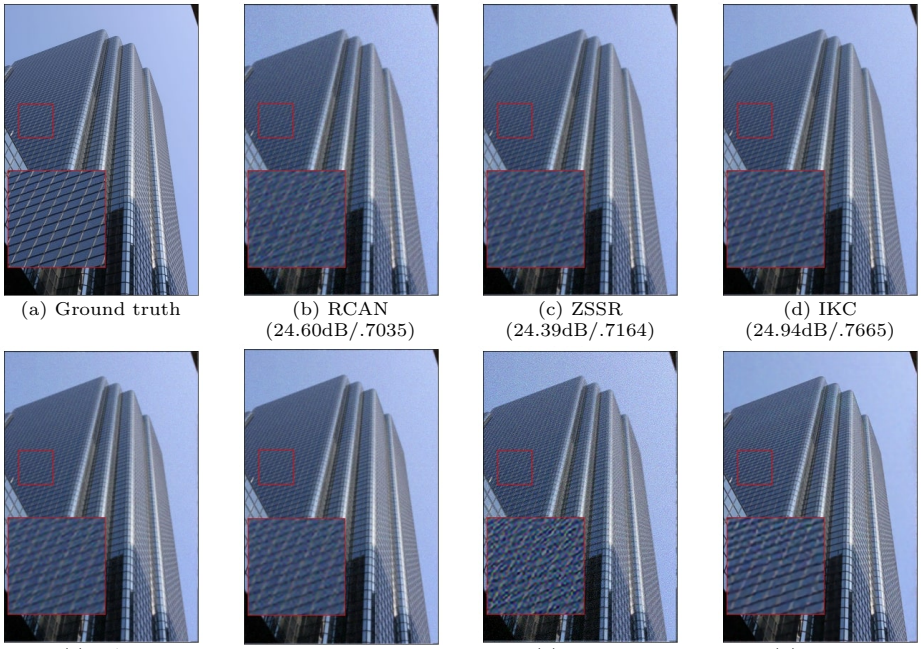
Fig. 7: BISR results (PSNR/SSIM) on "86000" in BSD100 with s=3 and σ=0.



(a) Ground truth (b) RCAN (27.03dB/.7888) (c) ZSSR (28.21dB/.8267) (d) IKC (28.35dB/.8547)

(e) DAN (28.79dB/.8418) (f) DASR (28.86dB/.8065) (g) DFKP (24.61dB/.6229) (h) UDKE (30.17dB/.8755)

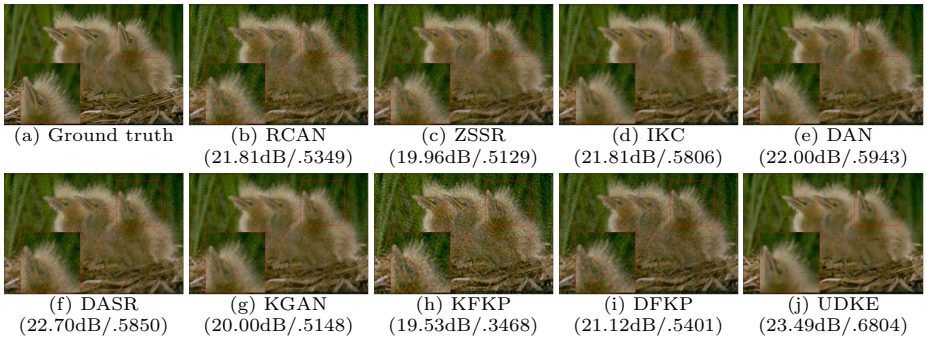
Fig. 8: BISR results (PSNR/SSIM) on "baby" in Set5 with s=3 and σ=2.55).



(a) Ground truth (b) RCAN (24.60dB/.7035) (c) ZSSR (24.39dB/.7164) (d) IKC (24.94dB/.7665)

(e) DAN (24.71dB/.7442) (f) DASR (24.29dB/.7631) (g) DFKP (20.62dB/.3900) (h) UDKE (25.98dB/.8240)

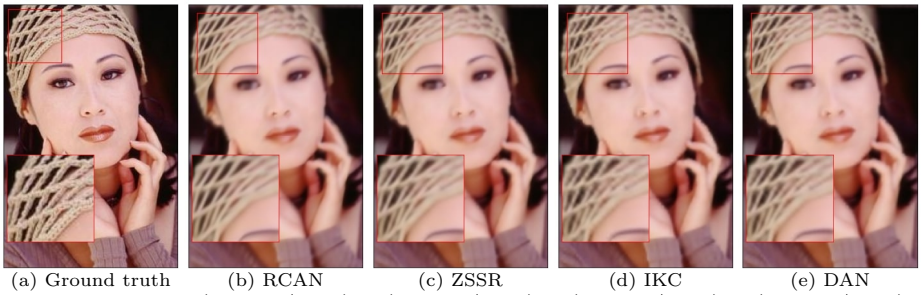
Fig. 9: BISR results (PSNR/SSIM) on "074" in Urban100 with s=3 and σ=7.65.



(a) Ground truth (b) RCAN (21.81dB/.5349) (c) ZSSR (19.96dB/.5129) (d) IKC (21.81dB/.5806) (e) DAN (22.00dB/.5943)

(f) DASR (22.70dB/.5850) (g) KGAN (20.00dB/.5148) (h) KFKP (19.53dB/.3468) (i) DFKP (21.12dB/.5401) (j) UDKE (23.49dB/.6804)

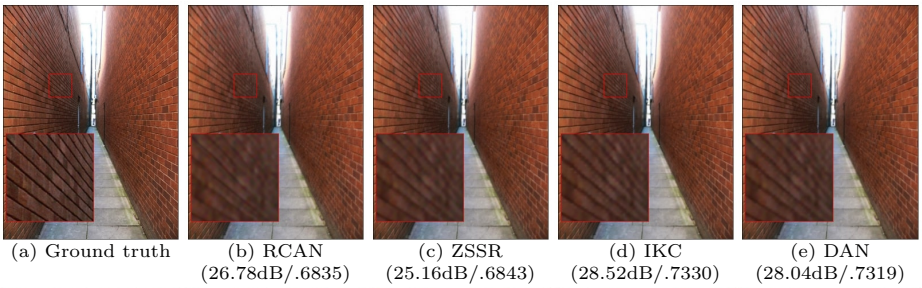
Fig. 10: BISR results (PSNR/SSIM) on "163085" in BSD100 with s=4 and σ=7.65.



(a) Ground truth (b) RCAN (18.45dB/.6491) (c) ZSSR (18.80dB/.6764) (d) IKC (19.03dB/.6998) (e) DAN (19.67dB/.7021)

(f) DASR (20.38dB/.7221) (g) KGAN (18.95dB/.6888) (h) KFKP (18.93dB/.6883) (i) DFKP (19.31dB/.6948) (j) UDKE (24.47dB/.8083)

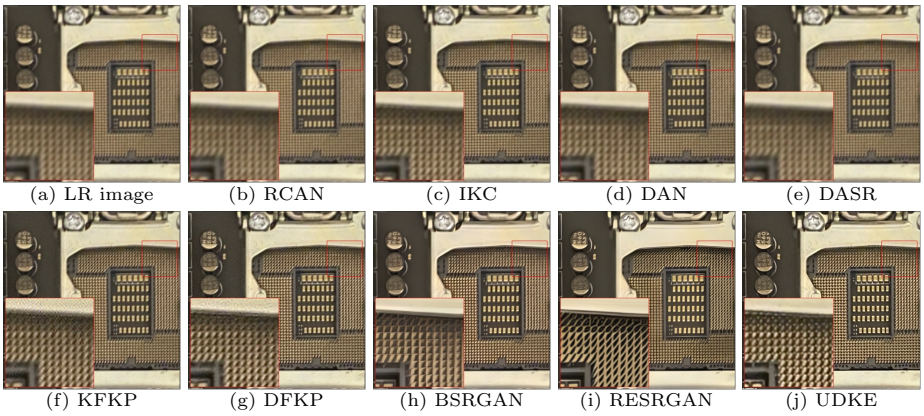
Fig. 11: BISR results (PSNR/SSIM) on "woman" in Set5 with s=4 and σ=0.



(a) Ground truth (b) RCAN (26.78dB/.6835) (c) ZSSR (25.16dB/.6843) (d) IKC (28.52dB/.7330) (e) DAN (28.04dB/.7319)

(f) DASR (27.68dB/.7330) (g) KGAN (25.09dB/.6735) (h) KFKP (24.63dB/.6062) (i) DFKP (25.41dB/.6446) (j) UDKE (30.03dB/.8342)

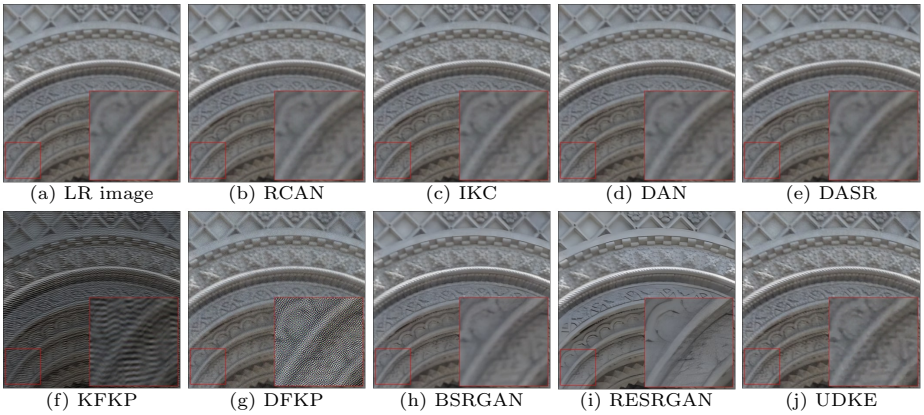
Fig. 12: BISR results (PSNR/SSIM) on "038" in Urban100 with s=4 and σ=2.55.



(a) LR image (b) RCAN (c) IKC (d) DAN (e) DASR

(f) KFKP (g) DFKP (h) BSRGAN (i) RESRGAN (j) UDKE

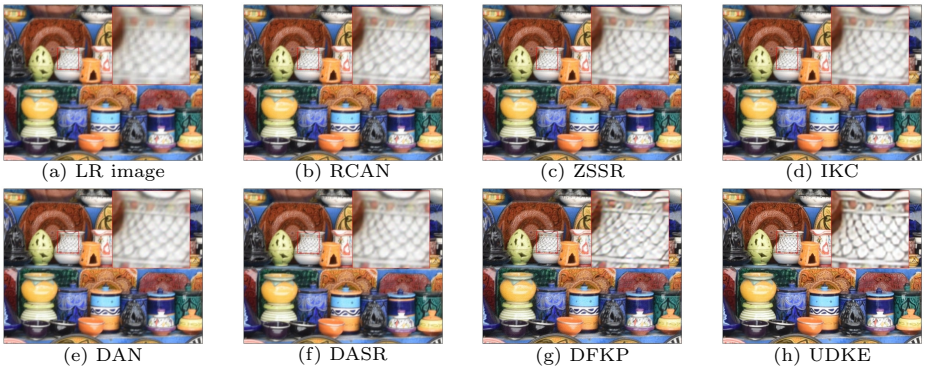
Fig. 13: $\times 2$ BISR results on a real-world image (better viewed on screen).



(a) LR image (b) RCAN (c) IKC (d) DAN (e) DASR

(f) KFKP (g) DFKP (h) BSRGAN (i) RESRGAN (j) UDKE

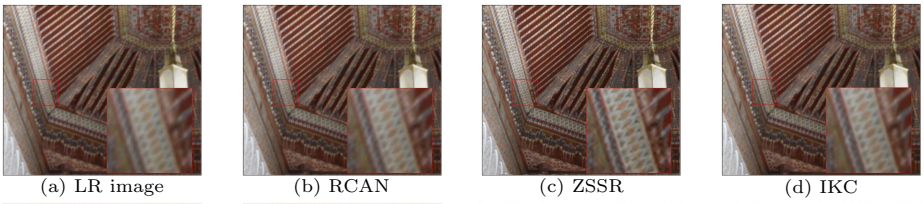
Fig. 14: $\times 2$ BISR results on a real-world image (better viewed on screen).



(a) LR image (b) RCAN (c) ZSSR (d) IKC

(e) DAN (f) DASR (g) DFKP (h) UDKE

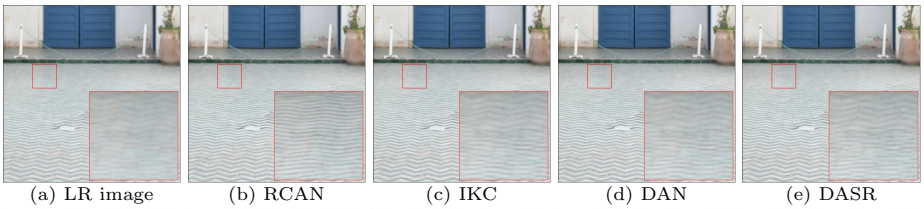
Fig. 15: $\times 3$ BISR results on a real-world image (better viewed on screen).



(a) LR image (b) RCAN (c) ZSSR (d) IKC

(e) DAN (f) DASR (g) DFKP (h) UDKE

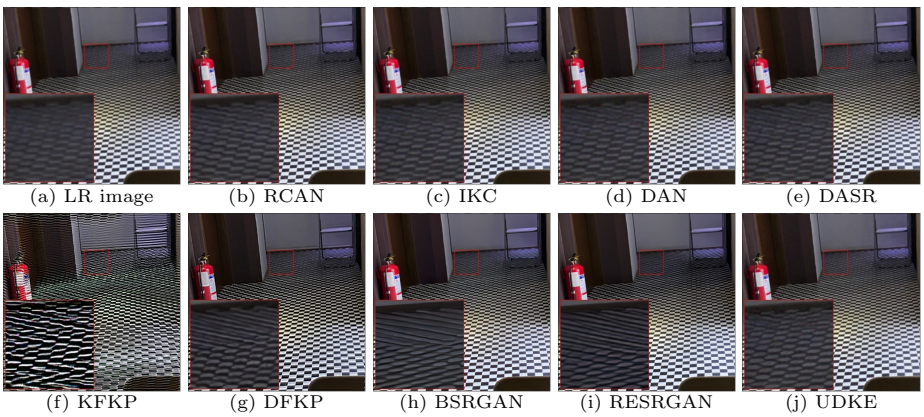
Fig. 16: ×3 BISR results on a real-world image (better viewed on screen).



(a) LR image (b) RCAN (c) IKC (d) DAN (e) DASR

(f) KFKP (g) DFKP (h) BSRGAN (i) RESRGAN (j) UDKE

Fig. 17: ×4 BISR results on a real-world image (better viewed on screen).



(a) LR image (b) RCAN (c) IKC (d) DAN (e) DASR

(f) KFKP (g) DFKP (h) BSRGAN (i) RESRGAN (j) UDKE

Fig. 18: ×4 BISR results on a real-world image (better viewed on screen).