

Learning Discriminative Data Fitting Functions for Blind Image Deblurring

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Abstract

Solving blind image deblurring usually requires defining a data fitting function and image priors. While existing algorithms mainly focus on developing image priors for blur kernel estimation and non-blind deconvolution, only a few methods consider the effect of data fitting functions. In contrast to the state-of-the-art methods that use a single or a fixed data fitting term, we propose a data-driven approach to learn effective data fitting functions from a large set of motion blurred images with the associated ground truth blur kernels. The learned data fitting function facilitates estimating accurate blur kernels for generic scenes and domain-specific problems with corresponding image priors. In addition, we extend the learning approach for data fitting function to latent image restoration and non-uniform deblurring. Extensive experiments on challenging motion blurred images demonstrate the proposed algorithm performs favorably against the state-of-the-art methods.

1. Introduction

The goal of blind image deblurring is to recover a blur kernel and a sharp latent image from a blurred input. It is a classical vision problem, and significant progress has been made in recent years [10, 11, 14]. When the blur is spatially invariant, the blur process can be modeled by a convolution operation:

$$B = I * k + n, \quad (1)$$

where B , I , k , and n denote the blur image, latent image, blur kernel, and noise, respectively; and $*$ is the convolution operator. Blind image deblurring is an ill-posed problem because there are infinite pairs of I and k which satisfy (1), and a trivial solution exists, i.e., original blurred image and delta blur kernel.

Although the number of solutions is infinite, the solution space of natural images can be constrained. Numerous methods [2, 4, 15, 16] have been developed based on sparsity of image gradients for kernel estimation. On the other hand, recent algorithms exploit various image priors to recover sharp images, e.g., normalized sparsity prior [13], re-

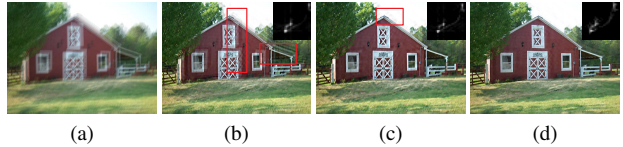


Figure 1. Effect of data fitting functions on kernel estimation. (a) Blurred image. (b) Results of [16] by a data fitting function based on intensity. (c) Results of [16] by a data fitting function based on image gradient. (d) Our results. All the results are generated with the same settings for fair comparisons. The parts enclosed in the red boxes in (b) and (c) contain significant blur residual and artifacts (Best viewed on high-resolution displays with zoom-in).

current internal patch recurrence [18], text image prior [20], and dark channel prior [23]. These image priors are based on statistical assumptions of clear images and have been shown to be effective in deblurring. Discriminative methods [32, 37] have been developed to learn effective image priors [25] for blur kernel estimation. In contrast to statistical priors, several methods use exemplars for kernel estimation [1, 6, 19, 28].

In addition to image priors, another group of methods focus on sharp edge predictions for blur kernel estimation. However, these methods usually involve heuristic edge selection steps [3, 33] to estimate blur kernels.

We note that the aforementioned methods focus on developing effective image priors for deblurring. Among the methods in the literature, intensity information is commonly used to define the data fitting term. Levin et al. [16] show that proper use of image gradients in a data fitting function helps improve blur kernel estimation. Some recent algorithms [3, 20, 22, 23, 33, 35] use intensity in latent image restoration (e.g., minimizing ℓ_2 reconstruction errors) and gradient in the kernel estimation (e.g., minimizing ℓ_2 errors). However, the effect of intensity and gradient information in blind image deblurring has not been well analyzed.

In this paper, instead of proposing image priors, we study the effect of data fitting functions for kernel estimation. We show that the data fitting function also plays a crucial role in blind image deblurring as it measures the goodness-of-fit to the motion blur model in (1). Figure 1 demonstrates the importance of different data fitting functions on blur kernel estimation.

To address this issue, we propose a two-stage approach for blind image deblurring. In the first stage, an effective data fitting function is learned for blur kernel estimation. In the second stage, the data fitting function is optimized for latent image restoration. We present an efficient numerical algorithm to learn the data fitting functions for both blur kernel estimation and latent image restoration. In addition, we show that the proposed algorithm can be applied to other domain-specific deblurring tasks with different priors and non-uniform deblurring.

2. Proposed Algorithm

In this section, we present an algorithm to learn effective data fitting functions for blind image deblurring. We first consider the blur kernel estimation problem, and extend it to the latent image restoration task. In this work, the blind deblurring problem is formulated as

$$E(I, k) = \sum_i \omega_i \|f_i * I * k - f_i * B\|_2^2 + \varphi(I) + \phi(k), \quad (2)$$

where ω_i denotes the i -th weight, f_i denotes a linear filter operator which can be learned by fields of experts [24], and $\varphi(I)$ as well as $\phi(k)$ are the priors of latent image and blur kernel. As the weights control the importance of each term for blur kernel estimation, the main goal is to estimate these values effectively.

2.1. Learning Discriminative Data Functions

To estimate $\omega = \{\omega_i\}$, we collect a set of ground truth blur kernels $\{k_j\}$ as well as a set of clear images $\{I_j\}$, and propose the following objective function,

$$\begin{aligned} \min_{\omega_i} \quad & \frac{1}{2} \sum_j \|k_j(\omega) - k_j^{gt}\|_2^2 \\ \text{s.t.} \quad & \omega_i \geq 0, \sum_i \omega_i = 1, \end{aligned} \quad (3)$$

where k_j^{gt} denotes the j -th ground truth blur kernel, and $k_j(\omega)$ is the j -th estimated blur kernel, which can be obtained by

$$\arg \min_{k_j, I_j} \sum_j \sum_i \omega_i \|f_i * I_j * k_j - f_i * B_j\|_2^2 + \varphi(I_j) + \phi(k_j). \quad (4)$$

To derive the relationship between blur kernel k_j and weight ω_i in (2), we propose an efficient algorithm to solve (4).

2.2. Optimizing (4)

Similar to the existing methods [20, 22, 35, 30], we adopt $\varphi(I_j) = \lambda \|\nabla I_j\|_0$ and $\phi(k_j) = \gamma \|k_j\|_2^2$ as the regularization for the latent image and blur kernel of (4), where λ and γ are weight parameters. We use the half-quadratic splitting L_0 minimization method [34] and introduce an auxiliary variable $g_j = (g_j^v, g_j^h)$ corresponding to the image

gradient ∇I_j . Thus, (4) can be rewritten as

$$\begin{aligned} \min_{k_j, I_j, g_j} \quad & \sum_j \sum_i \omega_i \|f_i * I_j * k_j - f_i * B_j\|_2^2 \\ & + \beta \|g_j - \nabla I_j\|_2^2 + \lambda \|g_j\|_0 + \gamma \|k_j\|_2^2. \end{aligned} \quad (5)$$

2.2.1 Intermediate Blur Kernel Estimation

Given I_j , the optimization with respect to k_j is

$$\min_{k_j} \sum_j \sum_i \omega_i \|f_i * I_j * k_j - f_i * B_j\|_2^2 + \gamma \|k_j\|_2^2. \quad (6)$$

For simplicity, we use the matrix-vector form to express (6)

$$\min_{\mathbf{k}_j} \sum_j \sum_i \omega_i \|\mathbf{A}_{ij} \mathbf{k}_j - \mathbf{b}_{ij}\|_2^2 + \gamma \|\mathbf{k}_j\|_2^2, \quad (7)$$

where $\mathbf{A}_{ij}$ is the matrix form of $f_i * I_j$ with respect to blur kernel k_j , $\mathbf{b}_{ij}$ is the vector form of $f_i * B_j$ with respect to blur kernel k_j , and $\mathbf{k}_j$ is the vector form of k_j . Based on (7), the solution of k_j is

$$\mathbf{k}_j = \left(\sum_i \omega_i \mathbf{A}_{ij}^\top \mathbf{A}_{ij} + \gamma \right)^{-1} \left(\sum_i \omega_i \mathbf{A}_{ij}^\top \mathbf{b}_{ij} \right). \quad (8)$$

2.2.2 Intermediate Latent Image Estimation

The optimization problem (5) with respect to intermediate latent image I_j is

$$\begin{aligned} \min_{I_j, g_j} \quad & \sum_j \sum_i \omega_i \|f_i * I_j * k_j - f_i * B_j\|_2^2 + \beta \|g_j - \nabla I_j\|_2^2 \\ & + \lambda \|g_j\|_0. \end{aligned} \quad (9)$$

Note that this problem involves variables I_j and g_j . It can be efficiently solved through alternatively minimizing I_j and g_j .

In each iteration, the solution of g_j is obtained by solving

$$g_j = \begin{cases} \nabla I_j, & |\nabla I_j|^2 \geq \frac{\lambda}{\beta}, \\ 0, & \text{otherwise.} \end{cases} \quad (10)$$

Given g_j , the intermediate latent image I_j can be obtained by solving

$$\min_{I_j} \sum_j \sum_i \omega_i \|f_i * I_j * k_j - f_i * B_j\|_2^2 + \beta \|g_j - \nabla I_j\|_2^2, \quad (11)$$

and the closed-form solution for this problem is

$$I_j = \mathcal{F}^{-1} \left(\frac{\sum_i \omega_i \overline{\mathcal{F}(f_i)} \mathcal{F}(k_j) \mathcal{F}(f_i * B_j) + \beta F_g}{F_k + \beta (\sum_{i \in \{h, v\}} \overline{\mathcal{F}(\nabla_i)} \mathcal{F}(\nabla_i))} \right), \quad (12)$$

Algorithm 1 Solving (9)

Input: Blurred image B_j and blur kernel k_j .

$I_j \leftarrow B_j, \beta \leftarrow 2\lambda$.

repeat

 solve g_j using (10).

 solve I_j using (12).

$\beta \leftarrow 2\beta$.

until $\beta > \beta_{\max}$

Output: Intermediate latent image I_j .

Algorithm 2 Learning discriminative features

Input: Blurred images $\{B_j\}$, ground truth blur kernels $\{k_j^{gt}\}$.

$\omega_i \leftarrow 0$.

initialize k_j with results from the coarser level.

while $l \leq \max_iter1$ **do**

while $t \leq \max_iter2$ **do**

 solve I_j using Algorithm 1.

 solve k_j using (8).

end while

$\omega_i = \omega_i - \alpha \sum_j \frac{\partial \mathcal{L}_j}{\partial \omega_i}$.

end while

Output: The weight ω_i .

where $\mathcal{F}(\cdot)$ and $\mathcal{F}^{-1}(\cdot)$ denote the Fourier transform and its inverse transform, respectively, $\overline{\mathcal{F}(\cdot)}$ is the complex conjugate operator, $F_k = \sum_i \omega_i \mathcal{F}(f_i) \mathcal{F}(k_j) \mathcal{F}(k_j) \mathcal{F}(f_i)$, and $F_g = \overline{\mathcal{F}(\nabla_h)} \mathcal{F}(g_j^h) + \overline{\mathcal{F}(\nabla_v)} \mathcal{F}(g_j^v)$, where ∇_h and ∇_v denote the horizontal and vertical differential operators. In case all the values of ω_i are zeros in (12) (which will lead to unstable kernel estimation), we set the terms $\omega_0 \overline{\mathcal{F}(k_j)} \mathcal{F}(f_0 * B_j)$ and $\omega_0 \overline{\mathcal{F}(k_j)} \mathcal{F}(f_0 * B_j)$ to be $(\omega_0 + 1) \mathcal{F}(k_j) \mathcal{F}(f_0 * B_j)$ and $(\omega_0 + 1) \mathcal{F}(f_0) \mathcal{F}(k_j) \mathcal{F}(k_j) \mathcal{F}(f_0)$.

The main steps for intermediate latent image estimation are summarized in Algorithm 1.

2.3. Optimizing (3)

After obtaining k_j with respect to ω_i , we can solve (3) by a gradient descent method. The gradient with respect to ω_i is

$$\begin{aligned} \frac{\partial \mathcal{L}_j}{\partial \omega_i} = \frac{\partial \mathcal{L}_j}{\partial \mathbf{k}_j} \frac{\partial \mathbf{k}_j}{\partial \omega_i} = & -(\mathbf{k}_j - \mathbf{k}_j^{gt})^\top \left(\sum_i \omega_i \mathbf{A}_{ij}^\top \mathbf{A}_{ij} + \gamma \right)^{-1} \mathbf{A}_{ij}^\top \mathbf{A}_{ij} \mathbf{k}_j \\ & + (\mathbf{k}_j - \mathbf{k}_j^{gt})^\top \left(\sum_i \omega_i \mathbf{A}_{ij}^\top \mathbf{A}_{ij} + \gamma \right)^{-1} (\mathbf{A}_{ij}^\top \mathbf{b}_{ij}), \end{aligned} \quad (13)$$

where $\mathcal{L}_j = \frac{1}{2} \|\mathbf{k}_j(\omega) - \mathbf{k}_j^{gt}\|_2^2$. The detailed derivations are presented in the supplemental material.

The main steps for learning discriminative data fitting functions are summarized in Algorithm 2. In this work, the step of gradient decent α is set to be 0.01.

Training Data. We construct a training dataset to learn

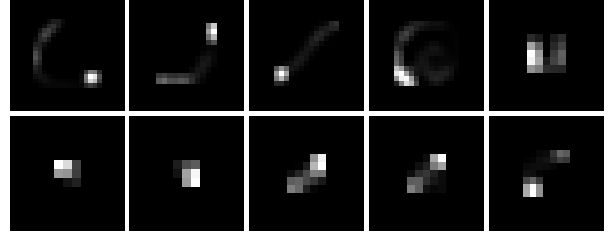


Figure 2. Some generated blur kernels that are used for training.

the weights in (2) by using 200 images from the BSDS dataset [17]. To generate blurred images $\{B_j\}$ and blur kernels $\{k_j\}$, we synthesize realistic blur kernels by sampling random 3D trajectories used in [25]. These trajectories are then projected and rasterized to random square kernel sizes in the range from 11×11 up to 27×27 pixels. Some examples of the generated blur kernels are shown in Figure 2.

With the blur kernels, we synthetically generate blurred images by convolving each clean image with 100 generated blur kernels. A set of 200,000 blurred images is constructed for learning the weights of (3).

2.4. Kernel Estimation

After learning the weights, we solve (2) to obtain the blur kernels. That is, we alternatively solve the intermediate latent image and blur kernel. The optimization algorithms with respect to the blur kernel and latent image are the same to those described in Section 2.2.1 and 2.2.2.

For the linear filters $\{f_i\}$, we choose the commonly used zero-order operator corresponding to the intensity information, and gradient operators including the first (two directions) and second order (three directions) operators. The concrete forms of 6 linear operators are presented in Table 1.

2.5. Discriminative Non-Blind Deconvolution

Once blur kernels are obtained, we can use a variety of non-blind deconvolution methods to recover latent images. However, we note that the proposed method used in the kernel estimation process can also be applied to non-blind deconvolution. We formulate the non-blind deconvolution problem as

$$\min_I \sum_i \omega_i \|f_i * I * k - f_i * B\|_2^2 + \phi(I), \quad (14)$$

where $\phi(I)$ is the regularization on the image I , e.g., hyper-Laplacian priors [12]. In this work, we use the commonly used total variation regularization, i.e., $\phi(I) = \mu \|\nabla I\|_1$, for non-blind deconvolution.

The weight ω_i can be obtained by solving

$$\begin{aligned} \min_{\omega_i} \quad & \frac{1}{2} \sum_j \|I_j(\omega) - I_j^{gt}\|_2^2 \\ \text{s.t.} \quad & \omega_i \geq 0, \sum_i \omega_i = 1, \end{aligned} \quad (15)$$

Table 1. Concrete forms of the linear filters used in the learning process.

Filters	f_1	f_2	f_3	f_4	f_5	f_6
Type	zero-order	first order	first order	second order	second order	second order
Forms	$I * k - B$	$\nabla_h I * k - \nabla_h B$	$\nabla_v I * k - \nabla_v B$	$\nabla_h \nabla_h I * k - \nabla_h \nabla_h B$	$\nabla_v \nabla_v I * k - \nabla_v \nabla_v B$	$\nabla_h \nabla_v I * k - \nabla_h \nabla_v B$

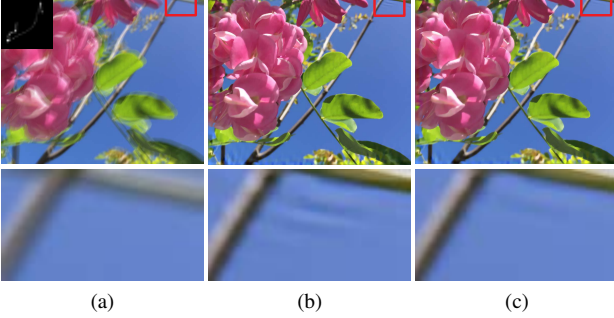


Figure 3. Non-blind deconvolution examples. (a) Blurred image and blur kernel. (b) Result with only intensity information in the data fitting function. (c) Our result. The part in the red box in (b) contains significant ringing artifacts (Best viewed on high-resolution display with zoom-in).

where $I_j(\omega)$ is the solution of (14) and I_j^{gt} is the clear image.

To determine the relationship between $I_j(\omega)$ and ω , we use the same alternative minimization method described in Section 2.2.2 to obtain $I_j(\omega)$. The weight ω_i can be obtained by

$$\omega_i = \omega_i - \alpha_I \sum_j (\mathbf{I}_j - \mathbf{I}_j^{gt})^\top \mathbf{W}_i, \quad (16)$$

where α_I is the gradient descent step. In the above equation, $\mathbf{I}_j, \mathbf{I}_j^{gt}$, as well as $\mathbf{W}_i$ denote the vectorization of I_j, I_j^{gt} and W_i , respectively. Each W_i is defined by

$$W_i = \mathcal{F}^{-1} \left(\frac{\Delta_b}{\Delta_d} - \frac{\Delta_f \Delta_n}{\Delta_d^2} \right), \quad (17)$$

where $\Delta_d = F_k + \beta(\sum_{i \in \{h,v\}} \mathcal{F}(\nabla_i) \mathcal{F}(\nabla_i))$, $\Delta_f = \mathcal{F}(f_i) \mathcal{F}(k_j) \mathcal{F}(k_j) \mathcal{F}(f_i)$, $\Delta_b = \mathcal{F}(f_i) \mathcal{F}(k_j) \mathcal{F}(f_i * B)$, and $\Delta_n = \sum_i \omega_i \mathcal{F}(k_j) \mathcal{F}(f_i * B_j) + \beta F_g$.

We use the same training data as discussed in Section 2.3 to learn ω_i . The details regarding the gradient of (15) with respect to ω_i and the optimization method with respect to I in (14) are included in the supplemental material.

Figure 3 shows an example of the non-blind deconvolution result using (14). We note that the recovered image by the conventional data fitting function contains some ringing artifacts (Figure 3(b)) while the one by the proposed method is sharper (Figure 3(c)).

3. Extension to Non-Uniform Deblurring

Our method can be directly extended to handle non-uniform deblurring where the blurred images are acquired from moving cameras (e.g., with rotational and translational movements) [5, 7, 26, 29, 31]. Based on the geometric model of camera motion [29, 31], the non-uniform blur process

can be formulated as:

$$\mathbf{B} = \mathbf{K}\mathbf{I} + \mathbf{n} = \mathbf{A}\mathbf{k} + \mathbf{n}, \quad (18)$$

where $\mathbf{I}, \mathbf{k}$, and $\mathbf{n}$ denote vector forms of I, k, n in (1). In this model, $\mathbf{A}$ as well as $\mathbf{K}$ denote the image matrix and blur kernel matrix with respect to the latent image $\mathbf{I}$ and blur kernel $\mathbf{k}$. Based on (18), the non-uniform deblurring problem is solved by alternatively minimizing:

$$\min_{\mathbf{I}} \sum_i \omega_i \|\mathbf{K}\mathbf{F}_i \mathbf{I} - \mathbf{F}_i \mathbf{B}\|_2^2 + \lambda \|\nabla \mathbf{I}\|_0, \quad (19)$$

and

$$\min_{\mathbf{k}} \sum_i \omega_i \|\mathbf{A}_i \mathbf{k} - \mathbf{B}_i\|_2^2 + \gamma \|\mathbf{k}\|_2^2, \quad (20)$$

where $\mathbf{F}_i$ is the matrix of the filter operator f_i . We use the fast forward approximation methods [7, 21] to estimate latent images and blur kernels.

4. Analysis of Proposed Algorithm

In this section, we analyze how the proposed algorithm performs on image deblurring. We also demonstrate the importance of the proposed learned data fitting functions and discuss the connections to other methods.

4.1. Effect of Discriminative Data Fitting Functions

The proposed method is able to automatically learn the most relevant data fitting functions for both blur kernel estimation and latent image restoration. We analyze its effect on blur kernel estimation and latent image restoration with comparisons to the commonly used data fitting functions.

Effect on Blur Kernel Estimation. The data fitting functions used in existing methods are based on intensity or gradient for both latent image restoration and kernel estimation [3, 20, 33, 35]. Figure 4 shows one example where the deblurred results by the methods with only intensity or gradient contain significant ringing artifacts. The methods using intensity for the intermediate latent image estimation and gradient for the kernel estimation perform better. However, the deblurred results still contain blur residual and blurry characters. In contrast, the deblurred results generated by the proposed method contain clearer characters, which indicate that the learned data fitting functions facilitate blur kernel estimation.

We quantitatively evaluate the proposed method and present the results in Table 2. The proposed method with learned data fitting functions performs well against other alternatives based on intensity, gradient, or combination.

Table 2. Quantitative comparisons with the commonly used data fitting functions for the image deblurring.

	With only intensity	With intensity and gradient	With only gradient	Ours
Average PSNRs	23.08	30.52	26.78	31.88

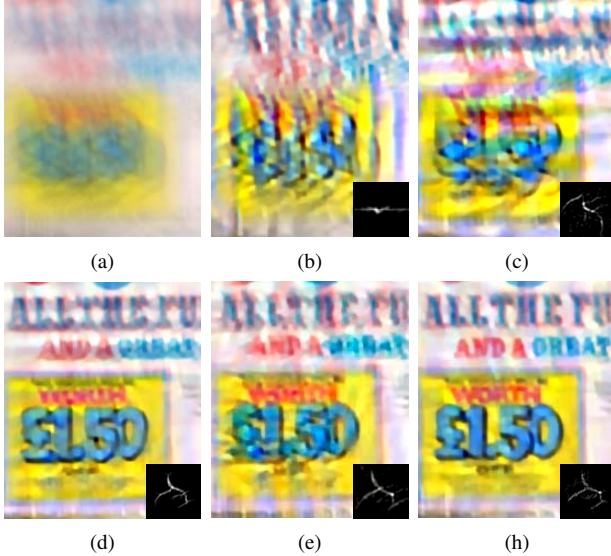


Figure 4. Effectiveness of the proposed learned data fitting function for blur kernel estimation. (a) Blurred image. (b) Results by only intensity in the data fitting function. (c) Results by only gradient in the data fitting function. (d) Results by intensity in the intermediate latent image estimation and gradients in the kernel estimation. (e) Deblurred results by [35]. (f) Our results.

Table 3. Learned weights for blur kernel estimation.

ω_1	ω_2	ω_3	ω_4	ω_5	ω_6
0	0.1954	0.1850	0.2463	0.2625	0.1108

Learned Weights for Data Fitting Terms. To illustrate the importance of each data fitting term in blur kernel estimation process, we show the learned weights in Table 3. We note that the learned weight of the data fitting term for intensity is 0, which demonstrates that intensity does not help the blur kernel estimation. The results are similar to the experimental analysis of the state-of-the-art methods [16, 3, 33, 35, 20]. In addition, we note that the weights, i.e., ω_4 and ω_5 , for the data fitting terms with the second order information are much larger than those of the data fitting terms with the first order intensity, which indicate that higher order information plays more important roles for blur kernel estimation.

Effect on Non-Blind Deconvolution. The learned weights of data fitting terms for latent image restoration are shown in Table 4. We note that the weight of the data fitting term with the zero-order filter is much higher than the others. This indicates that intensity information plays an important role in non-blind deconvolution. The learned weights in Table 3 and 4 demonstrate that different data fitting terms should be used as kernel estimation and non-blind deconvolution are different processes.

Table 4. Learned weights for latent image estimation.

ω_1	ω_2	ω_3	ω_4	ω_5	ω_6
0.2095	0.1581	0.1581	0.1581	0.1581	0.1581

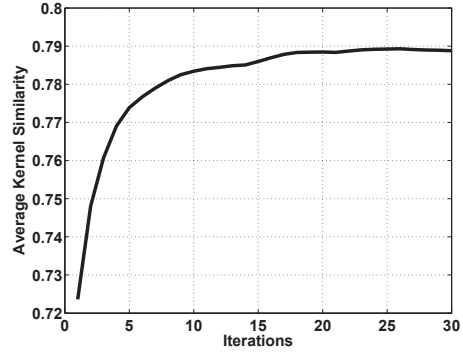


Figure 5. Fast convergence property of the proposed algorithm.

4.2. Fast Convergence Property

Compared to the existing methods with fixed data fitting functions based on only intensity, gradient or combination [20, 35], the proposed algorithm involves additional data fitting terms with different weights. However, this does not significantly increase the computational load. We evaluate the convergence rate of the proposed method on the dataset [15] and show the kernel similarity [9] with respect to iterations in Figure 5. The results demonstrate that the proposed method exhibits fast convergence. Table 5 shows that the run time of our method compares favorably against the competing methods.

Table 5. Run time (seconds) on the same computer with an Intel Core i7-4800MQ processor and 16 GB RAM. The run time of Xu et al. [35] is based on our implementation.

Method	255 × 255	600 × 600	800 × 800
Xu et al. [35]	3.10	19.10	36.53
Krishnan et al. [13]	34.01	196.09	315.41
Levin et al. [16]	144.61	501.67	862.81
Pan et al. [23]	17.07	115.86	195.80
Ours	4.93	23.11	41.52

5. Experimental Results

We present experimental evaluations of the proposed algorithm against the state-of-the-art deblurring methods. All the experiments are carried out on a machine with an Intel Core i7-4800MQ processor and 16 GB RAM. The run time for a 255 × 255 image is 5 seconds on MATLAB. In all the experiments, we set $\lambda = 0.002$ and $\gamma = 2$. We empirically set $\beta_{\max} = 10^5$ in Algorithm 1. We use the deblurring datasets by Sun et al. [27] and Levin et al. [15] as the main test datasets. Thus, the training and test datasets are not overlapped. For fair comparisons, we use the executable

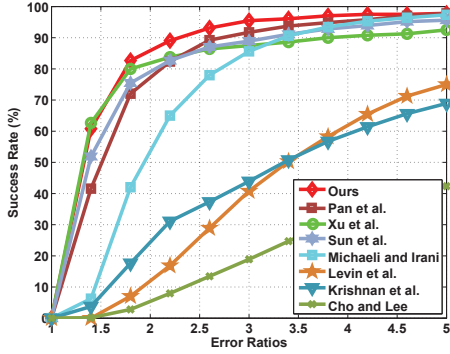


Figure 6. Quantitative evaluations on the benchmark dataset by Sun et al. [27]. Our method performs favorably against the state-of-the-art methods.

code provided by the authors and tune the parameters to generate the best possible results of other methods. The MATLAB code and datasets are publicly available on the authors’ websites. More experimental results can be found in the supplemental material.

5.1. Quantitative Evaluation

We evaluate the proposed method on the synthetic dataset by Sun et al. [27] and compare it with several state-of-the-art deblurring methods [3, 13, 16, 18, 21, 27, 35]. This dataset contains 80 images and 8 blur kernels from [15]. We use the original codes of the state-of-the-art methods [3, 13, 16, 18, 21, 27, 35] to estimate blur kernels and use the non-blind deblurring method [36] to generate the final deblurring results for fair comparisons. The error ratio [15] is used for performance evaluation. Figure 6 shows the quantitative results on the dataset [27]. Overall, the proposed algorithm performs favorably against the state-of-the-art deblurring methods. We note that the method [35] uses intensity in intermediate latent image estimation and gradient in the kernel estimation. Compared with this method, the proposed algorithm achieves higher success rates, which indicates the effectiveness of the learned data fitting functions.

5.2. Real Images

Figure 7 shows the deblurred results on a real image by the proposed algorithm and the state-of-the-art methods. We use the original source or binary codes and tune the parameters to generate the best possible results for fair comparisons. The deblurred images by [3, 13] contain significant ringing artifacts. While the state-of-the-art methods [16, 20, 23] generate better kernel estimates than other methods, the deblurred images contain significant ringing artifacts. We note that the main difference between the proposed algorithm and the method by Xu et al. [35] is that [35] uses intensity for latent image restoration and gradient for kernel estimation. However, the results demonstrate that

this manually designed data fitting function is not effective for blur kernel estimation on the real image. In contrast, the deblurred image by the proposed algorithm contains fewer artifacts, which shows that the learned function with different weighted combination of data fitting terms is effective for kernel estimation.

Figure 8 shows the deblurred results by the proposed algorithm and the state-of-the-art methods [3, 13, 16, 20, 23, 35] on a real blurred document image. The state-of-the-art deblurring methods designed for natural images [3, 13] do not generate clear images. Although the method by Pan et al. [20] mainly focuses on the text image deblurring, the deblurred results still contain significant blur residual and ringing artifacts. The recent method based on sparsity of dark channel prior for blur kernel estimation [23] does not perform well on this image as the assumption on zero-intensity values of an image does not hold. In contrast, the deblurred image by the proposed algorithm is clearer with significantly fewer artifacts. Furthermore, the deblurred results shown in Figure 8(e) and (h) demonstrate the effectiveness of the proposed algorithm that learns different weighted functions of data fitting terms for latent image restoration and blur kernel estimation.

5.3. Non-uniform Deblurring

As discussed in Section 3, the proposed algorithm can be extended to handle non-uniform blur. We present results on an image degraded by spatially variant motion blur provided by [5] in Figure 9. We compare the proposed algorithm with the state-of-the-art non-uniform deblurring methods [5, 7, 8, 21, 31, 35]. Figure 9 shows the letters of (b)-(f) contain ringing artifacts. Compared to the deblurred results by the state-of-the-art non-uniform methods, the restored image by the proposed algorithm contains sharper contents with fewer artifacts.

5.4. Extensions of Proposed Method

In this work, we focus on learning effective data fitting functions for blur kernel estimation and use the L_0 norm of image gradient [35] as the image prior. However, our method can be applied to other deblurring tasks with specific image priors, e.g., normalized sparsity prior [13], L_0 -regularized intensity and gradient prior [20], and dark channel prior [23], to name a few. To demonstrate the flexibility of the proposed method, we use the L_0 -regularized intensity and gradient prior [20] as an example and show the deblurred results in Figure 10. We note that the original text deblurring method uses intensity for latent image and gradient for kernel estimation. However, this combination does not always help blur kernel estimation (see Figure 10(b)). In contrast, the method with the learned data fitting function generates deblurred images with clearer characters as shown in Figure 10(c).

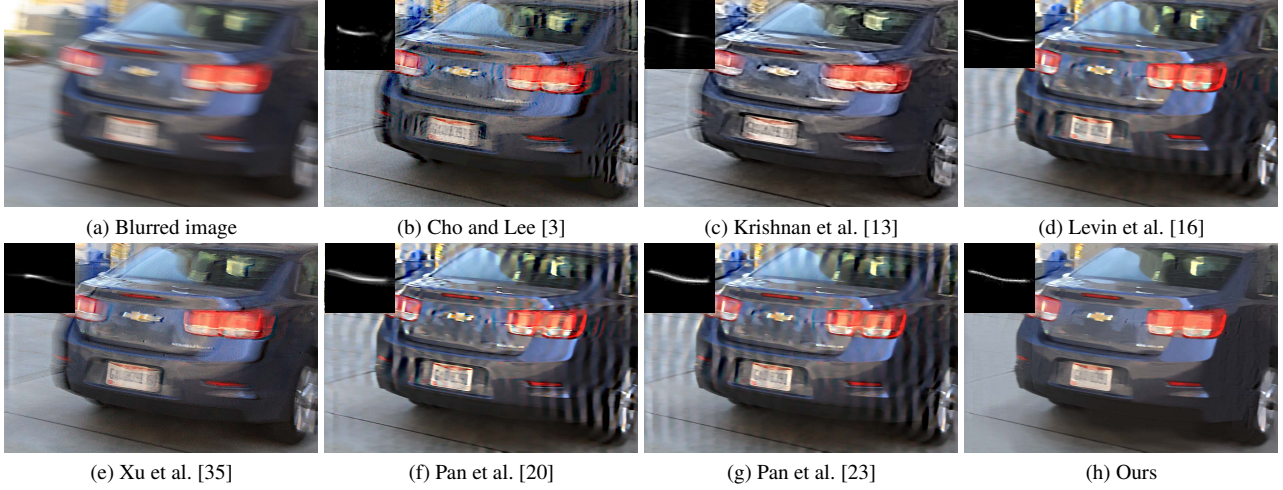


Figure 7. Comparisons on a real image. The proposed method generates a better kernel estimate and deblurred result with fewer ringing artifacts. The comparison results shown in (e) and (h) indicate the importance of the proposed automatically learned data fitting functions.

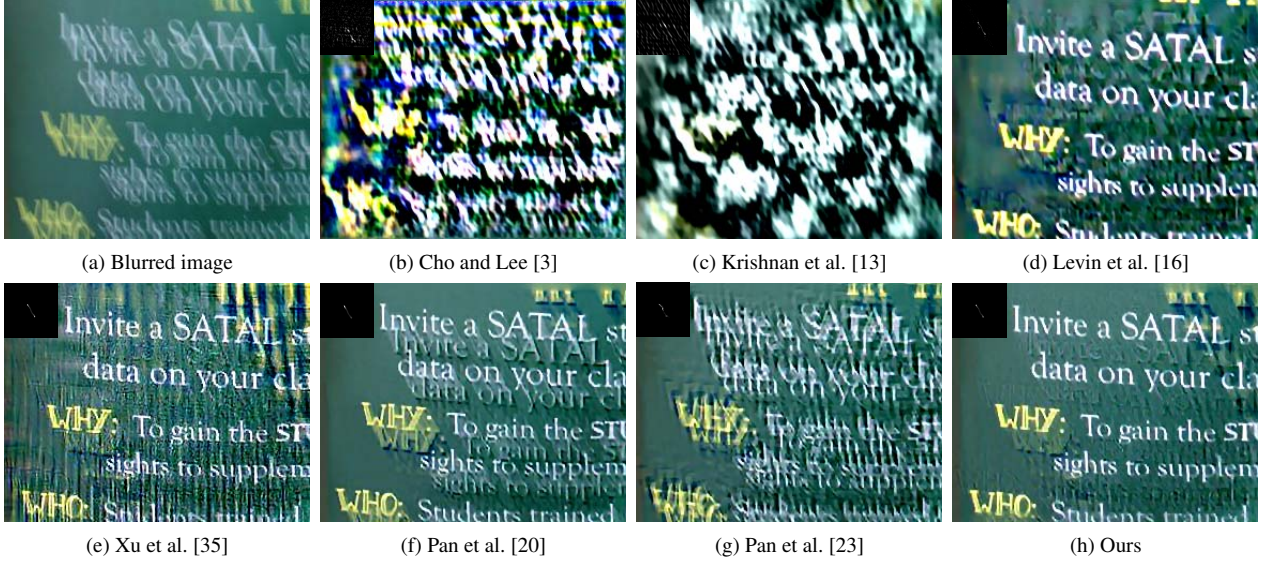


Figure 8. Comparisons on a real image with lots of characters. The proposed method generates an image with clearer characters. The comparison results shown in (e) and (h) indicate the importance of the proposed learned data fitting functions.

Comparisons with [32]. The recent method [32] aims to learn high-order filters for image deblurring. The image prior based on the learned high-order filters is especially effective for text images. However, our method focuses on learning good data fitting functions instead of image priors for image deblurring. Figure 11 shows a real blurred text image from [20]. The proposed method with the L_0 -regularized intensity and gradient prior performs competitively against the state-of-the-art text deblurring methods [20, 32].

6. Concluding Remarks

In this paper, we propose an effective algorithm which learns effective data fitting functions for both blur kernel estimation and latent image restoration. We discuss the effect of the proposed data fitting functions and show that intensity

has less effect on blur kernel estimation and has more effect on latent image restoration. We show that the performance of deblurring algorithms using the learned data fitting functions can be significantly improved. The proposed algorithm is also extended for non-uniform deblurring. In addition, we show that the proposed method can be extended to other specific deblurring tasks with corresponding image priors. Extensive experimental evaluations on benchmark datasets and real images demonstrate that the proposed algorithm performs favorably against the state-of-the-art methods for uniform as well as non-uniform deblurring.

While we focus on learning effective data fitting functions for blind image deblurring, the choice of linear filters is fixed. In addition, the optimization method may also play an important role [4, 16] and some models may accommo-



Figure 9. The proposed method directly applies to images with non-uniform blur. The images shown in (b)-(g) are directly obtained from the reported results in [21] (Best viewed on high-resolution display with zoom-in).

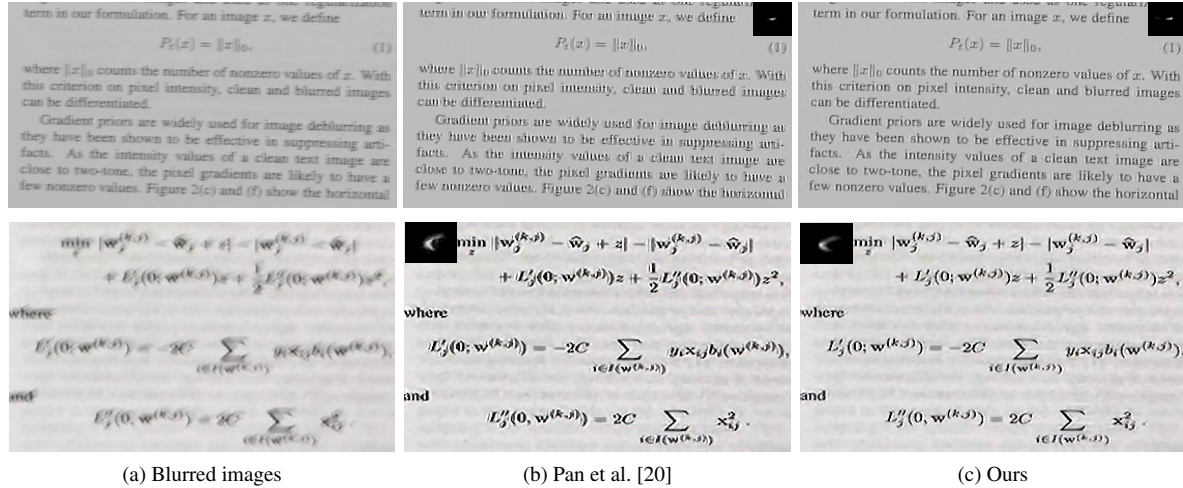


Figure 10. Extension of text image deblurring algorithm [20]. The results generated by the proposed method contain clearer characters and fewer ringing artifacts (Best viewed on high-resolution display with zoom-in).

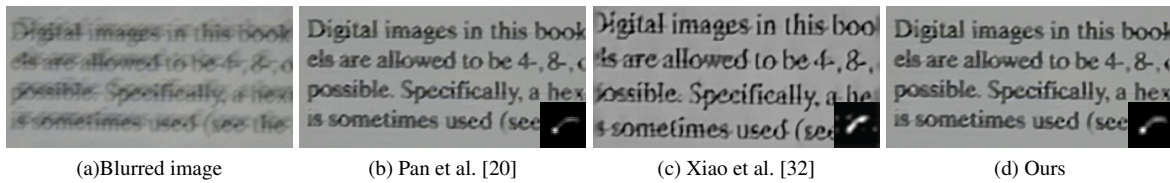


Figure 11. Comparisons with [32] on a real text image from [20]. The images shown in (b)-(c) are directly obtained from the reported results (Best viewed on high-resolution display with zoom-in).

date better optimization strategies than others. Our future work will focus on learning effective linear filters and optimization methods for image deblurring.

Acknowledgements. This work has been partially support-

ed by NSFC (No. 61572099, 61522203), NSF CAREER (No. 1149783), 973 Program (No. 2014CB347600), NSF of Jiangsu Province (No. BK20140058), the National Key R&D Program of China (No. 2016YFB1001001), and gifts from Adobe and Nvidia.

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