

Single-frame Image Denoising and Inpainting Using Gaussian Mixtures

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Abstract: This paper proposes a patch-based method to address two of the core problems in image processing: denoising and inpainting. The approach is based on a Gaussian mixture model estimated exclusively from the observed image via the expectation-maximization algorithm, based on which the minimum mean squared error estimate is computed in closed form. The results show that this simple method is able to perform on the same level as other state-of-the-art algorithms.

1 INTRODUCTION

Denoising and inpainting are two core image processing problems, with applications in digital photography, medical and astronomical imaging, and many others areas. As the name implies, denoising aims at removing noise from an observed noisy image, while the objective of painting is to estimate missing image pixels. Both denoising and inpainting are inverse problems: the goal is to infer an underlying image from incomplete/imperfect observations thereof.

Both in inpainting and denoising, the observed image $\mathbf{y}$ is modeled as

$$\mathbf{y} = \mathbf{H} \mathbf{x} + \mathbf{n}, \quad (1)$$

where $\mathbf{x}$ is the unknown image and $\mathbf{n}$ is usually taken to be a sample of white Gaussian noise, with zero mean and variance σ^2 . In denoising, matrix $\mathbf{H}$ is simply an identity matrix $\mathbf{I}$, while in inpainting it contains a subset of the rows of $\mathbf{I}$, accounting for the loss of pixels. The variance σ^2 may be assumed known, as there are efficient and accurate techniques to estimate it from the noisy data itself (Liu et al., 2012).

Most (if not all) state-of-the-art image denoising methods belong to a family known as “patch-based”, where the image is processed on a patch by patch fashion. Several patch-based methods work by finding a sparse representation of the patches, either in a transform domain (Dabov et al., 2007) or on a learned

dictionary (Aharon et al., 2006; Elad and Aharon, 2006; Elad et al., 2010), while others search the image for similar patches and combine them (Buades et al., 2006). Finally, some methods use probabilistic patch models based on Gaussian mixtures (Zoran and Weiss, 2012; Yu et al., 2012).

There are many (in fact, too many to review in this paper) approaches to inpainting, ranging from methods that smoothly propagate the image intensities from the observed pixels to the missing ones, to dictionary-based methods. Recent examples include the work of Ram et al. (2013), who propose rearranging the image patches so that the distance between them is the shortest possible and then interpolate the missing pixels, and Zhou et al. (2012), who developed a nonparametric Bayesian method for learning a dictionary that is able to sparsely represent image patches.

In this paper, we propose a GMM-based method that yields patch-based *minimum mean squared error* (MMSE) estimates, and which can handle both denoising and inpainting. Although GMM have been used before for image denoising and inpainting, our proposal has several novel features. Unlike the approach of Yu et al. (2012), we estimate the GMM parameters from the observed data using an exact *expectation-maximization* (EM) algorithm and perform exact MMSE patch estimation. Unlike the method of Zoran and Weiss (2012), ours estimates the GMM parameters directly from the observed image (rather than from a collection of clean patches) and deals with both denoising and inpainting. Unlike the proposal of Cao et al. (2008), our method also han-

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dles inpainting and corrects a technical flaw in their method (details below).

2 BUILDING BLOCKS

2.1 MMSE Estimation

Let $\mathbf{x}$ in (1) now be one of the image patches. As is well known from Bayesian estimation theory, the optimal (in the *minimum mean squared error* – MMSE – sense) estimate of $\mathbf{x}$ is the posterior expectation,

$$\hat{\mathbf{x}} = \mathbb{E}[\mathbf{x} | \mathbf{y}] = \int \mathbf{x} \frac{p_{Y|X}(\mathbf{y} | \mathbf{x}) p_X(\mathbf{x})}{p_Y(\mathbf{y})} d\mathbf{x}, \quad (2)$$

where $p_{Y|X}(\mathbf{y} | \mathbf{x}) = \mathcal{N}(\mathbf{y}; \mathbf{H}\mathbf{x}, \sigma^2 \mathbf{I})$ (with $\mathcal{N}(\cdot; \mu, \Sigma)$ denoting a Gaussian density of mean μ and covariance Σ), resulting from the Gaussian white noise model, and $p_X(\mathbf{x})$ is a prior density on the clean patch. It has been argued that the state-of-the-art performance of patch-based methods is due to the fact that they implement (or approximate) the MMSE estimate (Chatterjee and Milanfar, 2012). Of course, the quality of the MMSE estimate depends critically on the adequacy of the prior; however, the choice of prior should take into account the (computational) difficulty in computing (2).

2.2 MMSE Estimation with GMM Prior

GMM priors have the important feature that the MMSE estimate has a simple closed form expression, due to the fact that a GMM is a conjugate prior for a Gaussian observation model (Bernardo and Smith, 1994). Furthermore, it has been recently shown that Gaussian mixtures are excellent models for clean patches of natural images (Zoran and Weiss, 2012); but while those authors estimate the GMM parameters from a collection of clean image patches, we show below that it is also possible to estimate them from the noisy image itself, and still obtain competitive results. Mathematically, a GMM is given by

$$p_X(\mathbf{x} | \phi) = \sum_{i=1}^k \alpha_i \mathcal{N}(\mathbf{x}; \mu_i, \mathbf{C}_i), \quad (3)$$

where μ_i and $\mathbf{C}_i$ are the mean and covariance matrix of the i -th component, respectively, α_i is its probability (of course, $\alpha_i \geq 0$ and $\sum_{i=1}^k \alpha_i = 1$), and $\phi = \{\mu_i, \mathbf{C}_i, \alpha_i, i = 1, \dots, k\}$.

The combination of the Gaussian observation model (likelihood function) $p_{Y|X}(\mathbf{y} | \mathbf{x}) = \mathcal{N}(\mathbf{y}; \mathbf{H}\mathbf{x}, \sigma^2 \mathbf{I})$ with the GMM prior (3) allows obtaining the MMSE estimate in closed form (which is

a classical result in Bayesian estimation theory),

$$\hat{\mathbf{x}}(\mathbf{y}) = \mathbb{E}[\mathbf{x} | \mathbf{y}] = \sum_{i=1}^k \beta_i(\mathbf{y}) \mathbf{v}_i(\mathbf{y}), \quad (4)$$

where

$$\beta_i(\mathbf{y}) = \frac{\alpha_i \mathcal{N}(\mathbf{y}; \mathbf{H}\mu_i, \mathbf{H}\mathbf{C}_i\mathbf{H}^T + \sigma^2 \mathbf{I})}{\sum_{j=1}^k \alpha_j \mathcal{N}(\mathbf{y}; \mathbf{H}\mu_j, \mathbf{H}\mathbf{C}_j\mathbf{H}^T + \sigma^2 \mathbf{I})} \quad (5)$$

also satisfy $\beta_i(\mathbf{y}) \geq 0$ and $\sum_{i=1}^k \beta_i(\mathbf{y}) = 1$ (notice that the denominator in (5) is simply $p_Y(\mathbf{y} | \phi)$), and

$$\mathbf{v}_i(\mathbf{y}) = \mathbf{P}_i \left(\mathbf{C}_i^{-1} \mu_i + \frac{1}{\sigma^2} \mathbf{H}^T \mathbf{y} \right), \quad (6)$$

$$\mathbf{P}_i = \left(\mathbf{C}_i^{-1} + \frac{1}{\sigma^2} \mathbf{H}^T \mathbf{H} \right)^{-1}. \quad (7)$$

In fact, the posterior $p_{X|Y}(\mathbf{x} | \mathbf{y})$ is itself a GMM,

$$p_{X|Y}(\mathbf{x} | \mathbf{y}) = \sum_{i=1}^k \beta_i(\mathbf{y}) \mathcal{N}(\mathbf{x}; \mathbf{v}_i(\mathbf{y}), \mathbf{P}_i), \quad (8)$$

(from which (4) results trivially), where the weights and the means depend on the observed $\mathbf{y}$, although the component posterior covariances do not.

Finally, from (8), it is also possible to obtain the global posterior covariance, from its definition:

$$\begin{aligned} \text{cov}[\mathbf{x} | \mathbf{y}] &= \mathbb{E}[\mathbf{x} \mathbf{x}^T | \mathbf{y}] - \mathbb{E}[\mathbf{x} | \mathbf{y}] \mathbb{E}[\mathbf{x} | \mathbf{y}]^T \\ &= \sum_{i=1}^k \beta_i(\mathbf{y}) (\mathbf{v}_i(\mathbf{y}) \mathbf{v}_i(\mathbf{y})^T + \mathbf{P}_i) - \hat{\mathbf{x}}(\mathbf{y}) \hat{\mathbf{x}}(\mathbf{y})^T. \end{aligned} \quad (9)$$

2.3 Estimating the Gaussian Mixture

There are two alternatives to estimate ϕ , the vector of parameters of the prior (3), from data: it may be previously estimated from a collection of clean patches (Zoran and Weiss, 2012); it may be estimated from the patches of the observed data itself, which is the approach herein proposed.

Let $\mathcal{Y} = \{\mathbf{y}_1, \dots, \mathbf{y}_N\}$ be the set of observations corresponding to the set of image patches $\mathcal{X} = \{\mathbf{x}_1, \dots, \mathbf{x}_N\}$, where each $\mathbf{y}_i$ is related to the corresponding $\mathbf{x}_i$ via an observation model of the form (1): $\mathbf{x}_i = \mathbf{H}_i \mathbf{x}_i + \mathbf{n}_i$. In the (simpler) denoising case, $\mathbf{H}_i = \mathbf{I}$, and the maximum likelihood estimate of $\phi = \{\alpha_j, \mu_j, \mathbf{C}_j, j = 1, \dots, k\}$ is given by

$$\hat{\phi}_{\text{ML}} = \arg \max_{\phi} \sum_{i=1}^N \log \sum_{j=1}^k \alpha_j \mathcal{N}(\mathbf{y}_i; \mu_j, \mathbf{C}_j + \sigma^2 \mathbf{I}). \quad (10)$$

As is well known, $\hat{\phi}_{\text{ML}}$ cannot be computed in closed form, but it can be obtained efficiently using the *expectation-maximization* (EM) algorithm (Dempster et al., 1977), (Figueiredo and Jain, 2002).

The specific form of the EM algorithm for this problem is almost identical to that of a standard Gaussian mixture; namely, the E-step is precisely the same as for a standard GMM and amounts to computing

$$\bar{w}_{ij} = \hat{\alpha}_j \mathcal{N}(\mathbf{y}_i; \hat{\mu}_j, \hat{\mathbf{C}}_j + \sigma^2 \mathbf{I}), \quad w_{ij} = \frac{\bar{w}_{ij}}{\sum_{l=1}^k \bar{w}_{il}} \quad (11)$$

where $\hat{\alpha}_j, \hat{\mu}_j, \hat{\mathbf{C}}_j$, for $j = 1, \dots, k$, are the current parameter estimates.

In the M-step, the update equations for the α_j and μ_j parameters are the same as for a standard GMM,

$$\hat{\alpha}_j \leftarrow \frac{1}{N} \sum_{i=1}^N w_{ij}, \quad \hat{\mu}_j \leftarrow \frac{1}{N \hat{\alpha}_j} \sum_{i=1}^N w_{ij} \mu_j, \quad (12)$$

whereas the covariances are updated according to

$$\hat{\mathbf{C}}_j \leftarrow \mathbf{V}_j (\Lambda_j - \sigma^2 \mathbf{I})_+ \mathbf{V}_j^T, \quad (13)$$

where Λ_j is the diagonal matrix with the eigenvalues of the matrix

$$\mathbf{D}_j = \frac{1}{N \hat{\alpha}_j} \sum_{i=1}^N w_{ij} (\mathbf{y}_i - \hat{\mu}_j)(\mathbf{y}_i - \hat{\mu}_j)^T,$$

and $\mathbf{V}_j$ is the matrix with the corresponding eigenvectors; finally, $(\cdot)_+$ denotes the element-wise application of the *positive part operator* $z_+ = \max\{z, 0\}$.

Cao et al. (2008) also use EM to estimate the GMM parameters from the noisy patches. However, the covariance estimates are not computed as in (13), but simply as $\mathbf{D}_j - \sigma^2 \mathbf{I}$. As a consequence, several covariance estimates may have negative eigenvalues (thus being invalid), which is almost sure to happen in cases of moderate or strong noise.

The inpainting case, which is more difficult due to the presence of the $\mathbf{H}_i$ matrices, can be seen as the problem of estimating the parameters of a GMM, from a collection of observations with missing entries. This problem has been recently addressed by Eirola et al. (2014), and we adapt their algorithm to our particular parameterization of the covariance matrices. We omit details for lack of space.

3 PATCH-BASED METHOD

The proposed approach follows the standard patch-based denoising protocol using the building blocks described in the previous section.

1. All (overlapping) patches of size $p_d \times p_d$ are extracted from the observed image, yielding the collection of observed patches $\mathcal{Y} = \{\mathbf{y}_1, \dots, \mathbf{y}_N\}$.
2. The parameters of the GMM are estimated from $\mathcal{Y}$ via the EM algorithm presented in Section 2.3.

3. The MMSE estimates of all the patches are obtained as described in Section 2.1, yielding the set of estimated patches $\hat{\mathcal{X}} = \{\hat{\mathbf{x}}_1, \dots, \hat{\mathbf{x}}_N\}$.

4. The final image estimate is assembled by putting the patch estimates $\hat{\mathcal{X}} = \{\hat{\mathbf{x}}_1, \dots, \hat{\mathbf{x}}_N\}$ back in the same locations from where the corresponding noisy (or incomplete, in inpainting) patches were extracted. Since the patches overlap, there are several estimates of each pixel, which are standardly combined by computing a straight average.

Combining the overlapping patch estimates by straight averaging ignores that estimates coming from different patches may have different degrees of confidence. In a Bayesian framework, this confidence is given by the (inverse of the) posterior variance, *i.e.*, the diagonal of the posterior covariance matrix in (9). Accordingly, we combine the pixel estimates from each patch by weighted averaging, with weights set to the inverses of the posterior variances. The use of variances to weight the pixel estimates was already exploited by Dabov et al. (2007), but their method uses patch-wise variance estimates, rather than a posterior variance for each pixel in each patch. Individual pixel variances were also used to weight the corresponding estimates by Chatterjee and Milanfar (2012), but they use a single Gaussian per patch.

4 FURTHER IMPROVEMENTS

4.1 Dealing with the DC Component

To decrease the number of GMM parameters to estimate, it is possible to assume that all the components have zero mean. In principle, this assumption incurs in no loss of generality, as it is possible to center the image by subtracting its mean. In this case, all the expressions above simplify with $\mu_j = 0$, for $j = 1, \dots, k$.

Alternatively to removing the mean from the whole input image, it is also possible to center each patch with respect to its own mean (DC component). In this case, the processing chain starts by computing, storing, and subtracting the average from each patch; after the patch estimates are obtained, these means are added back to each patch before the final image assembling step. Under the assumption of additive white Gaussian (AWGN), the patch-wise averaging reduces the noise variance by a factor of $p_d \times p_d$ (the number of samples in each patch). Consequently, the set of observed patch means can be seen as resulting from the true patch means via the contamination with zero-mean Gaussian noise with variance σ^2/p_d^2 .

Table 1: PSNR comparison on gray-level image denoising of the following methods: BM3D (Dabov et al., 2007); K-SVD (Elad and Aharon, 2006); basic proposed algorithm (Section 3); improved proposed algorithm (Sections 4.1 and 4.2).

σ	Lena (512×512)				Cameraman (256×256)				House (256×256)			
	BM3D	K-SVD	Basic	Improved	BM3D	K-SVD	Basic	Improved	BM3D	K-SVD	Basic	Improved
5	38.72	38.53	38.86	38.86	38.29	37.97	38.57	38.58	39.83	39.47	39.92	39.94
10	35.93	35.55	35.88	35.88	34.18	33.76	34.44	34.49	36.61	36.05	36.58	36.62
15	34.27	33.74	34.11	34.11	31.91	31.54	32.15	32.21	34.94	34.41	34.65	34.69
20	33.05	32.40	32.83	32.84	30.48	30.07	30.64	30.70	33.77	33.21	33.34	33.46
25	32.08	31.34	31.81	31.82	29.45	28.94	29.50	29.58	32.86	32.21	32.34	32.49
30	31.26	30.46	30.99	31.00	28.64	28.12	28.58	28.66	32.09	31.25	31.44	31.66

Table 2: PSNR on gray-level image inpainting for different data ratios and methods: BP (Zhou et al., 2012), SOP (Ram et al., 2013), our basic method, and the one using sub-images (Section 4.3).

Method	Lena (512×512)			Cameraman (256×256)			House (256×256)			Barbara256 (256×256)		
	80%	50%	20%	80%	50%	20%	80%	50%	20%	80%	50%	20%
BP	41.27	36.94	31.00	34.70	28.90	24.11	43.03	38.02	30.12	41.12	35.60	26.87
SOP	43.01	37.43	31.94	36.19	30.71	25.13	44.34	38.77	32.60	42.25	35.97	28.98
Basic	41.91	37.22	31.25	33.74	28.85	24.11	45.20	39.30	31.71	43.90	37.11	28.05
Subimages	41.98	37.57	31.78	35.03	29.36	24.25	45.39	39.42	32.05	44.56	37.15	28.41

4.2 Dealing with Flat Patches

ideal, parallel implementation.

In a gray-scale image, a flat area is characterized by a constant intensity level, thus with zero variance. Considering AWGN with variance σ^2 , the variance of a flat area is approximately the same as the variance of the noise. It has been shown empirically that treating patches that are (almost) flat separately leads to an increase in performance (Lebrun et al., 2013); an observed image patches is declared as flat if its sample variance falls below $C\sigma^2$, where C is a constant close to 1. Of course, this criterion is not foolproof; in fact, for high values of σ^2 , it is difficult to distinguish between flat patches and textured patches. After the identification of the flat patches, these are denoised simply by replacing them by their sample mean.

4.3 Dividing the Image into Sub-images

The last improvement (also used by Dabov et al. (2007) and Ram et al. (2013)) is to divide the noisy image into a set of smaller (but much larger than the patches) sub-images and treat them independently from each other. To avoid artifacts at the boundaries, the sub-images should have a small amount of overlap, and the final image obtained by averaging the estimates coming from each sub-image. This strategy allows using different patch sizes and different numbers of mixture components on each sub-image, allowing a better adaptation of the model to different areas of the image. Finally, dealing separately with each sub-image reduces the memory requirements of the algorithm and allows a straightforward, yet not

5 RESULTS AND DISCUSSION

5.1 Denoising

Table 1 presents denoising results obtained with the basic version of the proposed method described in Section 3, a version with the improvements presented in Sections 4.1 and 4.2, as well as the results obtained with the well known BM3D (Dabov et al., 2007) and K-SVD (Elad and Aharon, 2006) algorithms. These two reference methods were chosen because they are state-of-the-art patch-based methods with publicly available implementations. In the results reported in Table 1, the patch size p_d and k were chosen to yield the best results.

We performed several experiments to study the impact of those parameters in the denoising performance of the method: for each input image and noise variance, both p_d and k were swept from 3 to 12 and from 10 to 60 (in steps of 5), respectively. Figure 1 reports some of those experiments, the results of which provide some insight on the behaviour of the method. As is clear by comparing the plots in Figure 1 (a) and (b)), the optimal patch size is larger when the noise is stronger, which is a natural result; in fact, using larger (overlapping) patches means having more estimates of each pixel, thus a more aggressive denoising. On the other hand, the mixture should have enough components to be sufficiently expressive, but the results

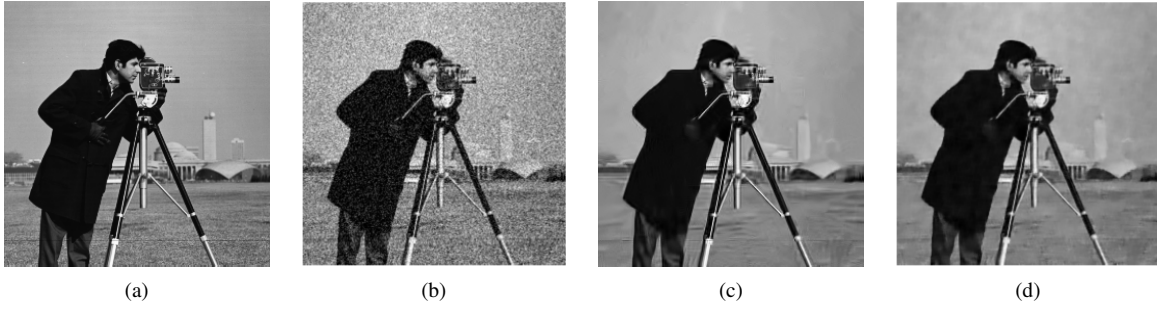


Figure 2: Denoising: (a) original image; (b) noisy image ($\sigma = 30$, PSNR = 18.59dB); (c) BM3D (Dabov et al., 2007); (d) Proposed.

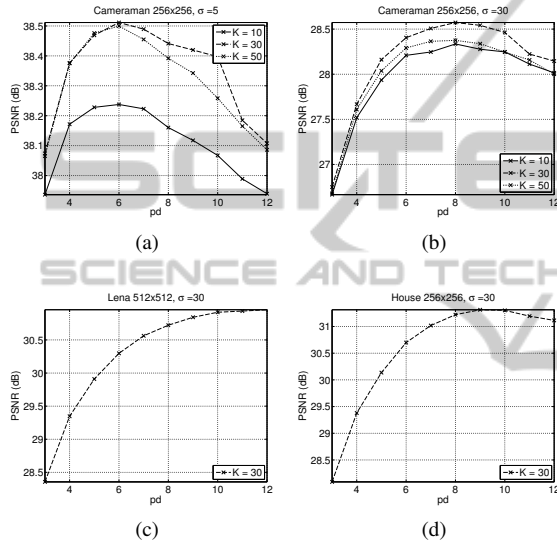


Figure 1: PSNR as a function of p_d and k : (a–b) varying p_d , with $k \in \{10, 30, 50\}$, for $\sigma = 5$ and $\sigma = 30$; (c) varying p_d on a larger image, for $K = 30, \sigma = 30$; (d) Varying p_d on a flatter input image, $K = 30, \sigma = 30$.

(specially with strong noise) depend weakly on k (notice that the range of the vertical axis in Figure 1 (a) is only roughly 0.5 dB). For higher resolution images (Figure 1 (c)), the method performs better with larger patches, arguably due to the sheer number of pixels. Finally, on images with many flat patches (Figure 1 (d)) relatively larger values of p_d yield better results, in agreement with the fact that for larger patches the DC component can be estimated more precisely.

These dependencies, although not very strong, are a downside of the proposed method (and of many other patch-based methods) and strategies to make the algorithm more adaptive should be developed. For example, the number of GMM components may be estimated directly from the data, *e.g.*, using the method proposed by Figueiredo and Jain (2002). Of course, there is no guarantee that the criterion therein used to select the number of components also yields the best denoising results when the estimated mixture is

used for that purpose. Nevertheless, the obtained results compete with other state-of-the-art algorithms, specially for lower noise variances (the most useful range in practice), and the modifications are able to slightly increase the output PSNR.

Finally, Figure 2 illustrates the visual quality of the obtained denoised images, in comparison with the BM3D method (Dabov et al., 2007). In this case, BM3D produces a slightly more appealing denoised image in the flatter regions.

5.2 Inpainting

For inpainting, we focused on finding the parameters leading to the best results as the data ratio decreases. An aspect worth stressing is that the patches should be large enough to allow each of them to have a significant fraction of known pixels. Table 2 shows the experimental results on pure inpainting ($\sigma = 0$). The reference methods (BP (Zhou et al., 2012) and SOP (Ram et al., 2013)) were chosen because they are patch-based, state-of-the-art, and publicly available. Figure 3 exemplifies the visual quality of the output; although in terms of PSNR the proposed method is behind SOP, our estimate is visually better. Table 3 shows results of simultaneous inpainting and denoising, for the test image used by Zhou et al. (2012). In both tables (2 and 3), the results were obtained with $p_d = 10$ and $k = 25$. The proposed method is able to obtain state-of-the-art results, not only in inpainting but also on simultaneous inpainting and denoising.

6 CONCLUSIONS

We have presented a patch-based method that handles both image denoising and inpainting, based on a Gaussian mixture model learned directly from the observed image and using the exact expression for the minimum mean squared error estimate. The proposed formulation also yields the posterior variances of each

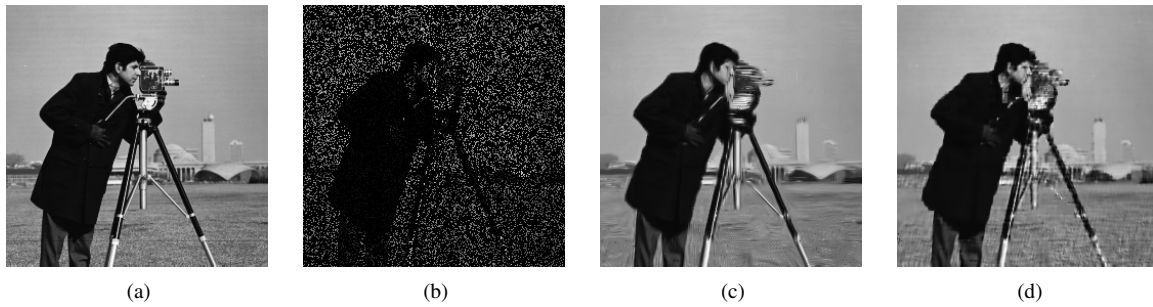


Figure 3: Inpainting: (a) original image; (b) corrupted image (80% missing pixels; PSNR = 6.56dB); (c) SOP (Ram et al., 2013); (d) Proposed.

Table 3: Simultaneous inpainting and denoising results in terms of PSNR - Methods: BP (Zhou et al., 2012); Basic algorithm (Section 2); Subimages framework (Section 4.3).

σ	Data Ratio	Barbara256 (256×256)		
		BP	Basic	Subimages
5	80%	36.80	37.16	37.25
	50%	33.61	33.82	34.02
	20%	26.73	27.45	28.04
15	80%	31.24	31.63	31.79
	50%	29.31	28.92	29.14
	20%	25.17	25.24	25.52
25	80%	28.40	28.92	29.05
	50%	26.79	26.46	26.61
	20%	23.49	23.53	23.74

pixel estimate, which provide the optimal weights to combine the patches when assembling the final image. The experimental results shows that the proposed method is competitive with the state-of-the-art.

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