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# Learning-based image restoration for compressed images

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In this paper, we propose a novel learning-based image restoration scheme for compressed images by suppressing compression artifacts and recovering high frequency (HF) components based upon the priors learnt from a training set of natural images. The JPEG compression process is simulated by a degradation model, represented by the signal attenuation and the Gaussian noise addition process. Based on the degradation model, the input image is locally filtered to remove Gaussian noise. Subsequently, the learning-based restoration algorithm reproduces the HF component to handle the attenuation process. Specifically, a Markov-chain based mapping strategy is employed to generate the HF primitives based on the learnt codebook. Finally, a quantization constraint algorithm regularizes the reconstructed image coefficients within a reasonable range, to prevent possible over-smoothing and thus ameliorate the image quality. Experimental results have demonstrated that the proposed scheme can reproduce higher quality images in terms of both objective and subjective quality.



## 1. Introduction

In order to accommodate with the bandwidth of the Internet and the storage space, image and video compression schemes are highly demanded. In most image and video coding standards, block-based discrete cosine transform (BDCT) coding has prevailed, which aims at reducing the inter-pixel statistical redundancy. However, for the sake of achieving higher compression ratio, BDCT together with the coarse quantization gives rise to the discontinuity of intensities between adjacent blocks which is named as blocking artifacts. Truncating the high frequency (HF) BDCT coefficients would also result in ringing artifacts around the edges. Consequently, the subjective quality of the compressed image is unpleasant and image restoration for ameliorating the image quality is necessary.

The compression artifacts can be suppressed in transform domain (e.g. DCT [1–3], overcomplete wavelet representation (OWR) [4–6]), spatial domain [7–10,12–14], or the combinations [15–21]. For DCT domain deblocking, direct manipulations on DCT coefficients can alleviate the artifacts before the images are fully decoded, which results in lower computations. In particular, Zeng [1] models the blocking artifact as 2-D step edge and suppresses it by applying the zero-masking scheme. A signal adaptive filtering scheme for reducing the blocking artifacts is proposed in Ref. [2], which considers the masking effect of HVS, adaptive weighting mechanism and quantization constraint. Liu and Bovik [3] propose to change a step edge into a slop one through modifying certain DCT coefficients to alleviate the blocking artifacts. Moreover, OWR is employed for deblocking. In Ref. [4], blocking artifacts are removed in wavelet domain by exploiting cross-scale correlations among wavelet coefficients and protecting the edge information. Liew et al. [5]

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propose to suppress blocking and ringing artifacts by analyzing statistical characteristic of block discontinuities as well as behavior of wavelet coefficients across scales for different image features.

Deblocking in spatial domain is proposed by applying spatial-adaptive filtration [7–10]. Apostolopoulos and Jayant [7] propose filtering pixel-by-pixel along the block boundaries to identify and reduce both the blocking and mosquito noise. Kim et al. [8] select two separate filtering modes to process the pixel around the block boundary according to its behavior. In Ref. [9], 1-D horizontal and vertical low-pass filtering for suppressing blocking artifacts and 2-D signal-adaptive filtering for removing ringing artifacts are utilized for postprocessing low bit-rate compressed videos. Based on the non-local denoising algorithms [11], postfiltering in shifted widows (PSW) of image blocks is proposed in Refs. [12–14], which suppresses blocking artifacts by averaging coefficients of neighboring image blocks in the shifted windows.

On the other hand, many researches regarded image compression as a distortion process and put forward iterative algorithms for restoring the original images. The projection onto convex sets (POCS) algorithms [15,20,22–25] represent the prior information of the original as convex sets, and they converge in the intersection of all the sets through iterating projections. The most commonly used convex sets are quantization constraint sets (QCS) and smoothness constraint sets (SCS). In Ref. [15], the deblocking algorithm presents the iterative procedure based on QCS and SCS to restore the coded image to its original artifact-free form. Yang et al. [20,23,24] propose to recover images by incorporating local statistical properties, human perceptual characteristics, and new family of directional SCS based on lineally modeling of image edge structure. Park and Kim [25] narrow down QCS to form the narrow quantization constraint sets (NQCS) for restoring images of higher quality.

However, all of the above traditional postprocessing or restoration algorithms may not recover the HF components [28], which have been discarded during the quantization step of compression. Recently, learning-based image restoration schemes have been proposed to reconstruct a high-quality image by introducing the learned HF information from pre-designed codebooks into the degraded low-quality image. Sheppard et al. [26] introduce nonlinear interpolative vector quantization (NLIVQ) into image restoration. It performs nonlinear restoration of diffraction-limited images concurrently with quantization. Based on NLIVQ, a blind image restoration method [27] is proposed by estimating the HF information of a given blurred image from its low-frequency (LF) information based on the designed multiple codebooks. Liaw et al. [28] propose to restore the image based on the classified vector quantization (CVQ), which employs a codebook to transform the compressed image into a set of indices, and decodes the indices to enhance the compressed image based upon another corresponding codebook. Actually, all of these existed learning-based image restoration schemes share the same assumption as image super-resolution [29,30], which is that the degraded image patch can be employed as the index of the proper HF image patch in the learnt codebook for restoring the image. However, it is an ill-posed problem. Since the number of the degraded image patches is always of smaller amount, whereas the number of HF image patches is of larger amount, one degraded image patch will be mapped to more than one HF patches. This situation often occurs in the quantization step of image/video compression. Many original image/video patches will be quantized into the same degraded patches. Consequently, one degraded image patch can be mapped to many original patches.

Several approaches have been proposed to solve this problem for image super-resolution and restoration. Freeman et al. [29,30] model the LF and HF patches as a Markov network and employ Bayesian belief propagation to find a local maximum of the posterior probability. Liu et al. [31] propose a two-step statistical modeling approach that integrates both a global parametric model and a local non-parametric one. Based on the locally linear embedding (LLE) [32], image super-resolution [34,35] and image restoration for compressed images [38] has been proposed by considering the local geometry during the mapping.

Inspired by image hallucination [33–38], a novel learning-based image restoration scheme is proposed. JPEG compression process is simulated by a degradation model, which comprises signal attenuation and additive Gaussian noise model. First, local filtering process is analyzed and employed to remove the additive Gaussian noise. Second, in order to strengthen the mapping relationship while synthesizing the HF component, a differential image enhancement algorithm is proposed to enforce consistency between primitives to meet the contour smoothness constraint. Third, a Markov-chain model is employed to handle the attenuation process of the degradation model by modeling the relationship between the existent HF primitives in the learnt codebook and the enhanced ones. Finally the quantization constraint algorithm regularizes the DCT coefficients of the restored image within a reasonable range.

The rest of the paper is organized as follows. In Section 2, we firstly introduce the degradation model for simulating JPEG compression process. Subsequently, based on the degradation model, learning-based image restoration scheme is proposed. Detailed information of learning and synthesizing strategy is introduced in Section 3. Experimental results are demonstrated in Section 4. Finally, Section 5 concludes the paper.

## 2. Proposed image restoration framework

### 2.1. Image degradation model

As many high-quality images could generate the same degraded images, restoring the original image from the single degraded image is an under-constrained problem. However, if the degradation process could be modeled accurately, image restoration will appear much easier.

Geman et al. [16] proposed a simple yet efficient image degradation model, which have been widely used for image restoration [16,17] and image quality evaluation [18,19]. The degradation model could be viewed as a simple signal