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A novel image restoration scheme based on structured side information and its application to image watermarking

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ABSTRACT

This paper presents a new image restoration method based on a linear optimization model which restores part of the image from structured side information (SSI). The SSI can be transmitted to the receiver or embedded into the image itself by a digital watermarking technique. In this paper we focus on a special type of SSI for digital watermarking where the SSI is composed of mean values of 4×4 image blocks which can be used to restore manipulated blocks. Different from existing image restoration methods for similar types of SSI, the proposed method minimizes image discontinuity according to a relaxed definition of smoothness based on a 3×3 averaging filter of four adjacent pixel value differences, and the objective function of the optimization model has a second regularization term corresponding to a second-order smoothness criterion. Our experiments on 100 test images showed that given complete information of the SSI, the proposed image restoration technique can outperform the state-of-the-art model based on a simple linear optimization model by around 2 dB in terms of an average Peak Signal-to-Noise Ratio (PSNR) value and around 0.04 in terms of a Structural Similarity Index (SSIM) value. We also tested the robustness of the image restoration method when it is applied to a self-restoration watermarking scheme and the experimental results showed that it is moderately robust to errors in SSI (which is embedded as a watermark) caused by JPEG compression (the average PSNR value remains above 16.5 dB even when the JPEG QF is 50), additive Gaussian white noises (the average PSNR value is approximately 18.4 dB when the noise variance σ^2 is 10) and image rescaling assuming the original image size is known at the receiver side (*e.g.* the average PSNR value is approximately 19.6 dB when the scaling ratio is 1.4).

1. Introduction

When it comes to image restoration, there are different scenarios with different problems to be solved. The classical image restoration problem refers to the operation of mitigating the visual quality degradation caused by some image processing steps [1]. Corruption may come in many forms like blur, noise, geometrical deformation, and camera misfocus. There are many existing algorithms for handling this type of image restoration problems, often based on an optimization model linked to some known information or model of the distortions.

There is another image restoration scenario where the image content is partly lost. Digital image inpainting is one of the image restoration techniques for handling this scenario. Many image inpainting approaches have been proposed in the literature [2–5]. The aim of image inpainting is often to restore a natural-looking image, but the authenticity and accuracy of the image content in the

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missing region are not necessarily guaranteed. There is normally no available side information about the missing region.

The above two image restoration scenarios have been well studied in the literature and many different approaches have been proposed. Many approaches are built upon an energy minimization model involving a smoothness criterion and a regularization (data energy) term which counts some known statistical information about the signal and/or the distortion.

Yet another class of image restoration problems are those with deterministic structured side information (SSI) of the missing region. By structured, we mean that some well-defined side information about missing pixels is available somewhere. One typical problem is Discrete Cosine Transform (DCT) coefficients restoration where one or more DCT coefficients of each block are missing in DCT-transformed images, so they have to be restored from other available DCT coefficients. A special case of this problem is DC coefficients estimation from AC coefficients, and has been studied as early as in the 1980s by Cham and Clarke [6] and new methods have also been proposed very recently [7,8] which can find applications in cryptanalysis of selective multimedia encryption. The state-of-the-art approach of solving this problem is to use a linear optimization model where the objective is to minimize the total discontinuity between all pixel pairs in the image (*i.e.* one form of total variation minimization). Compared with the traditional image restoration scenarios, in these models there are additional constraints representing some SSI which cannot be easily incorporated into the objective function and could potentially make the problem harder to solve.

The SSI based image restoration problems can also find applications in digital watermarking systems when the capability of recovering manipulated regions of a watermarked image is required (*e.g.* for forensic investigation purposes). In these applications, the SSI can be transmitted to the receiver or embedded into the image itself, so it is possible to choose the structure of the side information. In this paper, we focus on the application scenario where side information with a special structure is self-embedded as a digital watermark to assist image restoration at the receiver's end. In this application, the self-restoration watermark will work with an authentication watermark to localize manipulated regions that need restoring. In the following we briefly overview some related works on self-restoration watermarking.

Ho et al. proposed a semi-fragile authentication watermarking algorithm with self-restoration capability using the Pinned Sine Transform (PST) in [9]. The tamper detection accuracy rate of this scheme was shown to be higher than 98% even with light non-malicious image processing operations. The bits as restoration watermark were generated from the image coefficients after PST, and embedded into the least significant bits (LSBs) plane of the original image. However, the LSB based self-restoration watermark is fragile and could be easily distorted. To reduce the size of the restoration watermark and to improve the robustness, Region of Interest (ROI) self-restoration schemes were proposed in [10,11]. The two restoration schemes were shown to be more robust against JPEG compression. In addition, the quality of the restored image in ROI was improved compared with other Non-ROI restoration methods. However, the size of the ROI is limited if any region of the image should be protected for potential manipulation.

If any region of the image needs protecting, much more information is required to be hidden in the restoration watermark. On the other hand, semi-fragile watermarking requires more robustness against common signal processing operations, which will normally limit the embedding capacity. How to balance the requirements for both higher capacity and more robustness is an open research question. Lin and Lin [12] introduced a semi-fragile watermarking scheme with self-restoration ability based on (t,n) secret sharing and Reed–Solomon (RS) code. The restoration watermark is generated from the four lowest DCT coefficients and encoded as an RS code. This watermarking scheme was shown to be moderately robust to image processing operations including JPEG compression, noise and brightness adjustment. One major issue of this scheme is that the percentage of the tampered region is limited to around 16.66%. Phadikar et al. [13] proposed a semi-fragile watermarking scheme for image restoration based on halftoning. The restoration watermark is generated by halftoning the down-sampled image, and then embedded in Low-High Level 1 (LH1) and High-Low Level 1 (HL1) subbands of Discrete Wavelet Transform (DWT) coefficients by the Quantization Index Modulation (QIM) method. Experiments showed that the tampered region could be restored if its size is less than 40% of the whole image. Wang et al. [14] proposed a semi-fragile self-restoration watermarking scheme based on linear regression. In this scheme, the mean value of each 4×4 block is used as the restoration watermark. After a tampered 8×8 block is identified, its four lowest DCT coefficients are restored from linear combinations of mean values of its four 4×4 sub-blocks, where the weights of linear combinations are obtained via linear regression. The algorithm was shown to be moderately robust to JPEG compression and the percentage of the tampered region can go up to 50%.

In this paper, we propose an enhanced image self-restoration method based on a linear optimization model with mean values of 4×4 blocks as SSI (*i.e.* the self-restoration information used in the semi-fragile watermarking scheme proposed in [14]). Our experimental results on 100 test images showed that the proposed restoration method can recover the original image with better overall visual quality than the original linear regression based method and the simpler linear model in [8]. The image quality is assessed by both objective metrics (via two image quality assessment (IQA) metrics: Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index (SSIM) [15]) and subjective means (by manual inspection of the authors).

The rest of the paper is organized as follows. In Section 2, a detailed description of our proposed restoration method is given. Then, the self-restoration watermarking system, from which the structured side information comes and to which the proposed restoration model is applied, is