Signal Processing: Image Communication 65 (2018) 187–200

Contents lists available at ScienceDirect

Signal Processing: Image Communication

journal homepage: www.elsevier.com/locate/image

Towards a tone mapping-robust watermarking algorithm for high dynamic range image based on spatial activity

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ARTICLE INFO

Keywords:
High dynamic range imaging
Digital watermarking
Tone mapping
Spatial activity

ABSTRACT

High dynamic range (HDR) imaging has received increasing attention due to its powerful capacity to represent real scenes as perceived by human eyes. However, studies on effective HDR image watermarking algorithms remain limited. In contrast to watermarking algorithms proposed for low dynamic range (LDR) images, several critical problems, such as the peculiar HDR floating-point number data format and various tone mapping operators (TMOs) that are widely used to adapt HDR images to conventional displays, need to be properly addressed. Hence, a novel HDR image watermarking algorithm robust against the effects of TMOs is proposed in this paper. Two important spatial activity concepts, i.e. the activity of robustness and activity of perception, are respectively defined to characterize the spatial diversity of the robustness and imperceptibility of tone-mapped images. Then, nonsubsampled contourlet transform and singular value decomposition are successively performed to extract the associated structural information which is invariable in HDR images and their corresponding tone-mapped images. In addition, hierarchical embedding intensity and a hybrid perceptual mask are designed to enhance the imperceptibility and robustness of the HDR image watermarking. Experiments with numerous HDR images and TMOs were conducted and the results show that the proposed algorithm is superior to the current state-of-the-art watermarking algorithms in terms of imperceptibility, robustness and embedding capacity.

1. Introduction

In reality, a scene with wide luminance variations ranging from faint starlight to direct sunlight can be effectively perceived by human eyes [1]. However, existing low dynamic range (LDR) images adopt 8 bits/color/pixel to represent a limited range of luminance, and often include overexposed or underexposed phenomena, resulting in some loss of scene information. To address this deficiency, high dynamic range (HDR) imaging technology employs floating-point numbers to represent a wide range of luminance, which can represent the fidelity of a real scene accurately [2] Hence, HDR image/video has recently received significant attention in many multimedia applications, such as digital photography, ultra-high-definition movies and television, video games, remote sensing detection, and medical imaging [3–5]. Unfortunately, HDR image display devices are difficult to popularize because of their cost and technical problems. Thus, HDR images must undergo a tone mapping (TM) procedure to generate adaptive LDR data for conventional displays [6]. For an HDR image, the TM processing can make the pixel values of the different luminance regions fluctuate significantly. In fact, various TM operators (TMOs) have now emerged, and each has characteristics that differ from those of the others. As a digital image itself is easy to copy, spread and tamper with, the issue of intellectual property protection for HDR images needs to be solved urgently [7]. Although LDR image watermarking is quite mature, the existing watermarking technologies cannot be directly applied to HDR images because of their peculiar floating-point data format and the various effects of TMOs [8]. Therefore, it is particularly important to design an efficient HDR image watermarking algorithm robust against the effects of TMOs.

Recently, some researches on HDR image watermarking have been developed rapidly, and the existing algorithms can be divided into two categories: fragile watermarking and robust watermarking algorithms as shown in Fig. 1. The fragile watermarking algorithms for HDR images mainly rely on the characteristics of the HDR image storage format and embed watermarks in the pixel domain. Yu et al. [9], Wang et al. [10] and Chang et al. [11] directly exploited the same mapping relationship in different channels of the HDR image's RGBE format to realize lossless watermark embedding. Using the least significant bit approach, Cheng et al. [12], Li et al. [13] and Lin et al. [14] embedded watermarks

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https://doi.org/10.1016/j.image.2018.04.005
Received 23 June 2017; Received in revised form 6 April 2018; Accepted 6 April 2018
Available online 13 April 2018

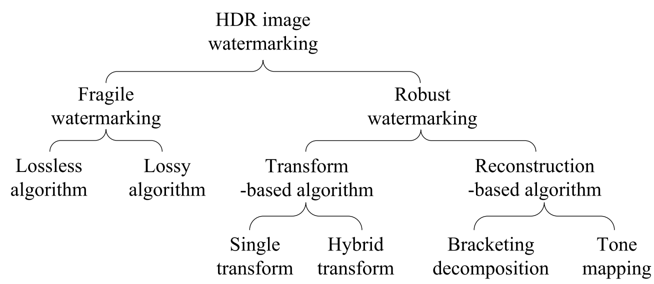

Fig. 1. Classification tree of the existing HDR image watermarking algorithms.

in HDR images with the RGBE, LogLuv (TIFF) or OpenEXR format, respectively. These algorithms are blind and have achieved some good results in terms of imperceptibility and embedding capacity, so they can be used for tamper detection and secret communication. But the HDR image features in these algorithms have not been considered, and the robustness of these algorithms is not high, and their applications are also relatively limited. Hence, this paper focuses on robust watermarking for HDR images.

Compared with fragile watermarking, previous robust HDR image watermarking algorithms primarily involve content-based characteristics and can be divided into two categories, i.e., transform-based algorithms and reconstruction-based algorithms. The former, i.e., the transform-based algorithms, often embed a watermark in a transform domain. Guerrini et al. [15] and Solachidis et al. [16] employed kurtosis or just noticeable difference as features, respectively, and embedded watermarks in the discrete wavelet transform (DWT) domain. Furthermore, both designed visual mask to enhance the imperceptibility. Following these algorithms, some algorithms have been designed in hybrid transform domains, including bilateral filtering with DWT [17] and the Radon–discrete cosine transform with DWT [18], and the watermarks are embedded in high-frequency subbands. The latter, i.e., the reconstruction-based algorithms, embed a watermark in LDR images derived from the HDR image, and then rebuild the stego HDR image. Solachidis et al. [19] embedded a watermark multiple times in each LDR image obtained through bracketing decomposition. However, their algorithm results in poor imperceptibility. Wu et al. [20] embedded a watermark into an LDR image of the HDR image obtained using a special TMO. However, this algorithm is only robust to the predetermined TMO. Clearly, this is not realistic in practical applications due to the existence of various TMOs. In brief, based on the characteristics of HDR images, the previous robust watermarking algorithms have made some progress towards robustness against TMOs, and shown relatively good performance in intellectual property protection such as copy detection and copyright certification. However, there are still some deficiencies as follows. (1) The effects of TMOs have not been sufficiently understood. Currently, numerous TMO types exist. Therefore, it is inaccurate to claim watermarking robustness against the TM process if robustness against only a few TMOs has been achieved. The essential characteristics of the TM process need to be analyzed in depth and accurately. (2) The features extracted for watermark embedding are not accurate. For robust HDR image watermarking, a method for extracting some features with strict invariance between an HDR image and its tone-mapped image is key. Currently, the problem has still a lack of reliable theoretical basis and detailed description. (3) The performance of HDR image watermarking algorithms has not yet been fully analyzed. With respect to imperceptibility, the distortion of the HDR images has been considered, but this has not yet been analyzed in detail for tone-mapped images.

Towards filling this gap, we propose a blind tone mapping-robust watermarking (TMRW) algorithm for HDR images, which can be used for copy detection and copyright certification. In other words, the watermark extraction only needs the stego HDR image or its tone-mapped image. The proposed algorithm has two major contributions. On the one hand, through a detailed analysis of the TM process, we propose the idea of spatial activity (SA), which consists of the activity of robustness (AoR) and activity of perception (AoP), to characterize the essential distinction between HDR and LDR image watermarking. Based on this idea, we analyze the reason why the existing LDR image watermarking algorithms cannot be applied directly in the HDR image domain in detail. On the other hand, the hierarchical embedding intensity (HEI) and hybrid perceptual mask (HPM) methods are designed according to the analysis of TM, SA, and the human visual system (HVS). In robust watermarking for LDR images, singular value decomposition (SVD) has been widely used by modifying the singular values [21] or unitary matrix [22] to embed watermarks. However, the algorithm's performance is uncontrollable when the global and equal-intensity embedding methods in [21] and [22] are directly adopted into the HDR image domain. To address this deficiency, the HEI and HPM are designed. As the watermark can be embedded in different regions with different intensities, the robustness and imperceptibility can be effectively guaranteed both in stego HDR images and tone-mapped images. In conclusion, to meet the robustness against TMOs, we modify the consistent structural information extracted from the HDR images, taking advantage of the nonsubsampled contourlet transform (NSCT) and SVD. In addition, the HEI and HPM are employed to enhance the imperceptibility of stego images. Experimental results on three HDR image databases containing 30 HDR images show that the proposed algorithm is sufficiently robust against 27 representative TMOs. Moreover, both the stego HDR images and their tone-mapped images achieve high visual quality.

The rest of this paper is organized as follows. The concept of SA is described based on the analysis of TMOs in Section 2 and the proposed algorithm is presented in Section 3, which includes our motivation and the HEI and HPM methods. Next, the experimental results and comparisons are detailed in Section 4. Finally, Section 5 gives the conclusions and discusses possible future work.

2. Analyses of TMOs and spatial activity

In image processing, dynamic range d is the logarithm of the ratio of the maximum to the minimum luminance of a digital image, that is $d = \log_{10}(L_{\max}/L_{min})$, where the unit of luminance is cd/m^2. In a real scene, there is a very wide range of luminance ranging from 10^{-3} cd/m^2 to 10^6 cd/m^2, which is as many as nine orders of magnitude [23]. At present, an LDR image adopts 8 bits/color/pixel to represent a real scene, which means that its dynamic range is less than three. Moreover, an HDR image employs 32 or 48 bits/pixel with a dynamic range of more than nine. Obviously, the wide data range in an HDR image/video, which differs from that of an LDR image, is one of the primary problems that HDR image/video watermarking must face.

Moreover, TMOs are widely used to adapt HDR images to conventional displays. With the rapid development of TM research in recent years, various TMOs have emerged and achieved good performance [24]. However, experiments with TMOs based on psychophysics [25–27] have shown that different TMOs have advantages with respect to different aspects of perception, and no single method can achieve optimal perception in all respects. Thus, the appropriate TMO should be selected to adapt for the diverse types of LDR displays that exist in practical applications. For HDR image watermarking, this means that a robust watermarking algorithm must be valid for all types of TMOs. Obviously, this is a great challenge for robust HDR image watermarking.

Here, the existing TMOs are briefly overviewed and analyzed. In fact, each TMO has characteristics that differ from those of the others, but the ultimate goal of TM is to generate adaptive LDR data retaining as much information, such as the scene details and the local contrast, as possible from the original HDR objects while reducing the overall contrast. Currently, various TMOs have emerged, but they can still be divided into two categories [24]: (1) Global TMOs, in which all pixel values