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High Dynamic Range Image Watermarking

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Abstract: High Dynamic Range (HDR) images represent the future format for digital images since they allow more sensitive rendering. However, nowadays special types of preprocessing collectively known as tone mapping operators are needed to adapt HDR images to currently existing displays. Tone mapped images, although of reduced dynamic range, have nonetheless high quality and hence retain some commercial value. In this paper we propose a solution to the problem of HDR watermarking, *e.g.* for copyright embedding, that should survive tone mapping. Therefore, the requirements imposed on the watermark encompass imperceptibility, a certain degree of security and robustness to tone mapping operators. The proposed watermarking system belongs to the blind, detectable category, it is based on the QIM paradigm and employs a higher order statistic as feature. Preliminary experimental analysis shows positive results; more work is needed and currently underway.

1. Introduction

High Dynamic Range (HDR) images represent the radiance of scenes captured by a device or generated by an artificial rendering system. Due to the wide dynamic of visible luminance, their pixels usually take floating point values and thus HDR images cannot be directly rendered by present-day displays. In fact, the original values must be adapted in order to fit the dynamic and color gamut of the target device. This adaptation, which transform a “scene referred” image into an “output referred” one, can be obtained by applying a so-called tone mapping (TM) process. Tone mapping techniques are all non-linear in nature and could vary depending on the algorithm: they can consist in something as simple as some kind of global transformation (*e.g.* clipping followed by histogram equalization) to more complex non-linear local processing.

Tone mapped images keep some commercial and intellectual value because of their high quality despite their limited dynamic range and hence they are possible targets for misappropriation or misuse by malevolent entities. This is an unavoidable problem which will have to be faced as soon as HDR images and their tone mapped versions reach widespread diffusion - and they certainly will. A possible solution is represented by data hiding techniques, such as digital watermarking, which would try to embed into any HDR image some kind of information that should have to stay therein even after a tone mapping processing. To the authors’ knowledge, no major work concerning the problem of HDR image watermarking has been widely diffused yet.

In this paper we therefore propose to embed a watermark to enforce or simply communicate property rights of a given HDR image to any possible user. The watermark needs only to survive to those processing that preserve perceptual value, as in the case of TM operators, while as soon as the tone mapped image loses its high quality, due to some other kind of manipulation, its commercial value is greatly diminished and therefore watermark loss could be afforded. This obviously implies that the watermark must be highly imperceptible. Depending on the application framework, the watermarking system could be either blind or non-blind, according to the availability of the original image during the watermark recovery; here we conduct a preliminary analysis by embedding a detectable (*i.e.* only the watermark presence must be assessed, but the watermark by itself bears no information), blindly recoverable, imperceptible watermark robust to non-linear value-metric attacks, using an improved version of the algorithm presented in [1]. The latter was originally proposed for 8 bpp grayscale images; however its structure and the particular nature of the problem at hand makes it suitable for a preliminary analysis of its feasibility in the HDRI context too.

The remainder of the paper is organized as follows. In Section 2, a thorough description of the watermarking system is reported, highlighting how it achieves its effectiveness in the proposed problem. Then, Section 3 shows some experimental results on a set of 20 HDR images, both in terms of detection performances and imperceptibility. Finally, Section 4 draws some conclusive remarks.

2. Description of the Proposed System

In this section we describe our proposed system for HDR image watermarking. We will first discuss the overall system framework in Subsection 2.1, assuming to have already at our disposal a reliable watermarking system, imperceptible and robust to both linear and non-linear pixel value-metric attacks, to use as a block box. The discussion on the watermarking system itself is postponed to Subsection 2.2.

2.1 System Framework

The ideal objective of our system would be to embed a detectable watermark into the original HDR image robust to any TM operator, that is the watermark should be still detected in tone mapped versions of the watermarked HDR image regardless of the particular TM operator used. It is arguable that all

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the tone mapped versions of a given HDR image are perceptually similar, in the sense that each of these can be obtained from any of the others by means of some unknown non-linear operator of mild strength and a global linear transformation (such as brightness adjustment); a similar point of view is endorsed by [2]. Since the watermarking system proposed in [1] is invariant to linear transformations and is robust to non-linear attacks, it is expectable that if the watermark is still present in one of the tone mapped images, then it should also be present in all the other tone mapped images as well.

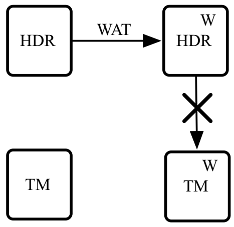
First, we need to obtain a signal with characteristics compatible with the working principles of the considered watermarking method, namely a 2-D luminance image. On the other hand, it is reasonable to work in the luminance domain for watermark robustness purposes, since tone mapping is likely to strongly tamper with the chrominance components in an unpredictable way (*e.g.* not monotonically). Therefore the first step of our system must be luminance component extraction from the HDR image, which will carry the watermark, while chrominance components will be left untouched.

Figure 1 schematically shows how the watermarking system could be conceived in three different ways. The most straightforward approach would be to watermark the HDR image and then hope that the watermark survive any successive TM process: see Figure 1(a). However, the tone mapping operation itself could always be pictured as a strong non-linear transformation which goes well beyond the robustness limit of the watermarking system at hand. Moreover, it would be probably an impossible task to make the watermark robust to such strong processing without introducing perceptible artifacts in the HDR watermarked image.

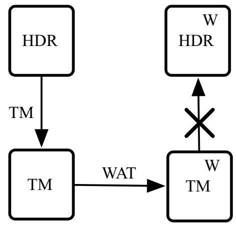
The successive thought would be to watermark a reference tone mapped image obtained from the HDR original image, as depicted in Figure 1(b). The above discussion implies that any other tone mapped image obtained through a different TM algorithm should also contain the watermark. Unfortunately, as it turns out, it is impossible to watermark directly a tone mapped image, since the TM operation is almost always non-invertible, especially in the case of higher quality tone mappings, and hence a watermarked HDR image can't be constructed (so it is impossible to obtain other watermarked tone-mapped images through TM processes different from the reference one).

The solution to this problem is illustrated by Figure 1(c). In [3] the LogLuv encoding for HDR images is presented; therein, it is implied that taking the logarithm of the luminance of any HDR image is by itself an operation somewhat comparable to tone-mapping. If this is the case, the transformation RGB-to-LogLUV can be considered as a pseudo-TM, meaning that any tone mapping algorithm will approximately handle the luminance component in a similar way. Since this transformation is readily invertible via LogLuv-to-RGB transformation, it represents a perfect candidate to approximate actual TM operators while allowing to obtain in a simple way the HDR watermarked image.

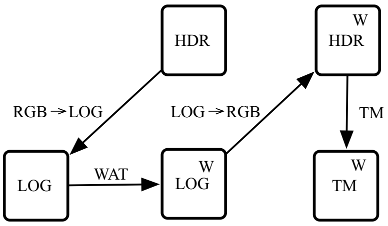
Hence, our proposed system works as follows. Initially, a reference log-luminance image is obtained from the original HDR by applying RGB-to-LogLUV transformation as described in [3]. Then, the algorithm embeds the watermark in the reference image. Lastly, the reverse transformation LogLuv-to-RGB is applied obtaining the watermarked version of the given original HDR image. Note that the watermarked HDR image hasn't the watermark embedded, but its LogLuv equivalent has. When TM is applied to the watermarked HDR image, the watermark is back again as long as the assumption of similarity between logarithm and tone mapping in the luminance component holds. The effectiveness of this approach is proved in Section 4.



(a) First hypothetical method: the watermark doesn't survive TM.



(b) Second hypothetical method: there is no way to invert TM.



(c) Third hypotethical method: using a LogLuv reference image to approximate TM.

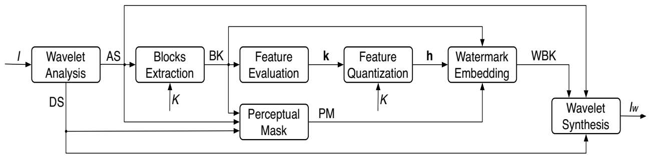
Figure 1. Sketch of HDR watermarking possible methods.

2.2 Watermarking System

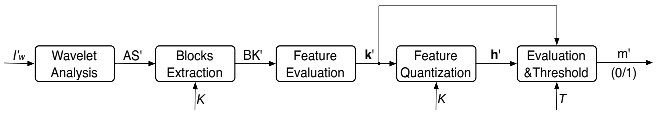
This Subsection briefly describes in turn the embedder and the detector used in the watermarking process of the reference log-luminance image; for more details the reader is referred to [1]. All the crucial steps of the system need a secret key K as a parameter to improve security.

The embedder is shown in Figure 2(a). First of all, N blocks of random shape and position are extracted from the approximation subband (AS) obtained by a two-level wavelet decomposition. Using this subband as the watermark domain enhances robustness because the coefficients are correlated thanks to the low-pass characteristics of the AS. However, imperceptibility is more difficult to achieve in this domain; in our system it is provided by a perceptual mask PM derived in the wavelet domain and acting as a constrain on the embedding process described below.

Next, a higher-order statistic, which represents our feature that has to be approximately invariant to attacks, is extracted from each block. To be more precise, every component of the feature vector $\mathbf{k}$ is the sample kurtosis (which is the fourth-order central standardized sample moment) evaluated on the



(a) Embedder flowchart.



(b) Detector flowchart.

Figure 2. Watermarking system overview.

coefficients comprised in each block.

Then, the embedder encodes a bit in each block following the Quantization Index Modulation (QIM) paradigm and hence by suitably quantizing every feature vector component by means of a numerical procedure. The QIM paradigm is slightly modified by using non-uniform quantization to better match feature behavior, given that the invariance requirement is less strictly met as its value increases. The quantization codebook is shifted by a random quantity given by K for added security.

Finally, the watermarked log-luminance image is obtained by wavelet reconstruction using the watermarked AS and the untouched detail subbands (DS).

The detector, depicted in Figure 2(b), decodes each bit separately by following in the steps of the embedder until it obtains a received feature vector $\mathbf{k}'$. Then, for each block, the distance between the received feature value and its nearest quantized value (using the same codebook as the embedder) is evaluated: if it is less than a quarter of the quantization step then the block is considered correctly decoded, otherwise it is counted as an incorrectly decoded block. The detector finally takes a decision using a threshold T on the number of correctly decoded blocks out of N.

Note that given the high non-linearity of the embedding problem discussed above and the perceptual mask constrain, it is possible that the numerical procedure underlying the quantization process is not successful; therefore, a certain number of blocks may fail the decoding process even if the detection is performed on the watermarked reference log-luminance image. Obviously, the number of these defective blocks must be as small as possible and certainly not sufficient to cause a miss by themselves only.

3. Experimental Results

This section shows how promising our approach is by means of experimental tests. Two types of experiments have been carried out and reported in each of the following Subsections: detection performances, concerning watermark robustness against tone mapping, and watermark imperceptibility assessment.

The experimental tests have been conducted on 20 HDR images taken from [4] and [5]. We extracted $N = 250$ blocks in the watermarking process. The tone mapping operators used here are respectively Drago's, Durand's, Fattal's, Mantiuk's, Pattaniak's and Reinhard's method: see [6] and references therein for more information.

3.1 Detection Performances

In this Subsection we evaluate the detection performances, that is we check whether the watermark is still detectable in tone mapped versions of the HDR images of our database which have been previously watermarked as described in Section 2.

It is important to note that for unwatermarked images the probability of correctly decoding a block is 0.5, given the complete independence between the received feature value and its quantized value, whereas for watermarked blocks there should be little distance between the latter. Therefore, the false alarm probability P_{FA}, defined as the probability of wrongly deciding an unwatermarked image as watermarked, is given by a sum of binomial factors depending on the threshold T:

$$P_{FA} = \sum_{i=T}^{N} \binom{N}{i} \left(\frac{1}{2}\right)^{-N} \tag{1}$$

Increasing the threshold T, which has to be greater than half of the blocks to make sense, obviously decreases P_{FA}. On the other hand, the miss probability P_M, which conversely is the probability of wrongly deciding a watermarked (and possibly processed) image as unwatermarked, will be higher as the threshold increases since fewer blocks are allowed to be incorrectly decoded. The miss probability P_M for a given threshold T could be either theoretically estimated or experimentally evaluated. Varying the threshold T, a ROC (Receiver Operating Characteristics) can finally be drawn, depicting P_{FA} versus P_M, usually in logarithmic scale.

Since our test are conducted on a small database, estimating P_M by counting how many misses in the tone mapped images have occurred is impossible. To obtain an approximate figure for P_M, we evaluate a mean block error probability $\overline{p}$ and then we assume that every block in every tone mapped image has the same decoding error probability $\overline{p}$. Consequently, P_M could be evaluated as follows:

$$P_M = 1 - \sum_{i=T}^{N} \binom{N}{i} (1-\overline{p})^i \, (\overline{p})^{N-i} \tag{2}$$

The corresponding ROC is depicted in Figure 3 ($\overline{p} = 0.267$). As can be observed, miss probability slightly higher than 10^{-5} are achievable when P_{FA} is around 10^{-4}. However, using the mean decoding error probability may lead to overly optimistic results since some HDR images are more intrinsically fragile to a given TM operator than others.

Table 1 reports for each TM operator the actual misses encountered for P_{FA} approximately equal to 10^{-4} and 10^{-6} respectively (corresponding to $T = 89$ and $T = 96$). As expected, more misses than those predicted by Figure 3 are encountered. However, it is also worth noting that the tone mapped images reporting a detection miss possess almost always noticeable lower perceptual quality than the other ver-

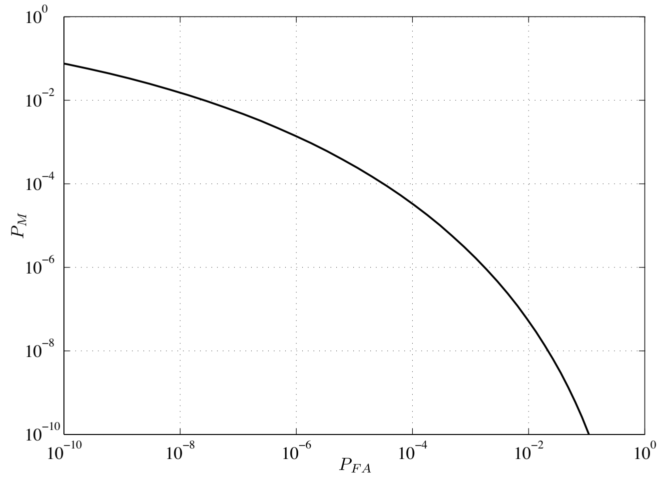


Figure 3. Projected ROC using $\overline{p} = 0.267$.

sions in which the watermark is found, hinting to possible overly aggressive processing.

3.2 Imperceptibility Assessment

The imperceptibility is validated through Visual Difference Predictor (VDP) [7] analysis. The VDP distance, which indicates the percentage of pixels in the tested image that will be perceived differently with a given probability (75% or 95%), has been obtained by comparing the original HDR with the corresponding one carrying the watermark. On average the values for these indicators are $VDP_{75\%} = 0.59\%$ and $VDP_{95\%} = 0.36\%$ which are satisfactory considering the used perceptual mask, not necessarily suitable for HDR signals.

4. Conclusions

In this paper we presented an algorithm representing the first step toward a practical HDR image detectable watermarking system with the requirements of imperceptibility and robustness against tone mapping operators as well as security. A previously developed watermarking system for grayscale image has been employed in the LogLuv domain, which is considered here as an invertible approximation of TM operators. Experimental results have proven to be very encouraging, especially considering how no ad-hoc system adjustment has been implemented yet. A number of these will in fact be considered in our future work. First, the perceptual mask was not conceived for the LogLuv domain and therefore its behavior may be improved. Then, given that increasing the number of blocks N is highly beneficial to robustness, using more blocks for wider images could boost detection performances. Finally, it could be interesting to switch to non-blind watermarking, which will probably be the most likely applicative scenario for HDR image watermarking. This would allow to choose which blocks to use for embedding, avoiding those difficult to watermark; to this aim, an extensive study of feature variability could be of great aid in determining in which zone of the image the watermarking system is more effective.

	Drago02		Durand02		Fattal02	
$\approx P_{FA}$	10^{-4}	10^{-6}	10^{-4}	10^{-6}	10^{-4}	10^{-6}
Misses	0	0	1	0	5	2
	Mantiuk06		Pattaniak00		Reinhard05	
$\approx P_{FA}$	10^{-4}	10^{-6}	10^{-4}	10^{-6}	10^{-4}	10^{-6}
Misses	2	1	2	2	1	0

Table 1. Actual miss figures.

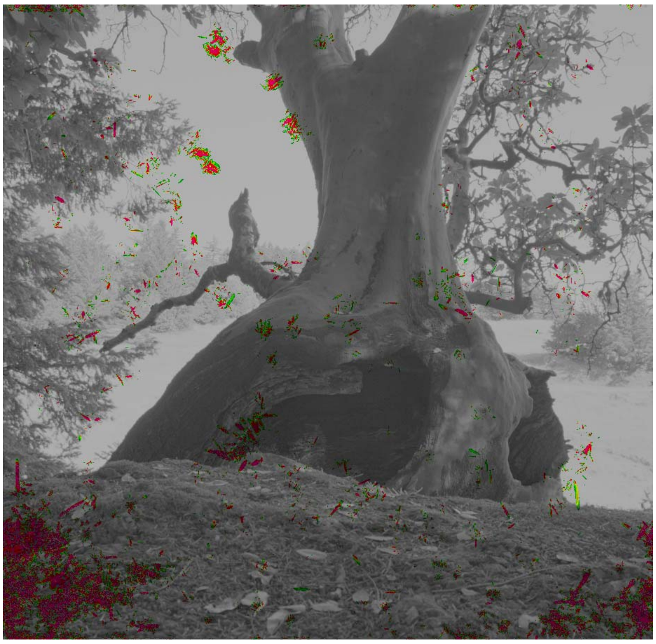


Figure 4. VDP map (darker pixels) for the worst case image, ”Tree” taken from [4]: ($VDP_{75\%} = 2,72\%$ and $VDP_{95\%} = 1,86\%$.)

References

[1] F. Guerrini, R. Leonardi and M. Barni, “Image watermarking robust to non-linear value-metric scaling based on higher order statistics”, in *Proc. of ICASSP 06*, May 2006, vol. 5.

[2] R. Mantiuk and H.P. Seidel, “Modeling a Generic Tone-Mapping Operator”, in *Proc. of EUROGRAPHICS’08*, 2008, vol. 27(2), pp. 699-708.

[3] G. Ward Larson, “LogLuv encoding for full-gamut, high-dynamic range images”, in *Journal of Graphics Tools*, 1998, vol. 3(1), pp. 15-31.

[4] Anyhere Software Database, cured by G. W. Larson, url: www.anyhere.com/gward/hdrenc/pages/originals.html.

[5] Munsell Color Science Laboratory Database, url: http://www.cis.rit.edu/mcsl/icam/hdr/rit_hdr.

[6] PFStmo, Implementation of Tone Mapping Operators by Max Planck Institut Informatik, url: http://www.mpi-inf.mpg.de/resources/tmo.

[7] K. Myszkowski, R. M. and H. P. Seidel, “Visible difference predictor for high dynamic range images”, in *International Conference on Systems, Man and Cybernetics*, 2004, pp. 2763–2769.