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Recent Trends in Color Image Watermarking

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Abstract. *This article provides a review of the state of the art in watermarking techniques specifically designed for color images. It presents an overview of the color image watermarking methods and an analysis of the advantages and disadvantages of several recent schemes. It also presents solutions and arguments supporting the idea that methods based on human visual sensitivity provide more robust watermarks than do other ones. Furthermore, this article treats the question of the evaluation of watermarking quality according to fidelity. Finally, based on this analysis, research directions in color image watermarking are suggested. © 2009 Society for Imaging Science and Technology.*
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INTRODUCTION

The main motivation of this article is to provide an overview of watermarking techniques specifically designed for color images. The principle of watermarking is generally to embed data into a host image by introducing changes imperceptible to the human eye but which allow the data to be easily recoverable by a computer program. The locations of the embedded data in the image are determined by a secret key so that attackers cannot have direct access to it. Watermarking algorithms are useful in the domains of broadcast monitoring, owner identification, proof of ownership, transaction tracking, content authentication, copy control, device control, and legal enhancement applications.[1] Appropriate to the application considered, watermarks must be robust to different attacks such as watermark removal, watermark duplication, unauthorized detection, or print-and-scan process; signal processing algorithms such as compression, coding transformations, contrast enhancement, color enhancement, dithering, resampling; or geometrical transformations such as rotation, translation, cropping or scaling must be considered (see Figure 1).

Particularly, print-and-scan attack is a challenging problem for most of digital watermarks. Indeed, with the development of the Internet and multimedia, the protection of intellectual property rights for printed and/or scanned images is a key problem. The second section of this paper therefore, deals with the particular problem of print-and-scan process for watermarked images. Along with carrying a large volume of of data, a watermark must be both robust to some attacks and imperceptible to the human eye. These three conflicting properties are introduced in the third section of this paper.

Although many methods have been proposed to watermark gray level images, only a few methods have been applied to color images. The first reason for this is the difficulty for color watermarks to withstand color-to-gray conversion. In the last decade, color image watermarking algorithms were based either on an additive process or a multiplicative process.[2] Most of these methods embed data in one or independently in each of the three color components. Therefore they can be considered as scalar approaches. However, color cannot be considered as a vector of independent components, and we will see below how the correlation between these components is accounted for by some color watermarking approaches.

The fact that the human visual system (HVS) is more or less sensitive to variations in the spatial or in the frequency domain has always been exploited in watermarking. But recently, there is a trend towards watermarking techniques that take into account the sensitivity of the HVS more deeply. Accordingly we will discuss solutions and arguments supporting the idea that these methods provide more robust watermarks than other ones.

Most of the watermarking schemes embed data either in the spatial domain or in the frequency domain. By working in the spatial domain, the pixel values of the host images are directly modified to embed the watermark. On the other hand, the schemes which work in the frequency domain require transforming the images by using transformations such as discrete cosine transformation (DCT), discrete Fourier transformation (DFT), discrete wavelet transformation (DWT), etc. Then, the resulting frequency coefficients are modified to embed the watermark, and finally the inverse transformation is applied to get the watermarked images. Thus, these schemes require more processing time than the schemes which embed data in the spatial domain. However, since they are working in the frequency domain, these schemes are more robust to rotation, scaling and translation. More recently, new schemes have been proposed which are based on a color image quantization process. These will be discussed and the advantages and disadvantages of each of these three approaches will be presented.

Finally we will analyze the different solutions used to evaluate watermarking quality according to fidelity, and conclude the article with a discussion about color image

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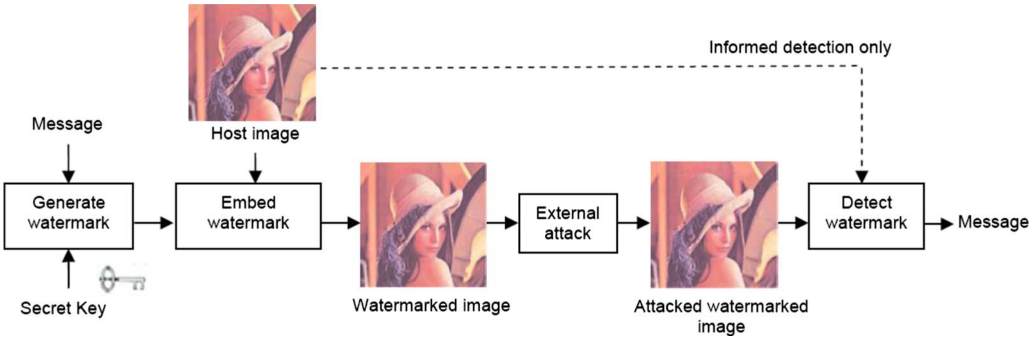


Figure 1. Flowchart of a watermarking scheme.

watermarking along with some suggestions for future research directions.

PRINT-AND-SCAN PROCESS

Figure 2 represents the print-and-scan attack in the watermark process.[3] The printing transforms a digital image to an analog one while scanning converts an analog image to a digital one.[4] The distortions provided by this attack are multiple. The first ones are global geometric distortions such as rotation, scaling or cropping, mainly due to the scanning. The second ones modify the colors of the images. They are due to brightness and contrast variations, gamma correction, halftone process, or noise addition. Furthermore, Song emphasizes that the colors of the images are converted into different color spaces during a print-and-scan process.[4] Indeed, an image can be displayed in an RGB color space on a computer monitor, be edited in the HSI color space and be published in the CMYK color space. Since these color spaces all have different color gamuts, some information may be lost during the conversions among them.

Yu proposes to summarize the particularity of the print-and-scan attack around three points:[5]

Randomness. According to the printer and scanner used, the resulting image of a print and scan process may vary considerably.

Human-dependency. During the print and scan process, the operator is free to adjust some parameters as by contrast variation, gamma correction, rotation, scaling or particular artistic operations.

Indistinguishability. A printed image cannot be analyzed without being scanned. The printing and the scanning cannot be separated from each other nor can the distortions provided from both.

Since the influence of the print-and-scan process on watermarks has not been fully investigated, it is not easy to design watermarks robust to this kind of attack. Furthermore, the next section shows that robustness is not the only characteristic required by a watermarking system.

THE CONFLICTING PROPERTIES OF WATERMARKING SYSTEMS

Even if several features can be used to characterize watermarking techniques, only four features are commonly cited in the literature: the hiding capacity, the perceptual transparency, the robustness, and the security aspects. Whatever the application, most of the watermarking methods attempt to find a trade-off among these features.

Three properties are commonly examined to determine the suitability of a watermarking scheme: fidelity, capacity, and robustness (see Figure 3).

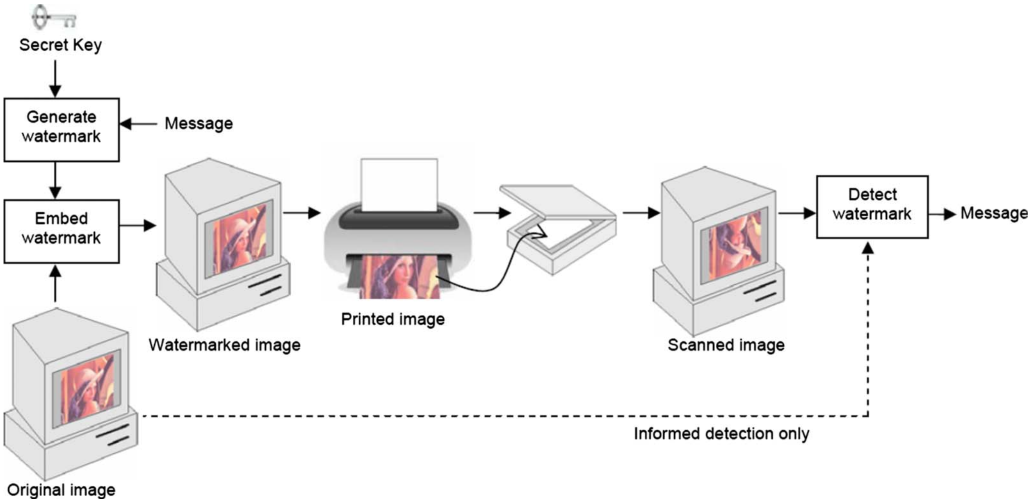


Figure 2. Print-and-scan attack in the watermark process.

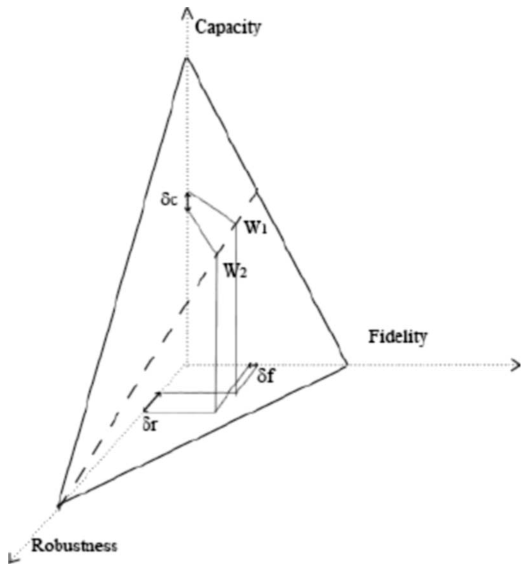


Figure 3. The conflicting properties of watermarking systems. W1 and W2 are two watermarking schemes. The robustness of W1 is lower than this of W2 but the fidelity of W1 is higher than this of W2.[6]

- The *fidelity* corresponds to the visibility of artifacts introduced into an image by the watermarking process. Cox et al. defined the fidelity as the "perceptual similarity" between watermarked and unwatermarked versions of an image.[1]
- The *capacity* corresponds to the amount of information which can be carried in the image by the watermarking process.
- The *robustness* corresponds to the ability of the watermarking process to be resilient to passive distortions that do not render the image unusable for its intended purpose. This category of operations includes standard image processing, transmission distortion, and storage distortion. Robustness also relates to the ability of the watermark to withstand active attempts at unauthorized removal. This category of operations includes statistical analysis and nonlinear geometric distortions.

In regard to these properties, some contradictions can be pointed out. On the one hand, Cox et al. show that, in order to be robust, a watermark has to be placed in the perceptually most significant components of the digital data.[7] Indeed, most of the attacks (like compression) compromise the perceptually less significant components of the data in order to be imperceptible. Consequently, the watermark must not be placed in these perceptually less significant components; otherwise it will be easily removed from it by most of the attacks. On the other hand, in order to have a high fidelity, a watermark has to be placed in the perceptually less significant components of the data in order to be imperceptible.[8] So, robustness and fidelity are conflicting properties. However, several papers have proved that it is possible to find a reasonable trade-off between fidelity and robustness by using some properties of the sensitivity of the HVS.[9]

Likewise, a watermarking scheme robust to a wide set of attacks cannot have a high capacity and we cannot increase the capacity without decreasing the fidelity.

In this context, there are two advantages of color watermarking relative to gray level watermarking. First, the potential amount of data which can be hidden is higher. Second, since the color perception depends, not only on the luminance but also on the chrominance most of time, the fidelity of a watermarking scheme based on the color components is higher than that of a watermarking scheme based only on the luminance.[6] Thus, by using color watermarking, one increases both the capacity and the fidelity relative to gray level watermarking.

FROM GRAY LEVEL TO COLOR WATERMARKING

The general purpose of the watermarking is to hide data in an image or in a video. Even if few others aimed at hiding palette-based 256-color secret images or true color secret images in color host images,[10–12] most of the previous works on watermarking considered only gray level host images.[13,14]

Table I summarizes the characteristics of the main color watermarking methods. This table points out that most of the color watermarking schemes can be considered as scalar methods since color is managed as three independent gray level components. Nevertheless, the correlation between color components cannot be disregarded. Indeed, it is well-known that the RGB color components are highly correlated, whereas the YCbCr color components are less correlated.[15] To solve the problem of the intercorrelation between color components, the Karhunen Loeve transform (KLT) has been used in several studies.[16] This transformation is based on a principal component analysis (PCA) whose aim is to transform a color space with correlated components to a new coordinate system where the three components are uncorrelated, and where the first principal component corresponds to the largest eigenvalue. The advantage of the KLT is that, after transformation, the color components can be embedded separately by a scalar scheme.[16]

Figure 4 presents the different strategies of color watermarking. It shows that, in a color image, a watermark can be embedded, either as a three-dimensional vector (3D in Fig. 4) or as three independent scalars (3×1D in Fig. 4). In the most usual case, the watermark is independently inserted in the color components. It can be inserted either in a correlated color space (3×1D in Fig. 4) such as YCbCr where Y represents the achromatic component and Cb and Cr, the chromatic components, or in decorrelated color components (3×1D independent in Fig. 4) resulting from the KLT transform. In either case, it can be inserted in one (1D), two (2×1D), or three (3×1D or 1D and 2×1D) components.

Finally, a few methods exploit the intercorrelation between the color components in the embedding process. For instance, Piva et al. proposed a DCT-based watermarking scheme where the watermark is inserted separately in each color component without exploiting the correlation between

Table I. Summary of color watermarking methods versus color data representations.

Method	Class	Mark	Technique	Color space
Battiato *et al.* (2000)[9]	3D-vector	Color index table	···	A BY RG (color opponency space)
Tsai *et al.* (2004)[22]	3D-vector	Color index table	···	RGB
Roy *et al.* (2002)[26]	2D-vector	Color components (CrCb)	···	YCrCb
Piva *et al.* (1999)[17]	Embedding: 3 × 1D-scalar Detection: 3D-vector	Color components (R, G,B) (weight B > 10 × weight G) (weight B > 5 × weight R)	···	RGB
Chou *et al.* (2003)[27]	3 × 1D-scalar	Color components (L^*, a^*, b^*)	···	$L^*a^*b^*$
Pei *et al.* (2006)[28]	3 × 1D-scalar	Color components (a^*, b^*) Lightness component (L^*)	···	$L^*a^*b^*$
Lo-varco *et al.* (2005)[24]	3 × 1D-scalar	Color components (Y, Cr, Cb)	···	YCrCb
Fu *et al.* (2007)[29]	3 × 1D-scalar	Color components (R, G, B) (weight B > weight G and weight R)	···	RGB
Chen (2007)[30]	3 × 1D-scalar	Color components (R, G, B)	···	RGB
Barni *et al.* (2002)[16]	3 × 1D-scalar (or 1D -scalar)	Principal component(s)	KLT	RGB
Kuo *et al.* (2005)[19]	1D-scalar/edges detection 1D-scalar/color quantization	First principal component First principal component	PCA PCA	RGB RGB
Hsieh *et al.* (2006)[23]	1D-scalar	Lightness component (Y)	···	YUV
Kutter *et al.* (1997),[31] Yu *et al.* (2001),[32] Tsai *et al.* (2007)[33]	1D-scalar	Blue component (B)	···	RGB
Fleet *et al.* (1997)[34]	1D-scalar	Yellow-blue component (YB)	···	BW RG YB (color opponency space)
Tsui *et al.* (2006)[35]	1D-scalar	Yellow-blue component (b^*)	···	$L^*a^*b^*$
Kim *et al.* (2001)[36]	1D-scalar	Saturation component (magnitude of CrCb)	···	YCrCb
Huang *et al.* (2005)[37]	1D-scalar	Saturation component (S)	···	IHS

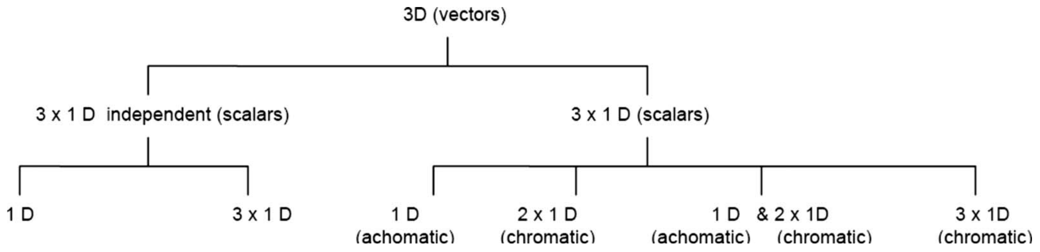


Figure 4. A classification of color watermarking strategies.

these components.[17] Indeed, the scheme takes into account the statistical redundancy between the color components only to recover the watermark. The intercorrelation is exploited in order to improve the detection process, not the embedding process. In this scheme, the magnitude of the mark is 10 times higher for the blue component than for the green component and five times higher for the blue component than for the red component. One problem of this scheme is that it is difficult to develop a theoretical model describing the joint probability density function of DCT coefficients from different color components. Vidal et al. have been faced with the same problem.[18] Barni et al. proposed to solve this problem by inserting different watermarks into uncorrelated bands through an additive/ multiplicative em-

Table II. Summary of the exploited HVS properties.

Methods	Exploited properties of the HVS
Lo-varco *et al.* (2005)[24], Wang *et al.* (2007)[38]	less sensitive to chrominance variations than to luminance variations,
Kim *et al.* (2001)[36], Huang *et al.* (2005)[37]	less sensitive to slight saturation variations than to slight hue variations,
Kutter *et al.* (1997)[31], Fu *et al.* (2007)[29], Tsai *et al.* (2007)[33]	less sensitive to blue variations than to green or red variations,
Reed *et al.* (2002)[39]	less sensitive to yellow-blue variations than to green-red variations,
Barni *et al.* (1998)[25]	less sensitive to high frequency variations than to low frequency variations,
Barni *et al.* (1998)[25]	less sensitive to noise components that are characterized by the same spatial frequency, orientation, and location as the components of the original image,
Barni *et al.* (1998)[25]	less sensitive to noise in dark and bright regions than in regions characterized by any other lightness values,
Barni *et al.* (1998)[25]	less sensitive to distortions in highly textured areas than near edges,
Barni *et al.* (1998)[25], Nikolaidis *et al.* (2001)[40], Kundur *et al.* (2004)[41]	highly insensitive to distortions in regions characterized by high activity and low saliency.

bedding rule.[16] In order to preserve high detection reliability, Barni et al. proposed to embed the watermark only in one band.

More recently, Kuo et al. proposed a watermarking method based on the fusion of color edge detection and color quantization.[19] The edges were detected thanks to a particular approach based on a PCA in the three-dimensional color space. Likewise, the authors proposed a color image partitioning strategy based on a PCA in order to quantize the image The problem of PCA- or KLT-based watermarking is that the transformation into a new coordinate system depends on the content of the particular image. Therefore, since the attacks change the image contents, the transformation before and after an attack may be different and the watermark may not be detected.

WATERMARKING AND HVS SENSITIVITY

Numerous properties of the HVS sensitivity have been exploited in color watermarking. They are summarized in Table II. Some of these characteristics can also be exploited with gray level images. The first HVS characteristic exploited in image watermarking is its lower sensitivity to lightness variations than to hue variations. This explains why the first color watermarking schemes only considered the lightness component.[7,20,21] More recently, Tsai et al. proposed to insert the mark in the lightness component V of the HSV color space to minimize the image degradation.[22] Likewise, Hsieh et al. proposed to insert the mark in the lightness component Y of the YUV color space.[23] It is also well known that for natural images, the intensity component contains more information than the chromatic components. For example, let us consider the luminance-chrominance YCrCb color space. One advantage of using YCrCb color space is that we can reduce the spatial resolutions of the chrominance components Cb and Cr, since most of the information is concentrated in the luminance component Y. Exploiting this property, Lo-varco proposed to embed a watermark in each of the components of the YCrCb color space after applying a segmentation step in order to extract regions of interest (ROI). [24]

In color images, the nonuniformity of the HVS sensitivity has to be accounted. In particular the HVS is more sensitive to low frequency variations than to high frequency variations. Therefore, several papers recommend inserting more information in high frequency regions than in low frequency regions.[25]

Another property of the HVS is that it is less sensitive to noise in dark and bright regions than in regions characterized by any other lightness values.[25] Likewise the HVS is more sensitive to distortions near edges than in highly textured areas.[25] Inversely the HVS is highly insensitive to distortions in regions characterized by high activity and low saliency. Luminance sensitivity, frequency sensitivity, contrast masking, edge masking, temporal masking, etc. have been studied by several authors such as Barni et al.[25] and Xenos et al.[42]

The gray component replacement (GCR) process used in color image printing also exploits the sensitivity of the HVS. It consists in replacing with black ink a combination of colored inks that was initially used to create an achromatic color. The same color under different GCR strategies must be perceived as equal color stimuli by the HVS. De Queiroz[43] exploited this characteristic and proposed to insert a watermark in a printed image by spatially varying the GCR along the image in a manner that is not perceptible. In order to extract the watermark from the image, he estimated the

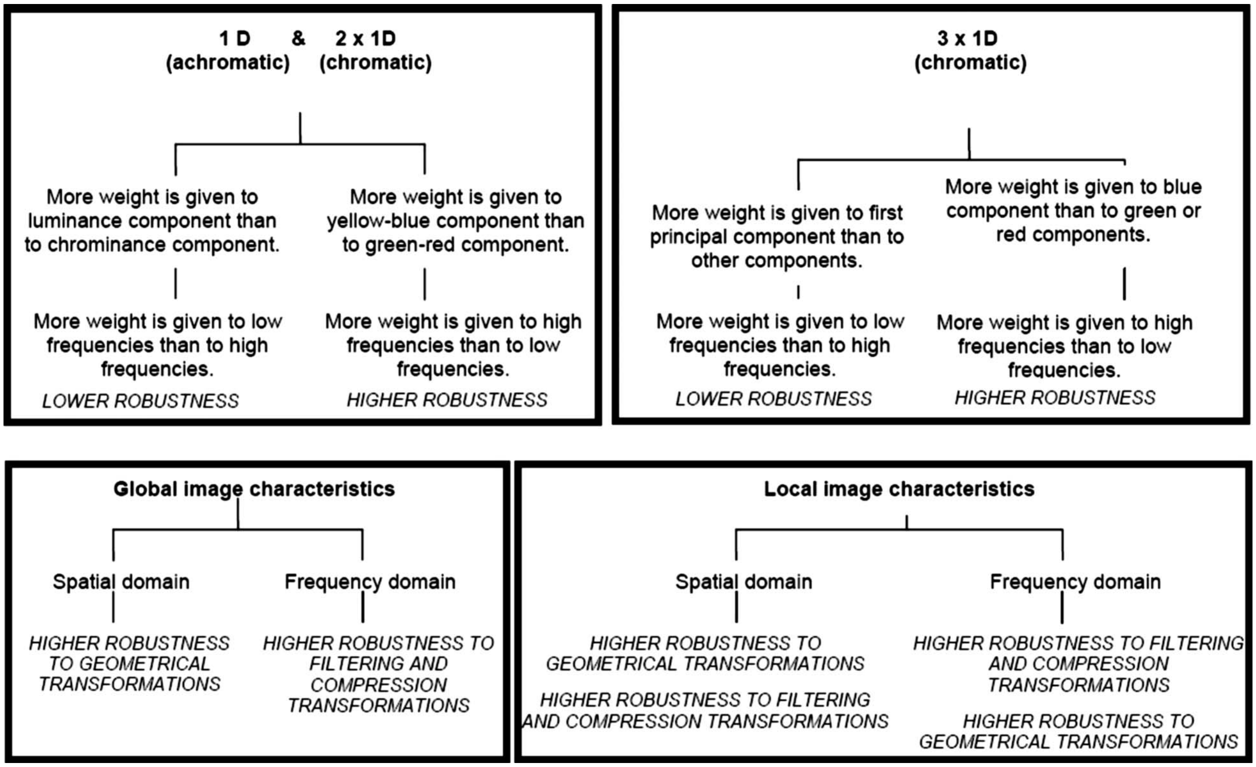


Figure 5. Robustness of several image watermarking strategies.

RGB value of each pixel and the CMYK values intended to be put onto the paper by scanning the printed page. This information allows him to estimate which GCR strategy was used and to retrieve the watermark message.

As previously noticed, robustness and fidelity are conflicting properties. Indeed, in order to be imperceptible, watermarks have to be placed in the perceptually less significant components of the digital data, but in order to be robust watermarks have to be placed in the perceptually most significant components. For example, a watermark should not be embedded in a high frequency region, even if the HVS is insensitive to high frequency variations, because these high frequencies might be easily distorted by a simple low-pass filter or by attacks which do not create visible artifacts. Figure 5 compares the robustness of the different watermarking strategies.

In order to simultaneously improve fidelity and robustness of watermark schemes, spatial masking watermarking methods have been proposed. The idea of the spatial masking schemes is to exploit the local image characteristics, such as the cross correlation of color data in local areas of an image. For example, Nikolaidis et al. proposed a watermarking scheme based on noise masking or distortion masking which is robust to JPEG compression and lowpass filtering.[44] The idea is to decrease the perceived intensity of a visual stimulus when this latter is superimposed over another stimulus. From this point of view, watermarking exhibits significant resemblance to lossy image compression.

More recently, Barni et al. and Bartolini et al. proposed to embed the watermark by modifying the magnitude of mid-frequency DFT coefficients thanks to an additive/multiplicative rule.[45,46] Next, a spatial masking is performed to improve the watermark invisibility. More recently, Kuo et al. proposed to combine color edge detection and color quantization to improve the watermark invisibility.[19] Edgy regions are regularly used in data hiding in order to increase robustness and imperception.[47] Edges are also useful to the HVS because they contribute to the perception of high level features such as shapes. The watermark is then hidden within the data by modifying a subset of selected edge points in order to resist to both geometric distortion and signal processing attacks such as JPEG compression. As previously seen, Lo-varco et al. proposed to synchronize the embedded message with the image content by extracting ROI thanks to a segmentation step.[24] Then, shape features are estimated from each ROI. This watermark scheme resists cropping, rotation and JPEG compression but is highly dependent on the segmentation scheme used. The region-based watermarking strategy was already proposed by Nikolaidis et al. [40] This watermark scheme resists several kinds of attacks such as compression, filtering, scaling, cropping, and rotation.

Another approach to the two main problems previously cited (i.e., the intercorrelation between color components and the non-uniformity of HVS sensitivity) is to use non-correlated color components, meanwhile taking into account the color sensitivity of the HVS. Thus, working in an opponent color space, Fleet et al. proposed to embed the yellow-blue component in the frequency domain.[34] This scheme consists in adding a sum of sinusoidal signals to the yellow-blue channel. The sinusoids are embedded iteratively. At each iteration the color difference between the watermarked image and the original image is evaluated. Next, the signal amplitude is attenuated when such a difference is too high, i.e., when the watermark is visible. The visibility of the watermark is tested in the S-CIELAB color space which is known to better model how color differences are perceived by the HVS. Finally, watermark detection consists in finding local peaks corresponding to the presence of the sinusoidal signals. Likewise, the CIEDE2000 color difference has been used by Chou et al. to measure the perceptual redundancy inherent in wavelet coefficients.[48] Indeed this difference is also considered as a uniform color metric. Although the CIELAB space ($L^*a^*b^*$) can be seen as a Euclidean color space, the S-CIELAB space has the advantage of taking into account the HVS sensitivity variations in the spatial domain. The scheme proposed by Fleet and Heeger[34] has been extended by Reed et al.[39] and Tsui et al.[35] In particular Reed et al. exploited the low sensitivity of the HVS to high frequency variations along the yellow-blue axis.[39] They proposed to embed most of the watermark in the yellow component while minimizing the changes in hue component. More recently Tsui et al. proposed to embed color watermarks (yellow and blue) in the frequency domain of the CIE a^*b^* chromatic channels by using a spatio chromatic discrete Fourier transform (SCDFT). [35] After encoding a^* and b^* as complex values, they apply a single discrete Fourier transform.

Rather than using only one color component such as yellow-blue, other authors proposed to use an opponent color space such as $L^*a^*b^*$, comprising three opponent components: black-white, red-green, and yellow-blue. For example, Battiato et al. proposed to project the colors into an opponent color space before watermarking the image using a specific scheme based on a vectorial approach.[9]

Since slight saturation variations are not perceived by the HVS, some authors proposed to embed chromatic components such as the saturation or Cr and Cb from the YCrCb color space. For example, Kim et al. proposed to insert a mark in the saturation component in the spatial domain.[36] Since the saturation variations are less visible than hue variations, Kim proposed a watermarking scheme which modifies the saturation values, i.e., the magnitudes of the CrCb components.[36] Likewise, Huang et al. proposed to hide grayscale logos in the saturation component of color images through the DWT.[37] Furthermore, according to Huang, watermarks are more robust when they are embedded in the saturation component than in the intensity component. Finally, since the HVS is very sensitive to hue variations this chromatic component cannot be used to watermark a color image.

WATERMARKING IN THE SPATIAL DOMAIN

The LSB Approach

One of the first spatial domain watermarking schemes, called the least significant bit (LSB) scheme, has been proposed by van Schyndel et al. [49] It consists in inserting the message in the low order bits of the pixels. There are two different approaches: either the LSB are replaced by a pseudo-noise (PN) sequence; or the PN sequence is added to the LSB. According to Fu et al., modulating the LSB is a good choice to reach a high capacity and a high fidelity because the human eye is not sensitive to small intensity differences.[39] However, since the LSB are highly sensitive to noise, the watermark can be easily removed by classical image manipulations such as resampling, rotation, format conversions or cropping. Thus, the use of the LSB provides a high fidelity but a low robustness. The LSB scheme was extended by Pei et al. who proposed an iterative LSB insertion for palette-based color images.[50]

Recently, new spatial domain schemes have exploited machine learning techniques for both embedding and extraction of watermark. Neural networks, genetic algorithms or support vector machine (SVM) have been used in order to select the best embedding positions or to extract the watermark from the spatial domain.[29,33,51] Thus, the robustness against common attacks is increased. Indeed, the linear discriminant analysis (LDA) approach proposed by Fu et al. is more robust against blurring, mosaic, cropping or luminance and contrast enhancement than Kutter's method.[29] One drawback of Fu's method is that the proposed watermark extraction is based on the assumption that neighbor pixels are highly correlated. Consequently, when the host image is not homogeneous, the watermarking scheme may fail.

Kutter's Approach

The watermarking scheme proposed by Kutter was the first work to be explicitly designed for color images.[31] It can be described as follows. The mark is considered as a bit string s of length X. These bits are embedded at positions determined by a pseudo-random sequence which depends on a secret key K. Actually, this secret key is used as a seed for a pseudo-random number generator. The original side of this approach is that the randomization provided by the watermark key is applied during the embedding stage.

The main weakness of Kutter's algorithm is that the first two bits have to be known (i.e., 0 and 1) to extract the mark, s. Furthermore, this scheme leads to false detection when the watermarked image is attacked by geometrical transformations or by classical image processing. Several authors such as Yu et al.[32] or Tsai et al.[33] proposed to improve the performance of Kutter's algorithm. A major difference between Kutter's method and Yu's method lies in the evaluation of the adaptive threshold used in the mark estimation. Yu's method calculates the adaptive threshold by using a nonlinear mapping which is realized by a neural network with multilayer perceptrons (MLPs). However, the learning algorithm employed to train the MLPs is often stuck on local minima.[33] To overcome the natural limits of neural networks, Tsai et al. proposed to employ the SVM solution. Tsai's method outperforms the methods of both Kutter and Yu in case of blurring or noise attacks. On the other hand, Tsai's method is not robust to geometric transforms such as rotation and scaling.

WATERMARKING IN THE FREQUENCY DOMAIN

Most of the transform domain watermarking schemes use DCT to insert the mark in the image.[16–18,24,25,52–54] By definition these algorithms are more robust to JPEG lossy compression but are not robust to geometrical attacks. Masking techniques based on transform domain are in particular more robust than LSB insertion with respect to compression, cropping, and some image processing. The advantage of masking techniques is that they embed information in large areas of the image rather than just hiding it in the "noise" levels, for example.

Several masking and filtering techniques have been proposed in the literature. For example, Piva et al. have proposed a scheme based on the DCT which took into account the statistical dependency between color channels.[17] With each color channel is then associated a set of coefficients which are next modified to embed the watermark. In order to take into account the channel sensitivity, the strength of the watermark is adjusted for each channel. One problem of this scheme is that it embeds the watermark in the DCT domain, whereas insertion in the DFT domain is more robust to some geometric manipulations such as cropping and translation.[16] With this scheme optimization is intended according to the Neyman–Pearson perspective, i.e., minimization of the probability of missing the watermark subject to a false detection rate. Another problem of DCT methods is that they may induce noise in images when they are used to hide a huge quantity of data in images.[55] One fundamental advantage of wavelet-based watermarking schemes is that they take into account the local image characteristics for various resolution levels.[48] Through a simultaneous spatial localization and frequency spread of the watermark within the host image, it is possible to embed more strongly the salient components of the image.[56]

Other transform domain watermarking schemes use the DFT such as the scheme proposed by Tsui et al.[35] or the scheme proposed by Chen.[30] These schemes are robust to rotations. In the DFT domain, the phase is a suitable location for secret data embedding because it has high noise immunity. Furthermore according to Chen, an adaptive phase modulation (APM) mechanism can dynamically adjust the phase alteration and also achieve more easily the imperceptibility of the watermark. In a recent paper, Tsui proposes a watermark process designed for color images based on the quaternion Fourier transform.[59] Thanks to the use of the quaternion, the watermark is embedded as a vector in the frequency domain. To ensure watermark invisibility, Tsui proposes embedding the watermark in the CIE $L^*a^*b^*$ color space. Finally, Li shows that the combination of the DFT with a log polar map allows inserting watermarks which are unaffected by rotation, scale, translation, or print-and-scan operations.[3]

Other transform domain watermarking schemes use the DWT.[23,30,60–62] For example, Hsieh et al. have proposed to compute the contextual entropies of the host wavelet coefficients in order to control the imperceptibility and the robustness of the watermarks.[23] The advantage of image adaptive watermarks in the transform domain is that they are particularly robust to signal processing attacks such as filtering or compression.[63] For example, the DWT watermarking schemes are robust to JPEG compression. Another advantage is that they are able to determine the salient areas of an image, i.e., the perceptually most significant information, and consequently adjust the strength of the watermark to embed.[41]

Some watermarking schemes combine different frequency domain transforms. For example, Zhao et al. have proposed a DCT-DWT domain dual watermarking scheme exploiting the orthogonality of image sub-spaces to provide robust authentication.[64] Likewise, Song proposed to first apply a wavelet transformation in order to obtain detail and approximation images, and second to embed the watermark in the most important DCT coefficients of the approximation image.[4] This approach is designed to be robust to print-and-scan processes. The corresponding watermark is extracted through threshold judgment and the threshold is determined through the difference between two print-and-scan cycles and one print-and-scan cycle of the images. The watermark is embedded in the CIE $L^*a^*b^*$ color space. Pramila also proposed a multiple domain approach for print-and-scan and JPEG resilient watermarking.[65] The idea consists in inserting three separate watermarks out of which two are used for inverting the eventual geometrical attacks in order to be able to read the third watermark that is the message watermark. Therefore, Pramila exploited the idea of Chiu where an additional template watermark is embedded in the image for solving problems related to geometrical attacks.[66] Thus, a local peak in frequency domain is utilized to synchronize the reading of a message arranged in a circular structure.[66] Pramila proposed to insert a watermark in the Fourier domain to detect and remove rotation and scale transformation and a watermark in the spatial domain to detect and remove translation.[65] The message watermark is embedded in the DWT domain. These three watermarks are inserted in the luminance channel of the image.

Whereas the data hiding algorithms add perceptually irrelevant information in the images, the compression algorithms remove this irrelevancy and redundancy to reduce storage requirements.[67] Therefore, the goals of these two approaches seem to be contradictory. However, they both try to apply imperceptible treatments and so the improvements in the compression context can be exploited in the data hiding context. Consequently several watermarking methods used the DCT transform to increase their robustness to JPEG compression. Inversely, few compression methods used a DCT-based embedding process to improve color image coding.[67]

Watermarking in Histogram Space or by Color Quantization

Another way to watermark a color image is to use its color histogram. The main advantage of color histogram is to be robust to rotations and other geometric transformations. However, since the inverse transform from a color histogram to its image is not unique, it is impossible to deduce a

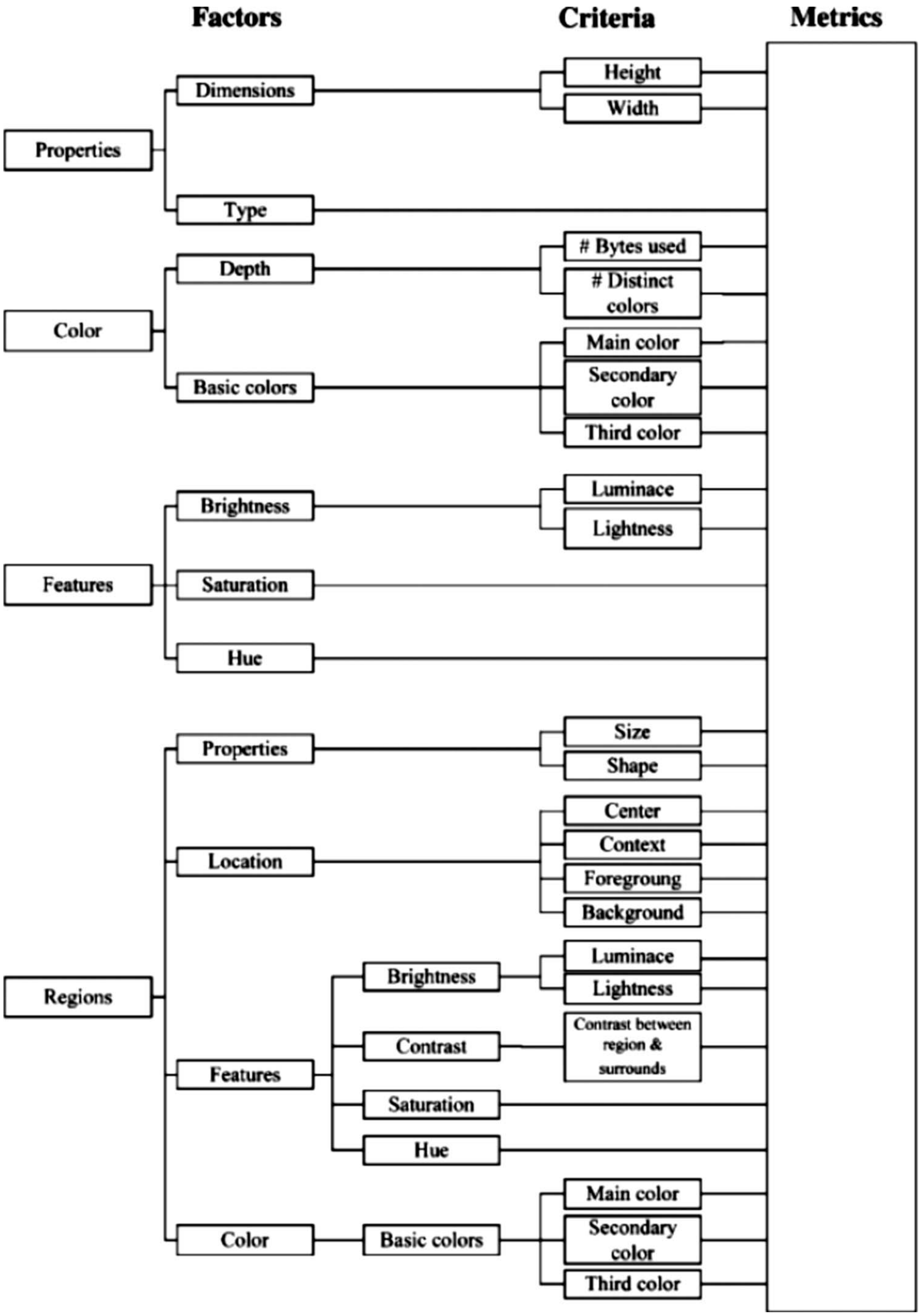


Figure 6. Low-level criteria and middle-level factors proposed by Xenos *et al*. to model watermark fidelity.[42]

watermarked image from its watermarked histogram. To cope with this problem, Roy has proposed to use the Earth mover distance (EMD) to modify an image so that its histogram becomes identical to a target histogram.[26] Other watermarking methods based on color histogram have been proposed.[57,68] Another problem with exploiting the color histogram of an image is the complexity of its 3D representation. For this reason, the embedding process proposed by Roy et al. used only the CrCb 2D histogram from the YCrCb color space. Other solutions consist either in considering the three 1D histograms, corresponding to lightness, hue and saturation components, independently, or in considering only the lightness histogram. Nevertheless, neither solution takes into account the correlations between the color components.

Recently, new schemes have been proposed which are based on a quantization process.[12,22,53,69,70] The purpose of a color quantization process is to represent an image by a limited number of colors with a minimal visual distortion.[71] The definition of the relevant criteria that characterize the perceptual quality of the quantized image is still an open problem.[71]

Using a quantization process, Pei and Chen proposed an approach which embeds two watermarks in the same host image.[28] The first one, which is fragile, is embedded in the chromatic plane a*b* by modulating the indexes of a color palette obtained by color quantization. The second one, which is robust, is embedded in the lightness component L* by modulating the indexes of a gray level palette also obtained by quantization. Chareyron et al. have proposed a vector watermarking scheme which embeds one watermark on the xyY color space by modulating the color values of pixels previously selected by color quantization.[58] This scheme is based on the minimization of color changes between the watermarked image and the host image in the L*a*b* color space. It is robust to geometrical transformations and, within some limits, to JPEG compression but it is fragile to major color histogram changes. Tsai et al. have proposed a watermark scheme based on color quantization which simultaneously performs the pixel mapping step and the watermark embedding step.[22] This scheme provides stronger robustness when applied to images with uniform distribution palettes.

The quantization index modulation (QIM) method quantizes the color of each pixel in the host image by one of the numbers of the color quantizers whose indices are used to carry the watermark information.[72] According to Chou et al., in most QIM schemes quantization and processing steps are not optimal because they do not take into account the HVS sensitivity.[27] To guarantee the imperceptibility of the watermark, the color difference between a pixel and its watermark counterpart should be uniform over the whole image. To attain this goal Chou et al.[27] and Chareyron et al.[73] have proposed to apply a uniform quantization in a uniform color space with the quantizer step size tuned to provide imperceptible color differences between neighbor pixels. To further enhance the imperceptibility of the watermark, Chareyron et al. have proposed to use a quantization process which preserves the color gamut of the host image.[73]

Finally, Wang proposed a watermarking scheme designed for printing images.[74] The approach consists in embedding a watermark by halftone processing. Indeed, halftoning is a process to convert multilevel gray or color images to two-level images in the printing step. By modifying the halftone strategy, Wang proposed to insert the data and to adjust the error diffusion filter thanks to a neural network. This approach can be classified among the color quantization approaches.

FIDELITY OF COLOR WATERMARKS

Even if benchmarks have been proposed such as Stirmark or Checkmark, the question of evaluation and comparison of watermarking scheme is still an open question. One of the main weaknesses of most benchmarks is that they are limited to gray level images. Indeed, to evaluate the differences between an original and a watermarked image, color images are converted into gray level images by considering only the intensity component of the hue-saturation-intensity color space. A second weakness of these benchmarks is that they use a black-box approach to evaluate the performance of a scheme. Indeed, classical evaluations consist in calculating the weighted mean of various performance metrics and in giving the corresponding overall score. It would be more interesting to evaluate each performance metric independently. Thus, Xenos et al. have proposed a model based on four quality factors and around 20 criteria which are hierarchically organized in three levels[42] (i.e., high, middle, and low level) (see Figure 6). Thef aim of this model is to assess the fidelity of the watermark schemes. The four major factors considered are: properties (such as the image type), color (such as the depth and basic colors), features (such as the brightness, saturation, and hue) and regions (such as the contrast, the location, the size, and the color). The proposed model seems very promising for the evaluation of watermark fidelity. Nevertheless, this model is more efficient when applied to spatial domain watermarks than to frequency domain watermarks. According to Xenos et al., some work is still required in this latter area, since this model tends to find image degradations more perceptable than they are found by human evaluators.

Fidelity evaluation can be achieved either by human observation or by perceptual distance measure. It must be analyzed across robustness variation with a constant capacity value. Likewise, capacity must be analyzed across fidelity variation with a constant robustness value. For each watermark scheme, the aim is to evaluate the relative impact from one property variation to another in order to find a tradeoff within the space defined by fidelity, robustness and capacity. Fidelity evaluation by metrics is a hard problem because the HVS sensitivity has to be accounted for. Many papers proposed evaluating the mean-squared error (MSE) between original and watermarked images. It is highly recommended to compute this measure directly in the L*a*b* color space,[73] rather than independently calculating the MSE in each color component. When the color difference CIE L*a*b*ΔE is using to evaluate the fidelity, it is admitted that the difference is visible for the HVS if ΔE is greater than three.[73] Nevertheless, such a threshold depends on the image content. The peak signal-to-noise ratio (PSNR) is also commonly used to evaluate the fidelity. In a general way, if the PSNR value is lower than 25 dB, the difference between the two compared images is considered to be visible.[42] Likewise, if the PSNR value is higher than 40 dB, the difference is considered as imperceptible (see Figure 7). However, it is well-known that such a threshold depends on the image content.

For example, let us consider the images Parrots and Lighthouse in Figures 8 and 9. Lighthouse image presents higher frequencies than Parrots image. We notice that by embedding seven bits per pixel in each image, we get $\Delta E = 2.07$ and PSNR=37.34 for Parrots image and $\Delta E = 1.70$ and PSNR=37.91 for Lighthouse image. So, the differencebetween the original and the watermarked images is higher for Parrots than for Lighthouse whereas human observers would have said the inverse (the watermarked Lighthouse image seems more blurred than the original one).

Distortion metrics such as MSR and PSNR are simple and standardized measures. Their advantage is that they do not depend on subjective evaluations. Their disadvantage is

Figure 7. (a) Original Lena; (b) imperceptibly modified image ($\mathrm{PSNR}_{(A,\,B)}$=26.55 dB), and (c) Lena with moustache ($\mathrm{PSNR}_{(A,\,C)}$=40.55 dB). With regards of the PSNR image (c) is "better" than image (b)!

that they are not correlated with human perception of fidelity.[42,73] In other words, a small distance in the metric space between the original and the watermarked images does not always guaranty high fidelity. For example, MSE does not consider the spatial frequencies or the analyzed colors while evaluating the errors, whereas the HVS does. The fidelity evaluation by HVS-based metrics is still an open problem. These metrics have to incorporate both human sensitivity to color differences and human sensitivity to spatial frequencies, as is done by the S-CIELAB space[75] or the iCAM color space.[76]

Meanwhile the CIE L*a*b* ΔE metric can be seen as a Euclidean color metric, the S-CIELAB space has the advantage to take into account the HVS sensitivity in the spatial domain. We think that it will be interesting to undertake new investigations on color appearance models (CAM) and on saliency maps (e.g., local saliency maps) to develop a new generation of watermarking schemes. Likewise, it will be interesting to undertake new investigations on color watermarking schemes based on high level color descriptors such as those used in MPEG-7, as it has been done in image indexing and content-based image retrieval.[77,78]

The main difficulty we face is then to combine the various saliency maps that influence the visual attention, e.g., the intensity map, the contrast map, the edginess map, the texture map, or the location map.[42,54,79] Likewise, we think it will be necessary to propose a new generation of benchmarking systems in order to accurately measure the fidelity of a watermark process in terms of color perception and to measure the relative impact of color perception on robustness.

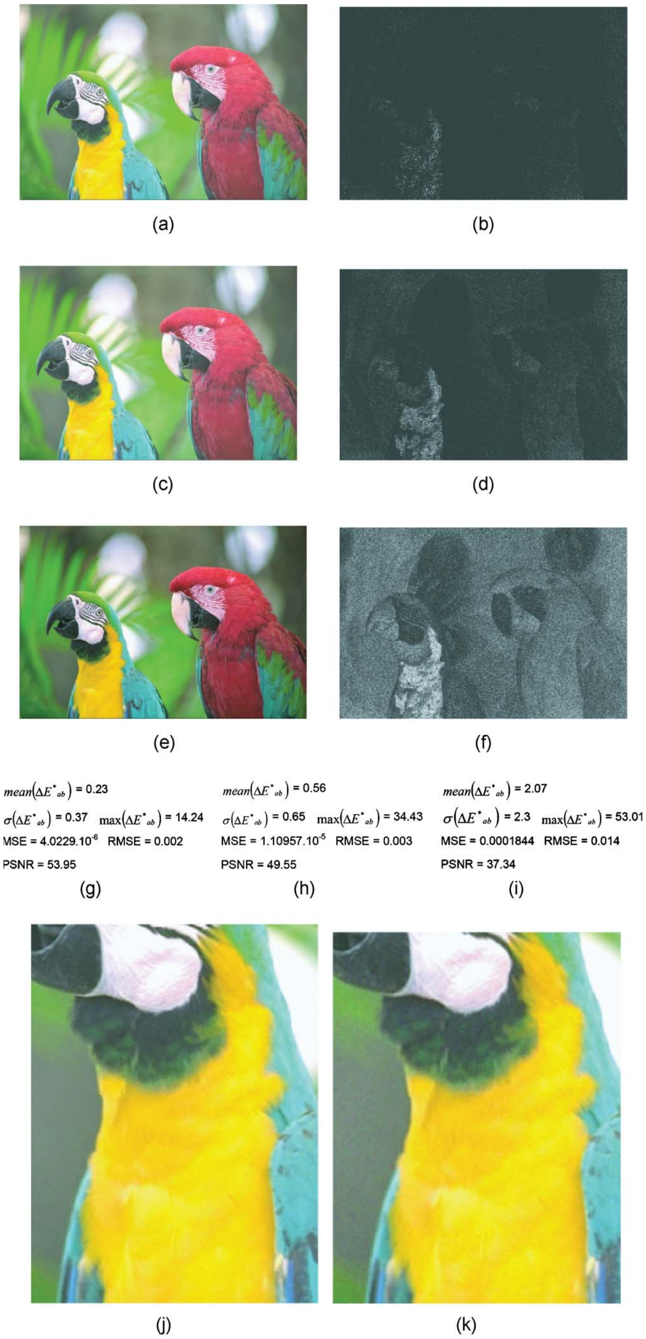
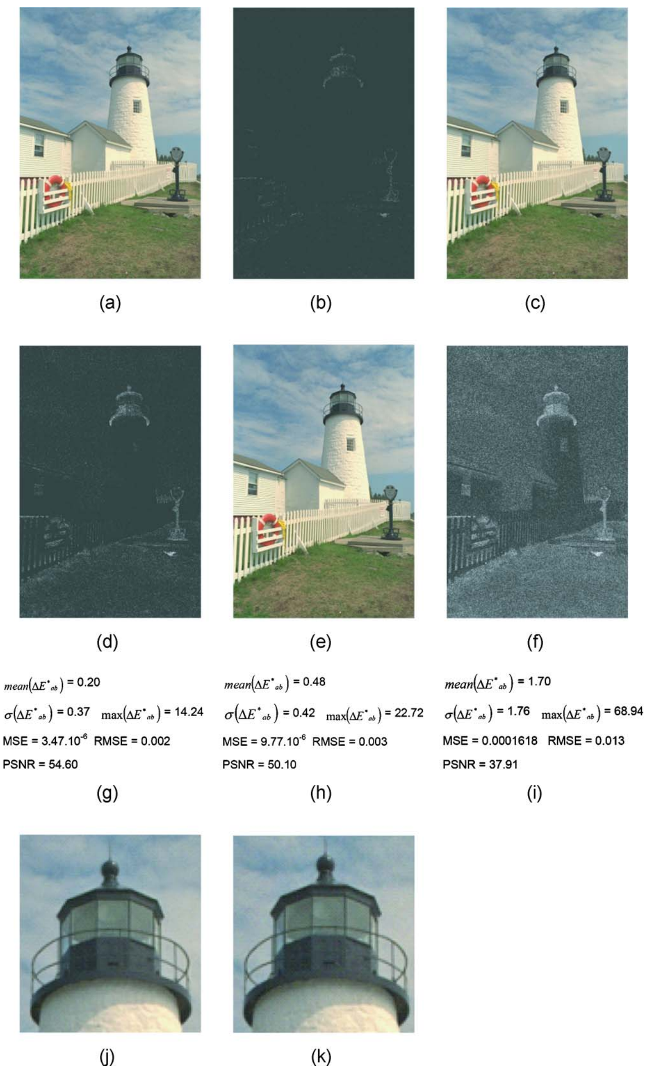


Figure 8. Image parrots watermarked with 1, 4, and 7 bbp, respectively. Color differences (ΔE) between the original and the watermarked image have been computed pixel by pixel and displayed with a logarithmic scale [from low differences (dark=0) to high (white=1)].[73] Other color difference features (MSE, RME, and PSNR) have also been computed pixel by pixel. Only images watermarked with 1 and 7 bbp have been zoomed to show where the most visible differences are located.

Most color watermarking schemes propose to take into account either the HVS sensitivity to frequency content or the HVS sensitivity to color changes. Unfortunately most of these schemes are designed to resist only a specific attack such as JPEG compression or geometrical transforms. From our point of view, in order to increase fidelity and robustness, hybrid watermarking schemes have to be defined which combine spatial and color features.



(g)
$mean(\Delta E^{*}_{ab}) = 0.20$
$\sigma(\Delta E^{*}_{ab}) = 0.37$ $\max(\Delta E^{*}_{ab}) = 14.24$
MSE = $3.47.10^{-6}$ RMSE = 0.002
PSNR = 54.60

(h)
$mean(\Delta E^{*}_{ab}) = 0.48$
$\sigma(\Delta E^{*}_{ab}) = 0.42$ $\max(\Delta E^{*}_{ab}) = 22.72$
MSE = $9.77.10^{-6}$ RMSE = 0.003
PSNR = 50.10

(i)
$mean(\Delta E^{*}_{ab}) = 1.70$
$\sigma(\Delta E^{*}_{ab}) = 1.76$ $\max(\Delta E^{*}_{ab}) = 68.94$
MSE = 0.0001618 RMSE = 0.013
PSNR = 37.91

Figure 9. Image lighthouse watermarked with 1, 4, and 7 bbp, respectively. Color differences (ΔE) between the original and the watermarked image have been computed pixel by pixel and displayed with a logarithmic scale [from low differences (dark=0) to high (white=1)].[73] Other color difference features (MSE, RME, and PSNR) have also been computed pixel by pixel. Only images watermarked with 1 and 7 bbp have been zoomed to show where the most visible differences are located.

DISCUSSION AND CONCLUSION

Most color watermarking schemes are based on scalar processes which embed data in one color component (generally the lightness component), or independently in each color component. It would be interesting to extend these schemes to multi-spectral images compound of three primaries (e.g., RGB), six primaries (RGBCMY), or more. The advantage of multispectral images is that the watermark capacity and robustness are increased without decreasing the fidelity. Another approach which also seems very promising consists in using an *ad hoc* color space adapted to a given set of images. Thus, Benedetto et al. proposed using the YST color space to watermark images of human faces where Y, S, and T represent the brightness component, the mean color value of a set of human faces and the color component orthogonal to the two others, respectively.[80] This watermarking process is robust to illumination changes since the S component is relatively invariant to illumination variations. Such a strategy was already used by Gilani et al..[15]

Finally, unfortunately very few works have been published in the literature about color video watermarking. Therefore, one of the next challenges of color watermarking will be to develop algorithms specifically designed for color videos. As with still images, the main difficulty for videos will be to define fidelity metrics which accurately evaluate the perceptual differences between videos. The first video quality metrics (VQM) which have been developed cannot be considered as sufficiently relevant to replace human evaluation. The next step will consist of selecting the most salient spatio-temporal components to embed the videos.

In the last several years, color has become a major component in security, steganography, and watermarking applications of multimedia contents. We have seen in this article that color embedding techniques can be classified in four categories: The data can be embedded either in the spatial domain; in the frequency domain; in the color histogram space; or by a quantization process. In this article, we have presented the advantages and disadvantages of each of these four categories (see Table III).

Until recently most of the color watermarking schemes managed color as three gray level components, consequently they were considered as scalar methods. However we have shown in this article that color cannot be considered as a vector of three independent scalar components. In other words, the correlation between color components cannot be disregarded. To solve this problem several solutions can be used, for example:

- detecting the most relevant color component and embedding the data in this color component through a scalar process;
- using an uncorrelated color space based on independent scalar component and embedding each color component through a scalar process;
- exploiting the statistical redundancy between color components to embed all color components through a pseudo-vector process.

In this article, we have studied the advantages and disadvantages of each of these strategies and shown how these strategies have been used to watermark color images.

For the past several years, most of the color image watermarking algorithms have tried to find a reasonable tradeoff between fidelity and robustness using some properties of the HVS sensitivity. Numerous secret hiding techniques explored the fact that the HVS is sensitive to small variations in the spatial or frequency domain. Thus, several algorithms have been proposed to take into account the sensitivity of HVS to color variations, edge variations, contrast variations or texture variations. These algorithms used either low-level features (computed from pixels) or high level features (computed for example from ROI). In this paper, we have presented the advantages and disadvantages of spatial masking watermarking methods and shown how these

Table III. Advantages and disadvantages of color watermarking classes.

Class	Advantages	Disadvantages
Spatial domain transforms (e.g. LSB)	• High embedding capacity and transparency.	• Highly sensitive to noise and low robustness.
Kutter *et al.* (1997)[31], Fleet *et al.* (1997)[34], Yu *et al.* (2001)[32], Tsai *et al.* (2007)[33], Fu *et al.* (2007)[29].	• Spatial characteristics can be used to ensure immunity to geometric transformations	• Not robust to image manipulations such as resampling, rotation, format conversions and cropping,
Frequency domain transforms (e.g. DCT, DFT, DWT, etc.)	• Image adaptive transform domain watermarks are particularly resistant to filtering or compression.	• Low robustness under many classical attacks, mainly because they consider globally the images without exploiting their local characteristics.
Piva *et al.* (1999)[17], Barni *et al.* (2002)[16], Huang *et al.* (2005)[37], Lo-varco *et al.* (2005)[24], Tsui *et al.* (2006)[35], Chen (2007)[30].	• The Fourier transform is theoretically rotation, translation and scale invariant.	• The robustness of the Fourier transform to filtering or compression depends on the range of frequencies used for watermarking.
Color histogram	• Robust to rotations and other geometric transformations.	• The complexity of the representation.
Lin *et al.* (2006)[57].		• Do not take into account the spatial distribution.
Color quantization (e.g. QIM)	• Better performance than other watermarking systems based on the standard spread-spectrum modulation which are not image-adaptive.	• To achieve a sufficiently small error probability embedded message needs to be quite large, the detection complexity is thus increased.
Battiato (2000)[9], Chou *et al.* (2003)[27] Tsai *et al.* (2004)[22], Kuo *et al.* (2005)[19], Chareyron *et al.* (2006)[58], Pei *et al.* (2006)[28].	• The detection of the watermark does not require knowing the original image. • It is difficult to extract the embedding information using optimal statistical analysis under certain conditions.	

methods have been used to watermark color images. We have also discussed solutions and arguments supporting the idea that methods based on HVS sensitivity produce more robust watermarks than other ones.

In the last section of this article, we have presented some perspectives on the issues, controversies and problems of color image watermarking. We have suggested new promising research directions, supported by several arguments. These arguments overlap those given by the most recent literature on image watermarking and color imaging. Thus, we have demonstrated that it is possible to find a reasonable tradeoff between fidelity and robustness using some properties of the HVS sensitivity. A very promising research direction will consist in developing hybrid schemes which combine spatial and color features in order to increase the robustness without decreasing the fidelity. Another very promising research direction will consist in working with color images through multispectral primaries in order to increase the capacity and robustness of watermark schemes, meanwhile preserving the invisibility of the watermark. Still another promising research direction will consist in using *ad hoc* color spaces adapted to the set of images being considered.

The main question we are faced with is the choice of watermarking scheme adapted to a specific application. We have seen that a number of performance metrics must be computed at low level (i.e., pixel level) and high level (i.e., region level) and combined to better describe the quality of a watermarked image with respect to fidelity. A new and promising approach to this problem will consist in defining fidelity metrics which incorporate both human sensitivity to color differences and human sensitivity to image content (e.g., spatial frequencies). Indeed, the future of color watermarking schemes will involve the development of fidelity metrics more correlated with the HVS. For example, a new promising research direction would be to exploit high level saliency maps and color appearance models in order to develop a new generation of watermarking schemes.

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