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A blind digital image watermarking method based on the dyadic wavelet transform and interval arithmetic

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ABSTRACT

We propose a new blind digital image watermarking method based on the dyadic wavelet transform (DYWT) and interval arithmetic (IA). Because the DYWT has a redundant representation, the amount of information that the watermark must contain is greater than in the case of the methods based on the ordinary discrete wavelet transforms. Our watermark is a ternary-valued logo that is embedded into the high-frequency components through use of the DYWT and IA. We describe the properties of the DYWT based on IA (IDYWT) and its computational method. We also describe our watermarking procedure in detail and present experimental results demonstrating that our method produces watermarked images that have better quality and are robust with respect to attacks on the following types: marking, clipping, median filtering, contrast tuning (`histeq` and `imadjust` commands in the MATLAB Image Processing Toolbox), addition of Gaussian white noise, addition of salt & pepper noise, JPEG and JPEG2000 compressions, rotation, resizing.

1. Introduction

Digital watermarking is one of the most widely used security techniques for embedding secret information into images and audio streams, and research on digital image watermarking has attracted a great deal of interest over the last decade. Watermarking schemes can be roughly categorized into two types: non-blind methods, which require the original image in the detection process, and blind methods, which use neither the original image nor the watermark in the detection process. In general, blind methods are more useful than non-blind methods, because the original image may not be available when the detection process is applied. The majority of watermarking schemes can also be categorized as operating either in the spatial domain or in the transform domain. Spatial domain schemes embed a watermark by modifying the pixel values directly, and for this reason, commonly used image processing operations can eliminate the watermark. By contrast, transform domain schemes are more robust with respect to signal processing attacks. The transforms most widely used in digital watermarking are based on the frequency domain. These include the discrete cosine transform (DCT) and the discrete wavelet transform (DWT). The existing digital watermarking schemes are discussed in some detail in Ref. [1]. For example, the DCT-based digital watermarking method was proposed in Ref. [2].

To this time, with the growing adoption of the JPEG2000 standard and the shift from DCT-based to DWT-based image compression methods, many DWT-based watermarking schemes have been proposed. Most of them employ the downsampling-type wavelet transforms described in Ref. [3]. One drawback to this approach, however, is its lack of translation invariance. Against this background, several watermarking methods based on the dual-tree complex discrete wavelet transform (DT-CDWT) have recently been proposed [4–6]. Watermarking methods based on the dyadic wavelet transform

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(DYWT) are contrastingly, still few in number [7,8], to the best of the authors' knowledge. Because the DYWT has a redundant representation and can be implemented with a fast algorithm, the amount of information that the watermark must contain is greater than that in the case of DWT-based methods, while the execution times for the two types of methods are roughly the same. These considerations lead us to conclude that the DYWT is a promising approach for developing new robust watermarking techniques.

We previously proposed a non-blind digital image watermarking method based on the DYWT and interval arithmetic (IA) [7]. However, the images produced by that method are not robust with respect to geometric attacks, such as rotation and resizing. Modifying this method and that proposed in Ref. [9], in which the DWT and IA are used in this paper, we propose a new blind digital image watermarking method based on the DYWT and IA that is robust with respect to several types of attacks, including rotation and resizing. Experimental results demonstrate that our method yields watermarked images that have better quality and are robust with respect to attacks of the following types: marking, clipping, median filtering, contrast tuning (e.g., `histeq` and `imadjust` commands in the MATLAB Image Processing Toolbox), addition of Gaussian white noise and salt & pepper noise, JPEG and JPEG2000 compressions, rotation, resizing. We also present a detailed description of the properties of the DYWT based on IA (IDYWT) from a general point of view. To the best of our knowledge, these properties have not been elucidated in any previous work. Furthermore, we propose a method for computing the interval-valued components that has never been applied previously in watermarking methods. This method is faster than any previously employed method of this kind.

The remainder of this paper is organized as follows. In Section 2, we briefly describe the basics of IA. In Section 3, we introduce the IDYWT. We describe the properties of this IDYWT and present the fast computational method in Section 4. With this preparation, we propose a new blind digital watermarking method in Section 5. Experimental results are presented in Section 6, and conclusions are given in Section 7.

2. Interval arithmetic (IA)

An interval A is a connected subset of the set of real numbers $\mathbb{R}$. A closed interval denoted by $[a_1, a_2]$ consists of the set of real numbers expressed as $\{t | a_1 \leqslant t \leqslant a_2, a_1, a_2 \in \mathbb{R}\}$. In this paper, the term "interval" will refer to a closed interval. The lower and upper bounds of an interval A will be denoted by $\inf(A) = a_1$ and $\sup(A) = a_2$, respectively, and the width of any nonempty interval A is defined as $w(A) = a_2 - a_1$. The four basis operations, namely, addition $(+)$, subtraction $(-)$, multiplication $(*)$, and division $(/)$, on two intervals $A = [a_1, a_2]$ and $B = [b_1, b_2]$ are defined as follows:

$$\begin{aligned} A + B &= [a_1 + b_1, a_2 + b_2], \\ A - B &= [a_1 - b_2, a_2 - b_1], \\ A * B &= [\min(a_1b_1, a_1b_2, a_2b_1, a_2b_2), \max(a_1b_1, a_1b_2, a_2b_1, a_2b_2)], \\ A/B &= [a_1, a_2] * [1/b_2, 1/b_1], \quad 0 \notin B \end{aligned} \tag{1}$$

For interval vectors and matrices whose elements consist of intervals, these operations are applied to each element.

Due to the properties of the basis operations given in (1), when these operations are applied to an interval, in general, the width of the interval expands by an amount that is roughly proportional to the number of computations. This phenomenon is sometimes called "interval expansion". This phenomenon often complicates the procedures involved in constructing rigorous computer-assisted proofs [10–12]. For our purpose, however, it provides a useful tool for producing the redundant part of the image from the original image.

3. Dyadic wavelet transform (DYWT)

The introduction to the DYWT given in this section is very similar to that presented in Ref. [13]. We include it here for the sake of convenience.

Throughout this discussion, we assume that the Finite Impulse Response (FIR) filters corresponding to the scaling functions ϕ and wavelets ψ and their duals $\tilde{\phi}, \tilde{\psi}$ are denoted by $h, g, \tilde{h}$, and $\tilde{g}$, respectively. Let us denote the discrete Fourier transform of the filters $h[k], g[k], \tilde{h}[k]$, and $\tilde{g}[k]$ be denoted by $\hat{h}(\omega), \hat{g}(\omega), \hat{\tilde{h}}(\omega)$, and $\hat{\tilde{g}}(\omega)$, respectively. These filters are defined for all integer values of k. Then, the reconstruction condition is given by

$$\hat{\tilde{h}}(\omega)\hat{h}^*(\omega) + \hat{\tilde{g}}(\omega)\hat{g}^*(\omega) = 2, \quad \omega \in [-\pi, \pi], \tag{2}$$

where the symbol $*$ denotes complex conjugation. Then, the following theorem provides formulas that are cascaded to compute a dyadic wavelet transform and its inverse.

Theorem 1 (Ref. [13, Theorem 5.14]). *Under condition (2), the samples $a_0[n]$ of the input discrete signal are decomposed by the transforms*

$$a_{j+1}[n] = \sum_k h[k] a_j[n + 2^j k], \quad j = 0, 1, 2, \ldots, \tag{3}$$