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Reversible data hiding using invariant pixel-value-ordering and prediction-error expansion

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A B S T R A C T

Recently, Li et al. proposed a reversible data hiding (RDH) method based on pixel-value-ordering (PVO) and prediction-error expansion. In their method, the maximum and the minimum of a pixel block are predicted and modified to embed data, and the reversibility is guaranteed by keeping PVO of each block invariant after embedding. In this paper, a novel RDH method is proposed by extending Li et al.'s work. Instead of considering only a single pixel with maximum (or minimum) value of a block, all maximum-valued (or minimum-valued) pixels are taken as a unit to embed data. Specifically, the maximum-valued (or minimum-valued) pixels are first predicted and then modified together such that they are either unchanged or increased by 1 (or decreased by 1) in value at the same time. Comparing our method with Li et al.'s, more blocks suitable for RDH are utilized and image redundancy is better exploited. Moreover, a mechanism of advisable payload partition and pixel-block-selection is adopted to optimize the embedding performance in terms of capacity-distortion behavior. Experimental results verify that our method outperforms Li et al.'s and some other state-of-the-art works.

1. Introduction

Nowadays, data hiding has been found useful in various applications such as authentication, ownership protection, annotation, and secret communication. Traditional data hiding techniques mainly concern on the robustness of embedded data against various attacks, but often cause permanent distortion in the cover medium. However, in some sensitive scenarios such as medical imagery, remote sensing and military imagery, misinterpreting digital content is strictly forbidden, and exactly retrieving the original content as well as the embedded data is required. To this end, reversible data hiding (RDH) technique is proposed to recover the original content from the marked medium without any distortion. Usually, for digital images, the capacity versus image fidelity trade-off is used to evaluate the performance of a RDH algorithm.

So far, RDH has been extensively studied. Existing RDH methods are primarily based on the techniques of lossless compression [1–6], difference expansion (DE) [7–10], histogram shifting (HS) [11–17], prediction-error expansion (PEE) [18–33], integer-to-integer transformation [34–40], etc. Among them, an interesting and valuable research [11,12,41,13,19,14,22,15,31] is to achieve high-level marked image fidelity by modifying each pixel value at most by 1. The first high fidelity RDH method is proposed by Ni et al. [11], where the PSNR is guaranteed over 48.13 dB. In their method, the pixels with the most

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population in the gray-scale histogram are expanded to embed data, while others are shifted by 1 to prevent ambiguity in data extraction. Later on, Lee et al. [12] proposed to use the residual image for histogram modification. Here, the residual image is obtained by computing the difference of two adjacent pixels. In [14], Wang et al. updated the residual value as the difference between the pixel value and the mean of its two neighboring pixels, and obtained an improvement both in capacity and image fidelity compared with [11,12]. In the other works [19,22], the authors proposed to use prediction-errors for data embedding. They employed advanced predictors by taking half-enclosing causal pixels for prediction, and hence improved the prediction accuracy.

Here, it is worth to mention that, as a supplement to DE/HS/PEE techniques, an effective strategy for distortion reduction, namely sorting or pixel-selection, is proposed and employed in recent RDH methods. Such a strategy is verified to be very helpful to the embedding performance, and can be well incorporated into nowadays RDH algorithms. For example, Sachnev et al. [21] proposed a sorting technique to process prediction-errors with small local variance at first. In another work [26], Li et al. utilized the pixel-selection for adaptive embedding, and embed more bits into a smooth pixel. Besides, in a recent work, Hong [30] proposed an energy estimator to estimate the magnitude of prediction-error from its half-enclosing causal pixels, and preferentially use the ones with small magnitude for data embedding.

Recently, Li et al. [31] proposed a novel RDH based on pixel-value-ordering (PVO). For this method, the pixels in a block are first sorted in an ascending order to get $(p_1, \ldots, p_n)$. Then, the maximum p_n is predicted by p_{n-1}. Finally, the pixel with the prediction-error of $p_n - p_{n-1} = 1$ is embedded with one data bit. Besides, in [31], by also considering the minimum p_1, i.e., predict p_1 using p_2, two bits can be embedded into a block at the same time. The experimental results reported in [31] show that the prediction using sorted pixel values is more accurate than the previous methods such as MED (median-edge-detector, [42,20,22]), GAP (gradient-adjusted-prediction, [43,19,26]) and the mean-value-predictor [21]. As a result, compared with the previous works [20,21,23,26], the marked image fidelity can be significantly improved by [31]. In addition, the pixel-selection technique is also utilized in this method to enhance the embedding performance.

The PVO-based embedding [31] has two major advantages. One is that the prediction derived from sorted pixel values is more accurate than the previous ones. The other is that, for low capacity case, larger sized blocks can be utilized to better exploit image redundancy. However, the potential benefit of PVO is not fully exploited by this method since some blocks suitable for RDH are not utilized. Taking the maximum case for example, the block with $p_n - p_{n-1} = 0$ is abandoned in [31]. In fact, these blocks can also be utilized to embed data using a similar mechanism as that of [31]. Based on the above consideration, we argue that the PVO-based embedding can be further improved.

In this paper, we extend the PVO-based embedding [31] into a more general form in which the maximum-valued (minimum-valued) pixels are considered together as a unit for data embedding. As an extension to [31], for each block, we use the second maximum- and minimum-valued pixels to predict maximum- and minimum-valued ones, respectively, and then simultaneously modify them to keep PVO invariant. For example, when the conditions $p_n - p_{n-1} = 0$ and $p_{n-1} > p_{n-2}$ hold, the block is ignored in [31] while it can be exploited in our method. In such a case, for our method, p_{n-2} is employed to predict p_{n-1} and p_n, and the maximum-valued pixels p_{n-1} and p_n will be modified together for data embedding, i.e., they are either unchanged or increased by 1 at the same time. In this way, more blocks can be utilized to embed data and the capacity is thus increased. Moreover, since the numbers of maximum- and minimum-valued pixels for each block remain unchanged, data embedding on different blocks can be classified into categories, and an optimized embedding to obtain the best image fidelity by considering the embedding payoff can be achieved. Experimental results demonstrate that both the capacity and the marked image fidelity can be improved compared with the PVO-based embedding [31]. Besides, in comparison with the state-of-the-art works [21,30], the proposed method also demonstrates a superior performance.

The remainder of this paper is organized as follows. In Section 2, by extending the PVO-based embedding [31], according to a parameter k, a new reversible embedding strategy namely PVO-k is introduced. PVO-k includes the original PVO-based embedding as a special case if taking $k=1$. Here, in Section 2, only the maximum-modification-based embedding is introduced to describe our idea. Then, by considering both the maximum and the minimum and by combining PVO-k with two parameters $k=1$ and $k=2$, a novel RDH scheme is proposed in Section 3. Moreover, to optimize the embedding performance in terms of capacity-distortion behavior, a mechanism of advisable payload partition and pixel-block-selection is also proposed in this section. The experimental results are given in Section 4. Finally, Section 5 concludes this paper.

2. A new PVO-based reversible embedding strategy

2.1. Related work: PVO-based embedding [31]

In Li et al.'s method [31], both the maximum and minimum pixel values in a block are utilized for data embedding. For the sake of simplicity, we only take the maximum-modification-based embedding phase for illustration. The main idea of this method can be summarized as follows:

- The cover image is first divided into non-overlapped blocks with size $n_1 \times n_2$ (see Fig. 1). For each block, the pixels are sorted in an ascending order to get $(p_1, \ldots, p_n)$, where $n = n_1 \times n_2$.
- Then, the maximum p_n is predicted by p_{n-1}. The derived prediction-error x is

$$x = p_n - p_{n-1} \geq 0. \tag{1}$$

- To keep PVO invariant, as shown in Fig. 2, p_i is unchanged for each $i \in \{1, \ldots, n-1\}$, while the maximum