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Reversible data hiding for depth maps using the depth no-synthesis-error model

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ABSTRACT

When embedding hidden data in 3D images, conventional reversible data hiding methods, which are designed for 2D gray and color images, can be applied to color and depth maps. However, directly applying these methods to depth maps may cause synthesis errors and lead to visual artifacts in the rendered virtual views. Two novel reversible data hiding methods based on the depth no-synthesis-error (D-NOSE) model are proposed to embed hidden data in the depth maps of 3D images. The proposed methods can preserve the quality of the rendered virtual view and achieve substantially higher embedding capacity. Experimental results show that the proposed methods achieve better performance than the existing state-of-the-art methods in terms of both embedding capacity and the quality of the rendered virtual views.

1. Introduction

Data hiding has become a promising technique for embedding secret data in an image. Conventional data hiding methods were specifically developed for gray and color images [6,11,12,17,19,21,34–36]. However, conventional data hiding usually induces irreversible distortions and hence leads to a disagreeable effect after extracting hidden data from the marked images. For reversibility, Barton [5] first developed a reversible data hiding technique, which recovers the original image after extracting the hidden data. Most reversible data hiding methods emphasize maximizing the embedding capacity while preserving the quality of the marked images. According to the format of the input images, the developed reversible data hiding methods can be classified into two categories: compression domain-based methods [7–10] and spatial domain-based methods [1,15,16,20,22,24,27–31,33,37]. The former embed the hidden data in the compressed images and the latter in the pixels of the original images. The spatial domain-based methods usually achieve higher embedding capacity and better quality of the marked images.

Compression domain-based methods embed the hidden data in the compressed information, such as discrete cosine transformation coefficients [8,10], vector quantization indices [7], and common bitmaps [9]. Since the hidden data are embedded in the compressed images, the compression domain-based methods usually produce lower embedding capacity and worse quality of the marked images. The spatial domain-based methods, which embed hidden data in the pixels by using

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the distribution of pixel values, can be divided into three categories: the difference expansion-based category, the histogram modification-based one, and the difference expansion- and histogram modification-based one.

The difference expansion method, first proposed by Tian [31], embeds the hidden data by expanding the difference in the gray values of two adjacent pixels, which are the high-frequency coefficients generated by integer-Haar-wavelet-transform [23]. Alattar [1] generalized Tian's method by embedding the hidden data in the high-frequency coefficients which are generated by any integer transform on gray values of successive pixels. Sachnev et al. [27] improved the embedding capacity of Alattar's method by embedding the hidden data in 2D quad pixels and further simplifying the location map. Kamstra and Heijmans [15] improved Tian's method by using the low-frequency coefficients to select the suitable expanding pixels, leading to substantial reduction in the distortion of the marked images. Kim et al. [16] improved Kamstra and Heijmans' method by developing a novel difference expansion transform with a simplified location map. Since the distortions of the marked images generated by the difference expansion methods depend on the difference magnitude, difference expansion methods may suffer from poor quality of the marked images. Furthermore, difference expansion methods usually involve more computations in generating the difference values by integer transforms and selecting the suitable expanding pixels.

The histogram modification method, first proposed by Ni et al. [24], embeds the hidden data by modifying the histogram of the image via shifting the bins between the maximal peak and the neighboring valley. Ni et al.'s method involves lower computational complexity and the theoretical lower bound on the quality of the marked image can be easily derived. Since higher peaks of the histogram imply larger embedding capacity, histogram modification methods can be improved by raising the peaks of the histogram. Lin et al. [20] achieved this using the difference image and hence increased the embedding capacity of Ni et al.'s method. Tai et al. [29] further improved Lin et al.'s method by removing the requirement of sending the multiple peak points to the extraction side. An et al. [2] applied the clustering scheme in the wavelet domain to raise the peaks of the histogram. In addition, An et al. [3] developed a novel statistical quantity histogram shifting and clustering-based method to enhance the visual quality and embedding capacity. Gao et al. [14] proposed a generalized statistical quantity histogram to achieve better performance for different kinds of images and for different capacity requirements. To solve the salt-and-pepper noise problem and achieve the tradeoff between invisibility and robustness, An et al. [4] proposed a content-adaptive reliable robust lossless data embedding method. Since only the peak bins are used to embed hidden data, the histogram modification methods usually suffer from limited embedding capacity.

Thodi and Rodriguez [30] integrated difference expansion and histogram modification by embedding, using difference expansion, the hidden data in the pixels with small prediction errors, avoided the problem of ambiguity by applying the histogram modification to the pixels with large prediction errors. This integrated method, usually referred to as the prediction error-based method, can result in higher embedding capacity and better quality of the marked images. Sachnev et al.'s integrated method [28] reduced the prediction errors to increase the embedding capacity by averaging the gray values of the four neighboring pixels in a rhombus shape. Luo et al.'s integrated method [22] reduced the prediction errors to increase the embedding capacity by using the interpolation-based prediction scheme. Li et al. [18] developed an integrated method which applies the adaptive difference expansion technique to increase the embedding capacity. Yang et al. [37] further developed an integrated reversible data hiding method based on the spectral-spatial correlation in the color difference domain [26] for color filter array mosaic images. Nowadays, prediction error-based methods have become the dominant methods in reversible data hiding fields because of their high embedding capacity and the good quality of the marked images.

Due to the advent of advanced technology, three-dimensional (3D) image representation systems have received considerable attention in the electronics market, and therefore equipping 3D images with a secret data embedding capability has become an important issue. Traditional 3D images are constructed by the multi-view representation which mimics the perception of human eyes. However, multi-view representation involves large storage and transmission requirements, and does not allow individual viewers to adjust the disparity range of stereoscopic videos based on their preference for the intensity of the 3D perception. To alleviate these problems, instead of multi-view representation, 3D image systems often exploit a classical 2D color image plus a depth map [38] to provide viewers with the immersive perception of a 3D scene. The view synthesis technique utilizes the color image and the depth map to generate a virtual view, which is then combined with the color image to construct the 3D image. The most well-known view synthesis technique is the depth-image-based rendering (DIBR) [13] and the generated virtual view is called the rendered virtual view. The 3D image with the format consisting of a color image plus a depth map involves low storage and transmission requirements, and allows individual viewers to adjust the disparity for comfortable 3D perception. When embedding hidden data in a 3D image with the format consisting of a color image plus a depth map, in addition to directly applying the conventional reversible data hiding methods mentioned above to the three color channels of the color image, it is natural to consider embedding hidden data in the depth map for maximizing the embedding capacity. However, directly applying conventional reversible data hiding methods to the depth maps may cause synthesis errors from changing the depth values, leading to visual artifacts in the rendered virtual view. This motivates us to develop, for the depth map, a reversible data hiding method which can achieve high embedding capacity without causing any synthesis errors after embedding.

In this paper, we propose two novel reversible data hiding methods, based on the difference expansion and histogram modification, respectively, for depth maps where the depth no-synthesis-error (D-NOSE) model [39] is used to avoid synthesis errors. The proposed two methods based on the D-NOSE model assure that each marked depth value falls within the allowable range, determined by the D-NOSE model, leading to no synthesis errors in the rendered virtual view. Thus, the rendered virtual view generated from the marked depth map, after embedding, is identical to that from the original depth