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# Two-stage filtering of compressed depth images with Markov Random Field

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ABSTRACT

Virtual view synthesis and image comprehension have become easier with the aid of depth information. However, when a depth image is compressed, severe distortions along boundaries may occur, thus leading to performance degradation. To solve this problem, we propose in this paper a two-stage filtering that consists of binary segmentation-based depth filtering and the reconstruction using a Markov Random Field (MRF) model. The MRF model adopted in our work consists of a data term and a smoothness term so as to preserve the boundary and maintain the smoothness simultaneously. We notice that directly applying the MRF model to a distorted depth image is usually unable to produce a satisfactory performance. Then, we propose that binary segmentation based depth filtering is used to remove artifacts over discontinuous regions in the distorted depth image. Experimental results show that, through our processing, the compressed depth image can render better quality for the synthesized images than many existing depth filtering methods.

## 1. Introduction

Multiview videos with associated depth map are a widely-adopted format for representing 3D video contents, owing to its ability of rendering virtual views, extracting foreground, understanding contents, etc [1]. With a limited band-width, videos need to be compressed, including the depth video. However, any coding inevitably degrades image's quality. In the 3D coding system, when a depth video is encoded by methods such as HEVC with relatively large quantization step-sizes, severe distortions over discontinuous regions often occur [2,3], such as blurring and some noisy ambiguity pixels, which may affect both accuracy of depth image itself and quality of the synthesized views in stereoscopic video applications. It is widely known that depth filtering techniques could improve the quality of coded depth images.

Recently, depth filtering has become a research issue in both depth measurement [4–8] acquired by a depth camera (such as Kinect and Time of Flight), and 3D video coding system [9–13]. Several novel filtering approaches have been explored to address different depth contaminations. Generally, filtering methods for compressed depth images can be linear versus non-linear and local versus global. It's well-known that linear filters have a drawback that edges in a depth image may get over-smoothed when filter's window-size becomes large. On the contrary, non-linear filtering can preserve edges through non-linear manipulations [14,15]. For instance, Silva et al. proposed an adaptive bilateral filter with adaptive filtering parameters for preserving edges by means of a non-linear combination of nearby pixel values based on both spatial distance and pixel similarity [9]. Similar to this method, Liu et al. proposed a trilateral filtering, which considers spatial correlation as well as luminance similarity of both depth images and color images [10]. In the meantime, Oh et al. proposed a depth boundary reconstruction filter and utilized it as an in-loop filter to code depth videos [11], and Xu et al. presented a low complexity adaptive depth truncation filter in which all edge pixels are replaced by a mean value in each block [12]. Although Xu's method can greatly reduce the artifacts of compressed depth image and achieve fast filtering, such a direct region-based replacement often leads to some distortions in non-flat regions, such as slop or curved surfaces. In our former work, we proposed a fast candidate values based boundary filtering method by utilizing spatial correlation and statistic property of local windows [13]. All these methods belong to the category of local filtering, which often corresponds to window-based operation with the correlation between window-centered pixels neglected. Different from these methods, a global method was proposed to solve the problem of generating high-resolution range images by Markov Random Field (MRF) models with low-resolution range images and registered high-resolution camera images [4,5]. Compared with local filtering methods without making filtered neighbouring pixels associated and consistency, the global method can usually provide better filtering performance because global optimization has been taken into consideration, which refers to mutual impacts between pixels during the filtering.

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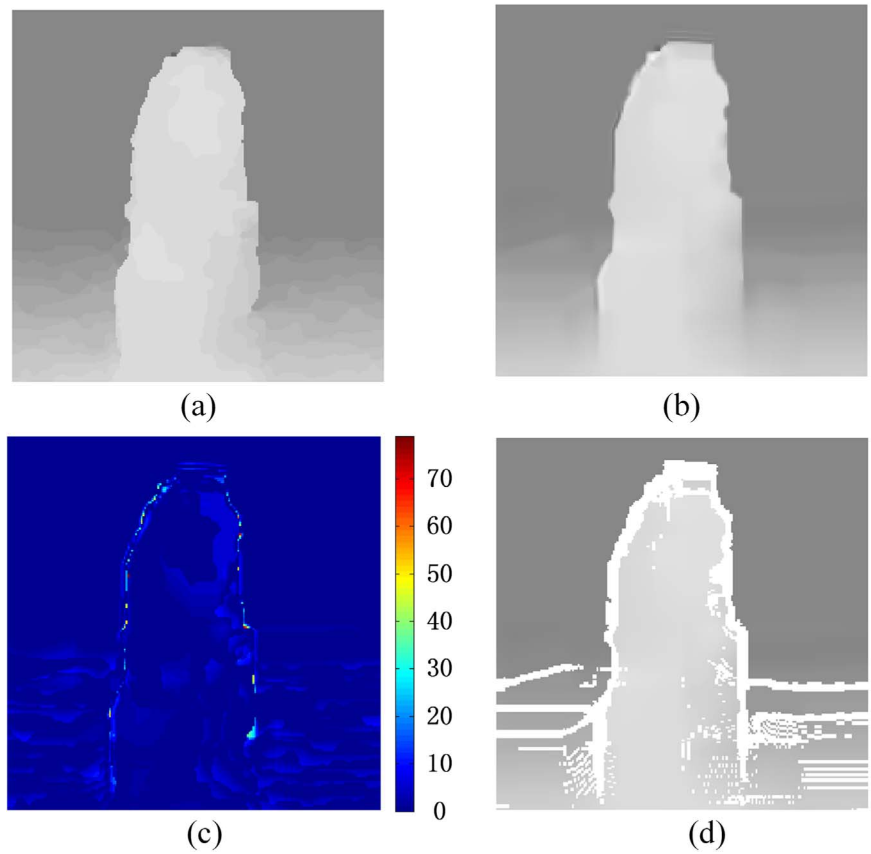


**Fig. 1.** (a) Part of the original depth image Book_Arrival; (b) compressed by HEVC with QP = 41; (c) coding errors; and (d) detected reliable and unreliable pixels from (b).

Because of MRF's superiority in producing more robust reconstruction against noises, such as coding artifacts or some ambiguity pixels, we attempt to use an MRF model in this paper to resolve the filtering problem of compressed depth images. According to the MRF model, reconstructed image can be obtained by taking the distorted image as prior information where pixels in smooth regions (regarded as reliable pixels) are used as measured depth values. However, directly applying the MRF model to a compressed depth image may lead to loss of some structural information in discontinuous regions in which pixels are usually regarded as un-reliable ones. To overcome this problem, we propose a two-stage filtering, denoted as TSF in this paper, where the distorted depth image is firstly dealt by binary segmentation-based depth filtering to get more reliable pixels. Note that this pre-filtering can well retrieve object boundaries with low-complexity. Then, an MRF-based reconstruction is carried out to maintain object surface smoothness and boundary sharp changes that are inherent characteristics of depth images, i.e., continuity within individual objects and discontinuity between adjacent objects. Although color guided filtering is meaningful, this paper concentrate on single depth filtering without color information, because color image couldn't always be provided in some cases.

## 2. Proposed method

### 2.1. Detection of reliable and unreliable regions

We employ an MRF model to filter the distorted depth image with binary segmentation based filtering as the pre-processing. First, we detect reliable and unreliable regions so that only unreliable pixels will be processed by binary segmentation-based filtering. To this end, a cross mask $\Psi(x, y)$ is formed around pixel $I(x, y)$: itself and 4 nearest neighbors. All five pixels are defined as reliable when the absolute difference between $I(x, y)$ and each neighbouring pixel is less than or equal to a threshold $\lambda$ (empirically set to 1). After all reliable pixels are detected, we collect them to form reliable region $\Re$, whereas the rest forms the unreliable region $\Im$. One example is shown in Fig. 1, in which the white areas shown in Fig. 1(d) represent the unreliable region. It can be seen from Fig. 1 that the unreliable region occupies only a very small percentage. We propose to apply binary segmentation-based filtering only on pixels in the unreliable region so as to achieve an efficient pre-filtering.

### 2.2. Binary segmentation based depth filtering

The binary segmentation-based filtering (Denoted as BSF) is carried out over un-reliable pixels only, which can be regarded as a prefiltering to remove artifacts and ambiguity pixels, which is usually caused by quantization in the DCT-based frequency domain [3]. To this end, we first obtain the boundary through a binary classifier, in which three different methods including mean based classifier, median based classifier [12,13], and Otsu's method [16] are investigated. In order to compare with mean based binary segmentation strategy of method [13], the filtering results of three methods are all presented in the experimental section.