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Lossless compression of HDR color filter array image for the digital camera pipeline

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ABSTRACT

This paper introduces a lossless color filter array (CFA) image compression scheme capable of handling high dynamic range (HDR) representation. The proposed pipeline consists of a series of pre-processing operations followed by a JPEG XR encoding module. A deinterleaving step separates the CFA image to sub-images of a single color channel, and each sub-image is processed by a proposed weighted template matching prediction. The utilized JPEG XR codec allows the compression of HDR data at low computational cost. Extensive experimentation is performed using sample test HDR images to validate performance and the proposed pipeline outperforms existing lossless CFA compression solutions in terms of compression efficiency.

1. Introduction

In digital cameras, color information of an real-world scene is acquired through an image sensor, usually a charge-coupled device (CCD) [1] or a complementary metal oxide semiconductor (CMOS) [2] sensor in the format of superimposition of three primary colors, red (R), green (G), and blue (B). Commonly used image sensors are monochromatic devices that sense the light within limited frequency range, and thus cannot record color information directly. To reduce production cost and complexity, most consumer level digital cameras exploit a single-sensor imaging technology, which captures a visual scene in color using a monochrome sensor in conjunction with a color filter array (CFA) [3]. A CFA is a mosaic of color filters placed on the top of conventional CCD/CMOS image sensors to filter out two of the RGB components in each pixel position. Since the image acquired through CFA only contains a single color component at each cell, the CFA image initially appears as an interleaved mosaic similarly to a grayscale image. Color demosaicking (CDM) estimates missing two components in each pixel location of the CFA image to produce the full-color image.

In a conventional digital camera pipeline, CDM is initially performed on the CFA image, followed by compression of demosaicked image. Due to its simple user interface and device compatibility, the CDM first pipeline became a dominant workflow in digital camera designs. However CDM increases the size of the data by a factor of 3, ultimately leading to inefficient usage of storage memory, despite the application of compression. As an alternative solution to the conventional approach, a compression-first pipeline has been introduced. This approach compresses the CFA image prior to applying a CDM, requiring less computational resource and storage capacity as a number of CFA samples are only 1/3 of ones in the full RGB images. In addition, it allows the user to acquire high quality images by performing sophisticated CDMs on the end devices, such as personal computers, where sufficient processing power is provided. The most straightforward implementation of the compression-first approach is a direct application of standard image compression tools, such as JPEG [4] and JPEG 2000 [5], on raw CFA images. However, it is found to be inefficient since

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intermixing pixels from different color channels generates artificial discontinuity whereas compression solutions are generally optimized for continuous tone images. In order to address this issue, advanced CFA compression schemes typically exploit various pre-processing operations for optimal use of compression tools.

The prior art CFA compression schemes are generally categorized into two types: lossy [6–12] and lossless [13–16], depending on nature of pre-processing algorithms and compression tools. Lossy approaches aim to minimize amount of image data by discarding visually redundant contents. They are suitable for the areas where the efficient usage of memory and computational resource is paramount. On the other hand, lossless compression is crucial in the field of medical imaging, cinema industry, and image archiving system of museum arts and relics, where the exact replica of the original data is preferred over high compression ratio. Lossless CFA compression schemes typically deinterleave color channels [15,16] or perform wavelet decomposition [13] prior to applying an encoding operation to alleviate the aliasing issue in the direct CFA encoding method.

In this paper, we present a new lossless CFA compression method that encodes a Bayer CFA image [17]. We focus on the Bayer CFA structure as it is the dominant CFA arrangement in the industry. The proposed scheme consists of color channel deinterleave, weighted template matching prediction, and lossless image compression operations.

There are two main differences of the proposed method compared to prior art CFA image compression solutions. First of all, we make use of the JPEG XR compression standard [18] to facilitate compression of CFA image in high bit-depth/high dynamic range (HDR) representation. HDR images require a higher number of bits per color channel than traditional 8 bit images to allow realistic representation of the scene with smoother tonal gradation from shadow to highlight. Due to the increasing popularity of HDR photography, digital camera manufacturers started to offer a HDR capture mode in their cameras that produces HDR CFA data in a raw format, typically between 10 and 16 bit per pixel (bpp), via high-end sensors or combined exposure operations. Although storage of raw images allows the user to retain the necessary high bit-depth data for the full range of post-processing operations, it leads to excessive usage of memory resources due to absence of compression operation. To the best of author's knowledge, most previous works in CFA compression are limited to codecs applied to conventional 8 bit input (except for a YDgCoCg transform based scheme [19] in HD Photo codec [20] capable of supporting greater than 8 bit CFA data). Such a conventional pipeline causes a loss of precision in HDR CFA data as the original HDR data stream is mapped onto an 8 bit equivalent representation prior to applying compression solution. Among various codecs capable of handling HDR input, we believe that JPEG XR's balance between performance and complexity makes it a suitable solution for digital camera implementation. Secondly, we introduce a predictive coding based lossless CFA compression scheme that employs a weighted template matching predictor to increase the accuracy of pixel prediction and achieve high compression efficiency. Our predictor is similar to the context matching based prediction (CMBP) presented in [16] in the sense that CFA image is separated into green and non-green sub-images, and each sub-image undergoes predictive coding procedure by computing weighted sum of neighbor pixels based on template matching. However, our proposed method allows for more precise prediction of pixel values due to its adaptive weight computation scheme whereas the CMBP uses pre-defined weight coefficients based on ranking of neighbor pixels.

The rest of paper is structured as follows. Section 2 studies background information behind the proposed scheme. Section 3 presents the proposed lossless CFA compression scheme in detail. Experiment results and analysis are demonstrated in Section 4 and conclusion is given in Section 5.

2. Background

This section provides background information necessary for an understanding of the proposed algorithm.

2.1. JPEG XR compression standard

JPEG XR (extended range) is a recently introduced image compression codec and the latest member of JPEG standards family derived from Microsoft HD Photo [21]. JPEG XR offers wide range of input bit-depth support from 1 bit through 32 bit per component. Eight-bit and 16-bit formats are supported for both lossy and lossless compression, while 32-bit format is only supported for lossy compression since only 24 bits are typically retained through internal operations.

Following the traditional image compression structure, JPEG XR's coding path includes color space conversion, block transform called Lapped Bi-orthogonal Transform (LBT), quantization, and entropy coding. The LBT is based on two basic operators: (i) Picture Core Transformation (PCT) that decorrelates signal within a block region, and (ii) Picture Overlapped Transformation (POT) which applies filtering across block edges to prevent blocking artifacts. As a result of the LBT the image data is converted from spatial domain to frequency domain, by producing three frequency subbands, DC (Direct Current), LP (Low Pass), and HP (High Pass). The LBT is a fully reversible operation, and thus allows lossless compression of image data.

JPEG XR provides many convenient features offered in its ancestor JPEG 2000 while maintaining its architecture considerably simpler than JPEG 2000 since it only uses integer based computations internally. Due to its wide dynamic range support, high rate-distortion performance, rich feature sets and efficiency codec architecture, JPEG XR is highly suitable for small, low powered consumer electronics.

2.2. Predictive coding

An algorithm called predictive coding, or differential coding, is widely used in lossless compression standards