Lossless Coding of HDR Color Images in a Floating Point Format Using Block-Adaptive Inter-Color Prediction

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SUMMARY This paper proposes a lossless coding method for HDR color images stored in a floating point format called Radiance RGBE. In this method, three mantissa and a common exponent parts, each of which is represented in 8-bit depth, are encoded using the block-adaptive prediction technique with some modifications considering the data structure.

key words: lossless coding, HDR color image, Radiance RGBE format, block-adaptive inter-color prediction

1. Introduction

Recently, with the advancement of image acquisition and display technologies, high dynamic range (HDR) images, which can record real scenes more accurately than the standard 24-bit RGB color images, are becoming much popular. The Radiance RGBE format [1], which represents three color components by floating point numbers, is widely used for recording HDR image contents. In this format, three mantissa parts of R, G and B components as well as a common exponent part E are represented in 8-bit depth, respectively. Specifically, a true value \( s \in \{r, g, b\} \) of R, G or B component at the pel \( p \) is expressed by:

\[
s(p) = \left( S(p) + 0.5 \right) \cdot 2^{-8} \cdot 2^{E(p) - 128},
\]

where \( S \in \{R, G, B\} \) means the mantissa part of each component represented as an integer of \([0, 255]\), and \( E(p) \) is an exponent value shared for the three components at each pel. Thus, it provides practically enough dynamic range for color exponent value shared for the three components at each pel.

Techniques cannot work well for the mantissa parts. These are main reasons why image coding of the mantissa parts disallows exploitation of inter-color correlations. These are main reasons why image coding techniques cannot work well for the mantissa parts.

In this paper, we propose an efficient lossless coding method for HDR color images stored in the Radiance RGBE format. As a tool for redundancy reduction of each information part, we adopt the block-adaptive prediction technique [3], which was developed for lossless coding of grayscale images. Moreover, to cope with the above-mentioned problems, we introduce the exponent equalization (EE) [4] as well as inter-color prediction (ICP) [5] into the prediction technique. Contributions of these techniques to the coding performance will be verified through computer simulations.

2. Block-Adaptive Prediction

In our past study, a technique of block-adaptive prediction named MRP was developed for lossless coding of grayscale images [3]. In this technique, a given image is partitioned into square blocks with variable sizes, and then classified into several classes. Each class has an individual predictor which is optimized for blocks belonging to the same class. When the current pel \( p_0 \) to be encoded is in the block classified to the \( m \)-th class \((m = 1, 2, \ldots, M)\), a predicted value \( \hat{S}(p_0) \) is calculated by the following equation:

\[
\hat{S}(p_0) = \sum_{k=1}^{K} a_m(k) \cdot S(p_k),
\]

where \( K \) indicates the number of reference pels \( p_k \) used for the prediction (i.e. prediction order), \( \{a_m(k)\} \) are prediction coefficients of the \( m \)-th predictor and \( S(p_k) \) represents an image value at the reference pel \( p_k \) \((k = 1, 2, \ldots, K)\).

Prediction error \( e = S(p_0) - \hat{S}(p_0) \) is then encoded using a multi-level arithmetic coder [6]. Probability distribution of the prediction errors used for the arithmetic coder is adaptively estimated by a technique of context modeling which makes use of the number of coding bits in a causal neighborhood as an index of prediction accuracy. Several parameters required for the decoding process, such as \( M \) sets...

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of prediction coefficients \((a_m(k))\), quad-tree based block partitioning and classification labels \((m)\) for assignment of the predictors in the respective blocks are iteratively optimized so that the resulting coding rate can be a minimum, and finally encoded as side information. This is the origin of the name MRP: Minimum-Rate Predictors.

3. Proposed Method

In the proposed method, information parts of \(R, G, B\) (mantissa) and \(E\) (exponent) in the Radiance RGBE format are first separated into four pseudo image data with 8-bit depth. Then these image data are encoded in the order of \(E \rightarrow G \rightarrow R \rightarrow B\). Figure 2 shows (a) a tone-mapped version of the original HDR image and (b)–(e) the separated four image data displayed by grayscale. It is shown that the exponent part \(E\) is totally flat with small variation. In practice, this exponent part can be re-encoded very efficiently by our MRP method [3]. On the other hand, the remaining three image data exhibit unique characteristics different from natural images. To enable efficient lossless coding of such image data, we introduce the following techniques into the above-mentioned block-adaptive prediction technique.

3.1 Exponent Equalization (EE)

As we can see in Fig. 2 (c)–(e), the pseudo images of the mantissa part contain strong contours with sawtooth-like waveform caused by different exponent values between adjacent pels. Such contours generally lower the coding performance. To cope with this problem, we perform the EE technique which adjusts mantissa part of the reference pels used in the prediction so that their exponent part can be regarded as same as \(E(p_0)\) [7]. In practice, Eq. (2) is replaced by:

\[
\hat{S}(p_0) = \sum_{k=1}^{K} a_m(k) \cdot \text{EE}\{S(p_k), E(p_k), E(p_0)\},
\]

where \(S_{\text{max}} = 511\) is an upper limit of the function \(\text{EE}(\cdot, \cdot)\) to prevent excessive adjustment. The condition of \(E_0 = 0\) in Eq. (4) infrequently occurs at completely dark pels. In such a case, the exponent equalization is mostly useless, and therefore, we force the result to zero [8]. It is worth noting that this EE technique requires no side information since the exponent part \(E(p)\) is already encoded.

3.2 Inter-Color Prediction (ICP)

We can also see in Fig. 2 (c)–(e) that there are clear correlations among three color components. To exploit such inter-color correlations, the block adaptive prediction technique is extended to use multiple color components as far as they are available [5]. For example, when the mantissa part of \(B\) is being encoded, not only the reference pels \(\{p_k\}\) on \(B\) component but also additional reference pels \(\{q_k\}\) on \(G\) and \(R\) components are simultaneously utilized in the prediction. Arrangement of these reference pels is illustrated in Fig. 3, where pels of \(p_0\) and \(q_0\) are at the same position. In this case, the predicted value is calculated from \(K = K_p + 2K_q\) samples by utilizing both the EE and ICP techniques:

\[
\hat{S}(p_0) = \sum_{k=1}^{K_p} a_m(k) \cdot \text{EE}\{S(p_k), E(p_k), E(p_0)\} + \sum_{k=1}^{K_q} a_m(K_p + k) \cdot \text{EE}\{S'(q_k), E(q_k), E(p_0)\} + \sum_{k=1}^{K_q} a_m(K_p + K_q + k) \cdot \text{EE}\{S''(q_k), E(q_k), E(p_0)\}.
\]

Fig. 2 An example of HDR image (Bigfogmap).

\(\text{EE}(S, E_k, E_0) = \begin{cases} 0 & \text{if } E_0 = 0 \\ \min(S_{\text{max}}, [S \cdot 2E_k - E_0]) & \text{otherwise} \end{cases}\)
where $S(p_k)$ represents mantissa part of intra-color components. $S'(q_{k-1})$ and $S''(q_{k-1})$ are those of inter-color components. Their combination is either $(S, S', S'') \in \{(G, -, -), (R, G, -), (B, R, G)\}$, where ‘-’ denotes that the inter-color component is not available and the corresponding term in Eq. (5) is just ignored.

4. Experimental Results

Figure 4 shows HDR color images used in our experiments. These images are originally provided in the Radiance RGBE format at [9]. In Table 1, “Independent” indicates the coding rates obtained by independent coding of $R$, $G$, $B$ and $E$ components, i.e. the predicted values are calculated by Eq. (2). “EE only” means only the EE technique is introduced into the block-adaptive prediction as shown by Eqs. (3) and (4). “EE + ICP” employs both of EE and ICP techniques, and the predicted values are calculated by Eq. (5). In these MRP-based methods, the number of predictors ($M$) is automatically determined during the optimization process, while parameters related to the prediction order ($K$) are defined by user. In this experiments, we fixed $K = 42$ for “Independent” and “EE only” methods and used settings of $K_p$ and $K_q$ shown in Table 2 for “EE + ICP” method. These parameters are embedded in the compressed bitstream as side information. In addition, results of the simple bitplane coding (SBC) method [10] as well as those of JPEG-LS which is known as the international standard [11] are also listed in the table. For all the methods, coding rates are calculated by summing up all the four information parts. Thus in the case of uncompressed data, a coding rate is almost equivalent to 32 bits/pel since the amount of header information is negligible. It should be noted that only the SBC method employs lossless color conversion as a preprocessing tool for reducing inter-

![Fig. 4](image-url)  

Tested HDR images (converted to standard dynamic range by tone-mapping).

| Image       | EE + ICP | EE only | Independent | SBC [10] | JPEG-LS [11] |
|-------------|---------|---------|-------------|----------|--------------|
| Apartment   | 11.365  | 13.684  | 15.294      | 13.652   | 17.019       |
| AtriumNight | 14.154  | 15.957  | 17.498      | 16.054   | 19.406       |
| bigFogMap   | 12.837  | 14.382  | 15.829      | 15.013   | 17.011       |
| daniBelgium | 12.330  | 14.377  | 15.877      | 15.211   | 17.590       |
| daniCathedral| 15.873  | 16.977  | 18.659      | 18.388   | 20.118       |
| daniSynagogue| 11.944  | 13.395  | 14.871      | 14.260   | 16.273       |
| Desk        | 14.335  | 15.728  | 17.389      | 17.817   | 19.085       |
| Display1000 | 14.247  | 16.494  | 17.674      | 16.455   | 19.204       |
| memorial    | 12.875  | 14.683  | 16.125      | 17.401   | 17.575       |
| Montreal    | 10.695  | 12.569  | 13.942      | 12.819   | 15.075       |
| MtTamWest   | 16.908  | 17.513  | 19.415      | 18.757   | 20.938       |
| nave        | 10.815  | 12.072  | 14.531      | 14.746   | 16.120       |
| rosette     | 11.491  | 12.985  | 15.407      | 15.526   | 17.295       |
| Spheron3    | 8.568   | 10.277  | 11.333      | 10.588   | 12.492       |
| NapaValley  | 10.966  | 11.519  | 13.039      | 13.116   | 14.110       |
| Nice        | 11.950  | 13.084  | 14.060      | 14.076   | 15.327       |
| PriceWestern| 14.638  | 16.659  | 17.885      | 16.746   | 19.529       |
| Siggraph2001| 11.667  | 11.865  | 12.856      | 13.770   | 14.801       |
| StillLife   | 15.991  | 16.170  | 16.819      | 20.206   | 18.801       |
| Tree        | 18.856  | 19.907  | 20.595      | 21.104   | 21.738       |

Average 13.124 14.515 15.955 15.785 17.485
Table 2  Settings for the prediction order in “EE + ICP” method.

| Component | $K_p$ | $K_q$ | $K$ |
|-----------|-------|-------|-----|
| $E, G$    | 42    | 0     | 42  |
| $R$       | 20    | 41    | 61  |
| $B$       | 12    | 25    | 62  |

Fig. 5  Encoding and decoding time in our methods.

color correlations. Therefore, the SBC method outperforms our “Independent” method for most images. On the other hand, introduction of the EE technique improves the coding rates by about 1.44 bits/pel. Moreover, the ICP techniques further reduces the coding rates by about 1.39 bits/pel. As a result, the proposed “EE + ICP” method attains the best results for all the tested HDR images.

For complexity analysis, both encoding and decoding times of our methods were measured on a computer with Intel Xeon E5-2690 v4 processor running at 2.60 GHz. Figure 5 shows relationship between the measured time and image size (the number of pels). A dotted line indicates the result of linear regression without a constant term for each method. We can see that the processing times are nearly proportional to the image size and the EE technique increases the encoding time by about 19%. Furthermore, the encoding time of “EE + ICP” is approximately 49% longer than that of “EE only”. This is mainly due to increase of the prediction order in the ICP technique. Since our MRP-based methods iteratively optimize the multiple predictors, a large amount of computation is needed for the encoding process in principle. However, the decoding speed is reasonably fast and most images can be decoded within a few seconds.

5. Conclusions

In this paper, an efficient lossless coding method for HDR color images stored in a floating point format has been proposed. In the method, three mantissa and a common exponent parts are separated into pseudo images with 8-bit depth. Then the images are encoded by a modified version of our lossless image coding scheme called MRP one-by-one. To deal with some unique characteristics observed in image data of the mantissa parts, techniques of exponent equalization and inter-color prediction are introduced. Experimental results demonstrate that the proposed method clearly outperforms other coding methods in terms of the coding efficiency.

References

[1] G. Ward, “Real pixels,” in J. Arvo (Ed.), “Graphics Gems II,” pp.80–83, Academic Press, 1991.
[2] T. Fang, “On performance of lossless compression for HDR image quantized in color space,” Signal Processing: Image Communication, vol.24, no.5, pp.397–404, May 2009. DOI: 10.1016/j.image.2009.01.002
[3] I. Matsuda, N. Ozaki, Y. Umezu, and S. Itoh, “Lossless coding using variable block-size adaptive prediction optimized for each image,” Proc. 13th European Signal Process. Conference (EUSIPCO-2005), Antalya, Turkey, no.WedAmPo3, Sept. 2005.
[4] Y. Kamataki, Y. Kameda, I. Matsuda, and S. Itoh, “Lossless coding of HDR color images in a floating point format using block-adaptive prediction with exponent equalization,” Proc. 23rd International Workshop on Advanced Image Technology 2020 (IWAIT 2020), Yogyakarta, Indonesia, Jan. 2020. DOI: 10.1117/12.2567005
[5] I. Matsuda, T. Kaneko, A. Minezawa, and S. Itoh, “Lossless coding of color images using block-adaptive inter-color prediction,” Proc. 2007 IEEE Int. Conf. Image Process. (ICIP 2007), San Antonio, TX, USA, vol.II, pp.329–332, Sept. 2007. DOI: 10.1109/ICIP.2007.4379159
[6] M. Schindler, “A fast renormalization for arithmetic coding,” Proc. Data Compression Conference (DCC ’98), Snowbird, UT, USA, p.572, 1998. DOI: 10.1109/DCC.1998.672314
[7] Y. Kamataki, Y. Kameda, I. Matsuda, and S. Itoh, “Lossless predictive coding of HDR images in a floating point format based on exponent value adjustment of reference pels,” Proc. 33rd Picture Coding Symposium of Japan (PCSJ 2018), no.P-3-13, pp.118–119, Nov. 2018 (in Japanese).
[8] Y. Kamataki, Y. Kameda, Y. Kita, I. Matsuda, and S. Itoh, “Performance improvement of the predictive lossless coding method for HDR color images in a floating point format by considering missing data,” Proc. ITE 70th Anniversary Convention, no.33C-2, Dec. 2020 (in Japanese).
[9] G. Ward, “High dynamic range image examples,” http://www.anywhere.com/gward/hdrec/pages/originals.html, accessed March 20, 2021.
[10] T. Fukumoto, J. Hwang, H. Kikuchi, K. Shinoda, and M. Okuda, “Lossless Compression of High Dynamic Range Images Encoded in 32-bit RGBA Format by Simple Biplane Coding,” IEICE Technical Report, vol.I12, no.485, pp.45–50, March 2013 (in Japanese).
[11] ISO/IEC, 14495-1:1999, “Information technology — Lossless and near-lossless compression of continuous-tone still images: Baseline,” Dec. 1999.