FAST MOTION BLUR COMPENSATION IN HEVC USING FIXED-LENGTH FILTER

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ABSTRACT

Motion compensation is one of the most important elements in modern hybrid video coders. It utilizes temporal information to predict the current block and reduces thereby the redundancy of a video. The prediction accuracy depends on the similarity between the reference block and the current block. It is decreased by varying motion blur caused by the acceleration of the camera or certain objects in a scene. Thus, we employ fixed-length filters to compensate varying motion blur in hybrid video coding. While former approaches needed additional signaling for blurring filters or a second motion estimation, our algorithm derives the blurring filter only based on the motion vector and needs only one motion estimation. We implemented our approach in the High Efficiency Video Coding (HEVC) reference software HM-13.0. Compared to the reference HM-13.0, we gain 2.54% in terms of BD-Rate in average for JCT-VC test sequences and 4.51% for self-recorded sequence containing lots of varying motion blur, with limited increase in coding time.

***Index Terms*—** Motion Blur, Video Coding, HEVC

1. INTRODUCTION

Motion compensation together with intra-frame prediction, quantization, transform and entropy coding has been the cornerstone of hybrid video coding system. It is used in the High Efficiency Video Coding (HEVC) [1] standard as well as in predecessors like MPEG-2 [2] and AVC [3]. Motion compensation uses already coded previous or future frames to predict the content of a block, called coding unit (CU) in HEVC. Instead of the original CU content, only a displacement vector called Motion Vector (MV) and the corresponding prediction error are used for coding and quantization, in order to generate the bit stream. The data rate can be vastly reduced by this prediction technique if the similarity between the reference frame and the current frame is high.

The common motion compensation (MC) method from video coding standards works well with stationary objects or moving objects of constant velocity. However, the accuracy is limited in case of varying motion blur. Motion blur occurs in the direction of the object motion if an object moves during the exposure time. The changing extent of blur between successive frames generally reduces the compression efficiency because of the increased prediction error.

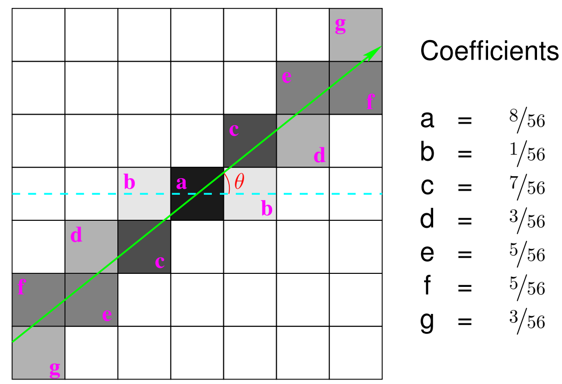


Fig. 1: Discrete version of linear motion blur ($\theta = \arctan \frac{4}{5}$)

Several approaches were proposed to reduce the prediction error by filtering the reference frame for varying motion blur compensation. Some of them use either pre-defined filter [4][5] or adaptive filter [6] for single layer coding . All three approaches need additional signaling for the choice of filter or for the filter coefficients, respectively. Other proposals avoid filter signaling by either exploiting information provided by the base layer in the context of scalable video coding [7] or introducing a sector structure [8]. However, in both cases the number of blurring filters is limited or predefined and two motion estimations (ME) will be executed in the process. Consequently the accuracy of the filter is restricted and long coding time is needed.

In this paper we propose a blur compensation algorithm for single layer coding that generates the blurring filter *in arbitrary direction* based only on the direction of the transmitted MV. We apply the identical MV for MC based on the filtered reference and spare one ME. No additional signaling for the filter coefficients is necessary, whereas the usage of the filter is signaled by the encoder for each CU in the bit stream.

The remaining paper is organized as follows: Section 2 analyzes the filter used for motion blur compensation and explains our method in detail. Experimental results are given in Section 3 before Section 4 concludes the paper.

Table 1: Discrete form of proposed 3×3 blurring filter for different $\theta \in [0, \pi)$

θ	$[0, \arcsin\frac{1}{3})$	$[\arcsin\frac{1}{3}, \arccos\frac{1}{3})$	$[\arccos\frac{1}{3}, \pi - \arccos\frac{1}{3})$	$[\pi - \arccos\frac{1}{3}, \pi - \arcsin\frac{1}{3})$	$[\pi - \arcsin\frac{1}{3}, \pi)$
a	0			$\frac{1}{2} - \frac{1}{6}\frac{1}{\min(\sin\theta, -\cos\theta)}$	0
b	0	$\max(0, \frac{1}{6}\left(\frac{1}{\cos\theta} - \frac{1}{\sin\theta}\right))$	$\frac{1}{2} - \frac{1}{6}\frac{1}{\sin\theta}$	$\max(0, -\frac{1}{6}\left(\frac{1}{\cos\theta} + \frac{1}{\sin\theta}\right))$	0
c	0	$\frac{1}{2} - \frac{1}{6}\frac{1}{\min(\sin\theta, \cos\theta)}$	0		
d	$\frac{1}{2} - \frac{1}{6}\frac{1}{\cos\theta}$	$\max(0, \frac{1}{6}\left(\frac{1}{\sin\theta} - \frac{1}{\cos\theta}\right))$	0	$\max(0, \frac{1}{6}\left(\frac{1}{\sin\theta} + \frac{1}{\cos\theta}\right))$	$\frac{1}{2} + \frac{1}{6}\frac{1}{\cos\theta}$
e	$\frac{1}{3}\frac{1}{\max(\lvert\cos\theta\rvert, \sin\theta)}$				

Table 2: Filter coefficients

3×3 Filter	θ = 15°	θ = 60°
$\begin{bmatrix} a & b & c \\ d & e & d \\ c & b & a \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0.327 & 0.345 & 0.327 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0.141 & 0.167 \\ 0 & 0.381 & 0 \\ 0.167 & 0.141 & 0 \end{bmatrix}$

2. PROPOSED REFERENCE FRAME FILTERING

Due to the variability of the extent of motion blur which is caused by the change of the velocity of the camera or of an object between frames, we suggest to filter the reference frame in order to add blur and increase the similarity between the reference CU and the current CU.

A commonly used linear uniform motion blur point spread function (PSF) in continuous time domain is described with a line segment L and an angle θ with respect to the horizontal axis [9], as given in Eq. (1):

$$h(x, y) = \begin{cases} \frac{1}{L}, & \sqrt{x^2 + y^2} \leq \frac{L}{2}, \frac{y}{x} = \tan\theta \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

L is proportional to the motion speed and the exposure duration, θ indicates the motion direction and (x,y) is the location in the Cartesian coordinate system.

The discrete version of Eq. (1) is acquired by considering a bright spot traversing across the sensors covered by the line segment during the exposure time with constant velocity [10]. Each coefficient of the blur kernel is proportional to the time spent on each sensor element. With the assumption of a constant motion, the filter coefficients are given by the normalized length of the intersection of the line segment with each pixel in the grid, as illustrated by Fig. 1.

In case of varying motion blur, a filtered reference may improve the coding performance. We assume that motion blur as well as the change of motion blur can be described by Eq. (1). Motion can be considered constant for the exposure time of a single frame. Since the time interval between two nearby frames is very short, e.g. 0.02 seconds for a 50 fps sequence, we suggest that the change of motion blur extent is small in most cases. Hence, we employ a fixed extent of 3 pels to describe the phenomenon of variation in blurring, i.e., $L = 3$.

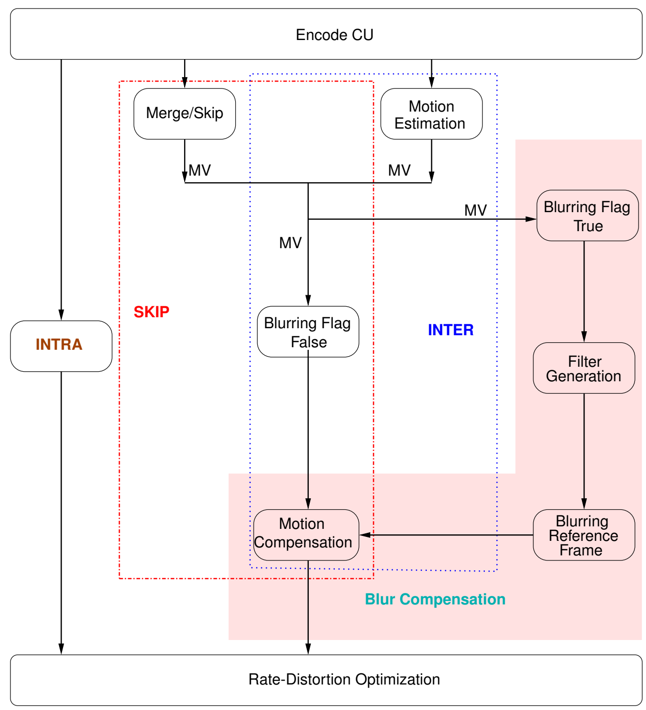


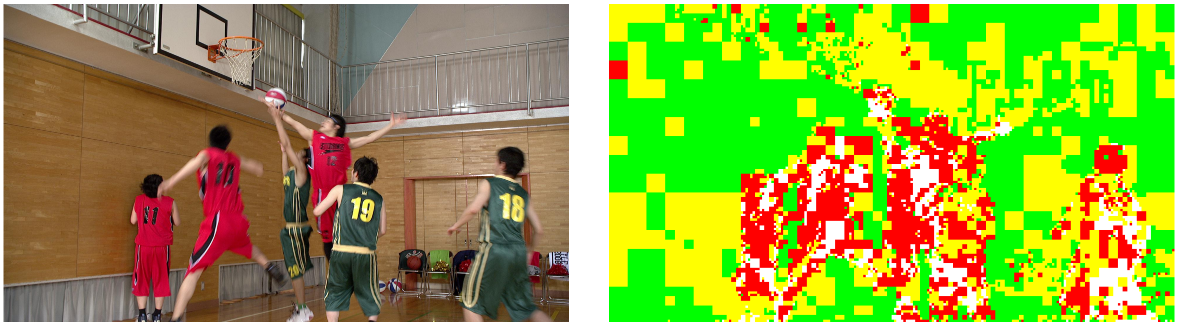
Fig. 2: Flow chart of motion blur compensation

The two dimensional blurring filter has a dimension of 3×3. We blur only the luminance component of the reference, since chrominance pixels lie at every other pixel position of the luminance component [11] for a 4:2:0 sequence.

The other degree of freedom for a blurring filter is the angle θ. It is derived from the MV found in non-blur case. Hence a standard ME in HEVC is executed before the blurring filter is established. The blurred reference frame is generated by using the directions of the MVs.

The general discrete version of our 3×3 filter has 5 different coefficients (a – e) due to symmetry and is calculated according to an arbitrary angle $\theta \in [0, \pi)$ using Table 1. The suggested filter is a low-pass filter. As an example, filter coefficients for $\theta = 15°$ and $\theta = 60°$ are listed in Table 2.

Besides the standard coding methods like Intra-frame and Inter-frame prediction (incl. Skip), we add a motion blur compensation mode to HEVC. This motion blur compensation



(a) Decoded Frame (b) Predicion Mode

Fig. 3: Coding mode distribution of Basketball Drive. Red (darkest): Blur, Green: Skip , Yellow: Inter and White: Intra.

can be considered as a complement of Inter mode (incl. Skip) of HEVC during the coding of a certain CU, as illustrated in Fig. 2. We create temporal reference frames by filtering the reconstructed frame with a filter of angle θ derived from the MV and use these reference frames for motion blur compensation. The temporal reference frames are parallel to the reconstructed ones, i.e., one reference index refers to either the reconstructed frame for general Inter-frame prediction or the blurred reference frame for motion blur compensation. For each frame in the reference picture list there is a corresponding frame for motion blur compensation, since the results of ME based on reconstructed frames and blurred frames do not always share the same reference index.

Compared to [8], we simplify the encoding structure by applying the same MV to MC based on filtered reference instead of a second ME. Meanwhile it is highly likely that a CU will be better predicted using our proposed method. The reasons are listed below.

1. Object should move in the direction where variation of blur exists. We create the temporal reference *exactly* in the direction given by MV without any modification.

2. Our Blurring filters are always symmetrical, which means no phase shift by filtering. It is probable that the majority of the MVs will not change with a second ME based on those blurred temporal references.

A side benefit is the reduction of coding time. We spare one additional ME and have smaller region of blurring. In place of blurring the whole area covered by standard ME, we blur only the CU on reference pointed by the given MV and its surrounding which will be used by interpolation later.

A "Blurring Flag" will be set within the encoding for each CU which is coded with the Inter mode (incl. Skip) for all partition sizes. The decoder is able to determine whether the reference frame is blurred during reconstruction of a CU and to replicate the blurring of the reference frame using the angle θ derived from the transmitted MV. The blurring flag is considered within the Rate-Distortion optimization (RDO).

Table 3: Distribution of MV on filtered reference

Sequence	Identical	± 1 Pel	± 2 Pel
Playground	70.72%	97.29%	98.40%
Bike 01	76.00%	91.63%	92.48%
Bike 02	77.53%	91.63%	93.00%
Bike 03	71.89%	86.13%	87.86%
Recorded Avg.	74.04%	91.56%	92.93%
Basketball Drive	77.59%	88.13%	89.58%
Kimono	75.64%	91.04%	92.37%
Cactus	74.96%	93.33%	95.25%
Park Scene	69.14%	92.64%	94.38%
BQ Terrace	62.49%	97.90%	98.84%
People On Street	59.52%	90.61%	92.13%
Traffic	64.11%	96.48%	98.50%
JCT-VC Avg.	69.06%	92.90%	94.44%
Average	70.87%	92.41%	93.89%

3. EXPERIMENTAL RESULTS

The implementation of our proposed algorithm is based on the HEVC reference software HM-13.0 [12].

We have applied the JCT-VC common test conditions [13] with the default configuration of Low Delay P (LD-P) and Random Access (RA) from HM-13.0 for the evaluation. Our test set includes JCT-VC sequences (*Basketball Drive*, *BQ Terrace*, *Cactus*, *Kimono*, *Park Scene*, *People On Street*, *Traffic*) as well as self-recorded sequences (1280 x 720). The latter include *Playground* [14] (filmed with a hand-held camera) and *Bike* (filmed with a camera attached to the helmet of a cyclist) [7]. We used a fixed focal length for all self-recorded sequences. Thus no blur contained in the sequences is caused by focus change.

The usage of motion blur compensation is illustrated in Fig. 3 which illustrates frame 437 of Basketball Drive as an example. In Fig. 3b, CUs coded with the proposed blurring method are shown in red while yellow, green and white represents inter, skip and intra modes, respectively. Looking at the decoded frame (Fig. 3a), motion blur compensation is chosen mostly for the areas where the obvious varying motion and related blur should occur: on the bodies of the players.

Table 3 shows the distribution of the new MV based on the blurred reference frames if we use a standard ME after blurring. "Identical" indicates that the MVs based on the temporal reference are exactly the same as the MVs from the reconstructed non-blurred reference. Column "± 1" and "± 2" show the ratio of new MVs, which have less than 1 and 2 full pels deviation to the original MV in each direction, respectively.

For both JCT-VC and self-recorded sequences around 70% of the MVs are identical, which means that only about 30% CUs have less good prediction than a standard search. A further 23.84% and 17.52% CUs have the best predictor inside 1-pel range of given MV. The positional deviation is subjectively unnoticeable while objectively it has small impact on the prediction unless some dramatic changes occur in the scene. Hence, the prediction inaccuracy brought by directly using the MV as motion search result instead of a second ME is small and it could be compensated by the improvement of filter accuracy.

The simulation result is presented in terms of Bjøntegaard delta (BD)-Rate [15]. Negative numbers mean gain compared to the anchor while positive numbers represent a loss. As an anchor we used HM-13.0 without motion blur compensation.

Our self-recorded sequences contain much more varying motion blur due to the camera motion as well as longer exposure time. Hence they benefit more from our proposed motion compensation method, as shown in Table 4. The average gain of these sequences compared to the HM-13.0 for $\{Y, U, V\}$ reaches $\{4.51\%, 2.44\%, 2.26\%\}$ for LD-P configuration, majority of which offer over 4% gain for luminance.

As expected, the proposed method works less good on JCT-VC sequences. Nevertheless, we get gain also for all those sequences, which is averaged to $\{2.54\%, 0.50\%, 0.10\%\}$ for $\{Y, U, V\}$ respectively. Because of the rapid change in motion blur from the players of *Basketball Drive* and from the leaves on background of *Kimono*, it is reasonable to observe higher luminance gains from them in this category.

The last column of Table 4 shows the ratio of CUs that choses blurring mode after RDO with LD-P configuration. The gain basically increases with the rise of the ratio in each set of sequences. The values for *Basketball Drive* and *Kimono* prove that motion blur compensation works well for these two in the set. Self-recored sequences work better with nearly the same level of ratio, since they have more shaking and noise, which make these sequences more sensitive to the low pass characteristic of the blurring filter.

Overall, the BD-Rate gain of motion blur compensation is $\{3.26\%, 1.20\%, 0.89\%\}$ on average for LD-P with 17% CUs standing by this method and $\{0.95\%, 0.38\%, 0.33\%\}$ for RA. Results based on LD-P are better than that based on RA, since the temporal distance between the reference frame and the current frame from LD-P is shorter and the proposed filter is only 3×3, which is especially designed for small variations of motion blur.

Table 4: BD-Rate vs. HM-13.0 and Ratio of blur in CUs

Sequence	Low Delay P Y	Low Delay P U	Low Delay P V	Blur
Playground	-4.28%	-2.91%	-4.12%	18.25%
Bike 01	-5.84%	-2.68%	-1.54%	18.30%
Bike 02	-1.36%	-1.05%	-0.64%	11.00%
Bike 03	-6.58%	-3.10%	-2.72%	26.67%
Self-Recorded	-4.51%	-2.44%	-2.26%	18.56%
Basketball Drive	-4.24%	-1.39%	-1.04%	24.75%
Kimono	-4.06%	0.93%	0.78%	35.64%
Cactus	-2.17%	-0.76%	-0.71%	12.00%
Park Scene	-1.32%	0.21%	-0.76%	7.89%
BQ Terrace	-2.12%	-1.08%	1.18%	14.08%
People On Street	-2.53%	-1.02%	-0.18%	17.90%
Traffic	-1.35%	-0.39%	0.01%	5.30%
JCT-VC	-2.54%	-0.50%	-0.10%	16.79%
Average	-3.26%	-1.20%	-0.89%	17.44%

Sequence	Random Access Y	Random Access U	Random Access V	Blur
Playground	-2.92%	-1.09%	-1.24%	21.64%
Bike 01	-2.14%	-0.91%	-0.22%	17.15%
Bike 02	-0.60%	-0.15%	-0.36%	11.14%
Bike 03	-2.49%	-1.09%	-0.69%	17.88%
Basketball Drive	-0.88%	-0.86%	-0.75%	9.22%
Kimono	-0.27%	0.31%	0.06%	11.11%
Cactus	-0.30%	0.04%	-0.27%	4.10%
Park Scene	-0.10%	0.07%	-0.04%	5.01%
BQ Terrace	-0.33%	-0.03%	0.02%	4.78%
People On Street	-0.38%	-0.65%	-0.32%	5.15%
Traffic	0.01%	0.23%	0.13%	2.67%
Average	-0.95%	-0.38%	-0.33%	9.99%

Coding time of encoder drops from over 500% based on [8] to 137% of HM-13.0 at the same time as a side benefit, with an additional 0.28% gain for LD-P configuration. Decoding time drops from over 200% to about 100% of HM.

4. CONCLUSION

The performance of the general motion compensated prediction in HEVC is limited by varying motion blur. To improve the prediction accuracy in order to reduce the coding data rate we propose 3×3 blurring filters for reference frame filtering. The filter is generated based on purely the arbitrary direction of the transmitted MV. No extra signaling of filter coefficients is needed. Compared to HM-13.0, our proposed motion blur compensation can provide an average BD-Rate gain of 2.54% for JCT-VC sequences and of 4.51% for consumer recorded sequences, with 137 % encoding and 100% decoding time.

5. REFERENCES

[1] Benjamin Bross, Woo-Jin Han, Gary J. Sullivan, Jens-Rainer Ohm, and Thomas Wiegand, "High Efficiency Video Coding (HEVC) text spec. draft 10 (for FDIS&Consent)," in *JCT-VC Doc. JCTVC-L1003*, 12th Meeting: Geneva, Switzerland, Jan. 2013.

[2] ISO/IEC and ITU-T, *Recommendation ITU-T H.262 and ISO/IEC 13818-2 (MPEG-2 Part 2): Information technology - Generic coding of moving pictures and associated audio information: Video*, Mar. 1995.

[3] ISO/IEC and ITU-T, *Recommendation ITU-T H.264 and ISO/IEC 14496-10 (MPEG-4 Part 10): Advanced Video Coding (AVC)-3rd Ed.*, Geneva, Switzerland, July 2004.

[4] M. Budagavi, "Video Compression Using Blur Compensation," in *Image Processing, 2005. ICIP 2005. IEEE International Conference on*, Sept 2005, vol. 2, pp. II–882–5.

[5] Jinik Jang, Hyuk Lee, Tae-Young Jung, Sung-Min Hong, and Jechang Jeong, "Pre-filtering with Locally Adaptive Filter Set for Reference Frame in Video Compression," in *Multimedia and Expo (ICME), 2011 IEEE International Conference on*, July 2011, pp. 1–6.

[6] Yu. Vatis and J. Ostermann, "Adaptive Interpolation Filter for H.264/AVC," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 19, no. 2, pp. 179–192, 2009.

[7] T. Laude, H. Meuel, Y. Liu, and J. Ostermann, "Motion Blur Compensation in Scalable HEVC Hybrid Video Coding," in *Picture Coding Symposium (PCS), 2013*, Dec 2013, pp. 313–316.

[8] Y. Liu, W. Wu, and J. Ostermann, "Motion Blur Compensation in HEVC Using Fixed-length Adaptive Filter," in *Picture Coding Symposium (PCS) 2015, submitted for review*.

[9] H. Lin and C. Chang, "Photo consistent motion blur modeling for realistic image synthesis," in *PSIVT 2006, LNCS 4319*, 2006, pp. 1273–1282.

[10] J.P. Oliveira, M.A.T. Figueiredo, and J.M. Bioucas-Dias, "Parametric Blur Estimation for Blind Restoration of Natural Images: Linear Motion and Out-of-Focus," *Image Processing, IEEE Transactions on*, vol. 23, no. 1, pp. 466–477, Jan 2014.

[11] M. Ghanbari, *Video Coding, an Introduction to Standard Codecs.*, The Institution of Electrical Engineers, London, United Kingdom, 1999.

[12] K. McCann, B. Bross, W. Han, I. Kim, K. Sugimoto, and G. J. Sullivan, "High Efficiency Video Coding (HEVC) Test Model 13 (HM 13) Encoder Description," in *JCT-VC Doc. JCTVC-O1002*, 15th Meeting: Geneva, Switzerland, Oct. 2013.

[13] Xiang Li, Jill Boyce, Patrice Onno, and Yan Ye, "L1009: Common Test Conditions and Software Reference Configurations for the Scalable Test Model. Joint Collaborative Team on Video Coding (JCT-VC) of ITU-T SG 16 WP 3 and ISO/IEC JTC 1/SC 29/WG 11. 12th Meeting, Geneva, CH, 14-23 Jan," 2013.

[14] Kai Cordes, Björn Scheuermann, Bodo Rosenhahn, and Jörn Ostermann, "Occlusion Handling for the Integration of Virtual Objects into Video," in *The 7th International Conference on Computer Vision Theory and Applications (VISAPP)*, Feb. 2012, pp. 173–180.

[15] Gisle Bjøntegaard, "Calculation of Average PSNR Differences between RD curves," in *ITU-T SG16/Q6 Output Document VCEG-M33*, Austin, Texas, April 2001.