Bit-inverted Gray Coded Bit-plane Matching for Low Complexity Motion Estimation

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Abstract: In this paper, a bit-inverted Gray coded bit-plane matching algorithm is proposed for low complexity motion estimation. Unlike the typical Gray coded bit-plane matching algorithms, the proposed algorithm uses bit-inverted Gray codes for transforming image frames and a corresponding extended matching criterion to enhance the motion estimation accuracy. Experimental results show that the proposed algorithm outperforms other bit-plane matching based motion estimation algorithms while preserving the binary matching characteristic.

1 INTRODUCTION

Motion estimation (ME) plays a key role in reducing the total video data efficiently by exploiting the correlation among neighbouring frames. The block matching algorithm (BMA) is the most popular and is deployed in many video compression standards due to its simplicity and effectiveness. Although the full search BMA (FSBMA) can find an optimal motion vector according to some matching criterion such as the sum of the absolute differences (SAD) or the sum of the squared differences (SSD), it is not suitable for real time applications due to the heavy computational complexity. Therefore, many techniques have been proposed to relieve the high computational complexity of the FSBMA in the literature (Li and Salari, 1995, Choi and Jeong, 2009). Among these techniques, there proposed some algorithms that use different matching criterion instead of the classical SAD or SSD to make the faster computation of the matching criterion itself exploiting the bit-wise operations. These algorithms are called as bit-plane matching (BPM) based ME. The advantages of these techniques over the matching algorithms using the classical SAD or SSD are two-fold: fast computation of the matching criterion and reduced memory bandwidth in the interim of ME process.

Natarajan et al. first proposed the one-bit transform (1BT) based ME, where the reference frames and the current frames are transformed into one-bit representations by comparing the original image frame with filtered output (Natarajan et al, 1997). A two-bit transform (2BT) based ME was proposed to enhance the ME accuracy of the 1BT-based ME algorithms (Erturk and Erturk, 2005). The 2BT-based ME shows some improvement especially in small block sizes. Gullu proposed to use a two-bit constraint mask according to the difference between a pixel and its 1BT threshold value (Gullu, 2011). Although this algorithm, weighted constrained 1BT (WC1BT), shows some improvement in terms of the ME accuracy, the binary matching characteristic doesn’t hold due to a two-bit constraint mask.

Ko. et al. proposed Gray-coded BPM based ME (Ko et al, 1999), which is also called truncated Gray-coded BPM (TGCBPM) (Celebi et al, 2009). And its variation weightless TGCBPM (WTGCBPM) (Celebi et al, 2010) were also proposed. Both TGCBPM and WTGCBPM use Gray-code mapping as transforming image frames into bit-planes, which is very simple compared to other bit-plane transformation algorithms using complex filtering operations. Let the gray-level of the pixel at location (i, j) be represented as follows:

$$f(i,j) = a_{K-1}2^{K-1} + a_{K-2}2^{K-2} + \cdots + a_1 2^1 + a_0 2^0 \qquad (1)$$

where a_k $(0 \le k \le K\text{-}1)$ takes on either 0 or 1. Then the corresponding Gray-code representation is given by

$$\begin{aligned} g_{K-1} &= a_{K-1} \\ g_k &= a_k \oplus a_{k+1}, \quad 0 \le k \le K-2 \end{aligned} \qquad (2)$$

where $\oplus$ denotes the Boolean XOR operation and

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a_k is the k-th bit representation. After this transformation, TGCBPM and WTGCBPM use respective number of non-matching points (NNMP) as matching criteria which are given as:

$$
\begin{aligned}
&NNMP_{TGCBPM,NTB}(m,n) \\
&= \sum_{i=0}^{N-1}\sum_{j=0}^{N-1}\sum_{k=NTB}^{K-1} 2^{k-NTB}\{g_k^t(i,j) \oplus g_k^{t-1}(i+m,j+n)\} \\
&NNMP_{WTGCBPM,NTB}(m,n) \\
&= \sum_{i=0}^{N-1}\sum_{j=0}^{N-1}\sum_{k=NTB}^{K-1} g_k^t(i,j) \oplus g_k^{t-1}(i+m,j+n)
\end{aligned}
\tag{3}
$$

where K represents the pixel-depth and NTB is the number of truncated bits, the motion block size is $N \times N$, and $-s \leq m, n \leq s$ is the search range. The kth most significant bit of the Gray-coded image pixel frame of time t is represented as $g_k^t(i, j)$. Compared with the previous BPM based ME algorithms, TGCBPM and WTGCBPM based ME show significant gains in terms of the ME accuracy.

Since all the matching criteria of BPMs try to replace the SAD or SSD with the bitwise operations for reduction of computational complexity, their output must be similar to the SAD or SSD in order to find a more accurate motion vector. Therefore, if one can find a matching criterion (using only the bitwise operations) whose output is similar to the SAD or SSD between two image bit-planes, its ME accuracy increases substantially. In this paper, a transformation method which is a slight modification of the typical Gray-code mapping is proposed. And together with a transformation method, a corresponding extended bitwise operation-only matching criterion shows similar characteristics with the output of the SSD. Experimental results demonstrate that the proposed algorithm outperforms other BPM based ME algorithms while preserving the binary matching characteristic.

The rest of this paper is organized as follows: In Section II, the proposed algorithm is presented. Experimental results and analyses are given in Section III. Finally, Section IV provides conclusions.

2 PROPOSED ALGORITHM

Since the Gray-coded BPMs use only some of the first most significant bits of pixels, they are very similar to the quantized frame based ME except the way of handling the quantized pixels and the matching criterion (Choi and Jeong, 2013). For example, when 2 bit-planes are used, their symbols for respective matching criteria are in Table 1.

Table 1: Symbols for the quantized frame based ME and the Gray-coded BPM based ME when using 2 bit-planes.

Quantized Symbol	Quantized Frame	Gray Coded
0	00	00
1	01	01
2	10	11
3	11	10

Note that the Gray-coded BPM based ME uses one of the metrics of (3) and the quantized frame based ME uses the metric of SAD. The metric distribution of Gray-coded BPMs in terms of the absolute difference between two quantized symbols is in Table 2.

Table 2: Metric distributions of TGCBPM and WTGCBPM when using 2 bit-planes.

Absolute Difference	TGCBPM	WTGCBPM
0	0	0
1	1 or 2	1
2	3	2
3	2	1

For TGCBPM, when two Gray-coded symbols are (00, 01) or (11, 10), their distances are 1. And when two symbols are (01, 11), their distance is 2. Note that when the absolute difference between two quantized symbols is k ($0 \leq k \leq 3$), its expected true absolute difference between two pixels is $64 \times k$ (when the pixel bit-depth is 8). That is, the actual distortion between two pixels in terms of the SAD is proportional to the absolute difference between these quantized symbols. Therefore, it would be better for a matching criterion if the absolute difference between two quantized symbols be small, its matching criterion output be small, and vice versa. To this end, the Gray coded bit-planes are inverted as follows:

$$h_k = \sim g_k, \quad NTB \leq k \leq K-1 \tag{4}$$

where K represents the pixel-depth, ~ represents the Boolean NOT operation, NTB is the number of truncated bits and g_k is the k-th Gray bit representation. Note that when NTB = 6, this code allocation is that of the typical 2BT. And note also that this inversion process does not violate the property of the typical Gray codes that consecutive codewords differ only in one bit position no matter what NTB is. A corresponding matching criterion of the bit-inverted Gray coded BPM (BGCBPM) is proposed as follows:

$$
\begin{aligned}
&NNMP_{gram,1}(m,n) = \sum_{i=0}^{N-1}\sum_{j=0}^{N-1}\sum_{k=NTB}^{K-1} h_k^t(i,j) \oplus h_k^{t-1}(i+m, j+n) \\
&NNMP_{gram,2}(m,n) \\
&= 2^{K-NTB} \times \sum_{i=0}^{N-1}\sum_{j=0}^{N-1}[h_{K-2}^t(i,j) \bullet \{h_{K-1}^t(i,j) \oplus h_{K-1}^{t-1}(i+m, j+n)\}] \\
&NNMP_{gram,3}(m,n) \\
&= 2^{K-NTB} \times \sum_{i=0}^{N-1}\sum_{j=0}^{N-1}[h_{K-2}^{t-1}(i,j) \bullet \{h_{K-1}^t(i,j) \oplus h_{K-1}^{t-1}(i+m, j+n)\}] \\
&NNMP_{BGCBPM}(m,n) = \sum_{i=1}^{3} NNMP_{gram,i}(m,n)
\end{aligned}
\tag{5}
$$

where • denotes the Boolean AND operation, K represents the pixel-depth, NTB is the number of truncated bits, the motion block size is $N \times N$, and $-s \leq m, n \leq s$ is the search range. The kth most significant bit of the bit-inverted Gray-coded image frame of time t is represented as $h_k^t(i, j)$. Note that this matching criterion is a generalized version of (Choi and Jeong, 2013) by allowing the number of bit-planes from 2 to (K-NTB).

To check whether the proposed bit-inversion of Gray coded bit-planes and the corresponding matching criterion reflect the properties of the discussed above, the metric distributions of BGCBPM in terms of the absolute difference are calculated. Table 3 and Table 4 show the results when 2 bit-planes and 3 bit-planes are used.

Table 3: Metric distributions of BGCBPM when using 2 bit-planes.

Absolute Difference	BGCBPM
0	0
1	1
2	6
3	9

Table 4: Metric distributions of BGCBPM when using 3 bit-planes.

Absolute Difference	BGCBPM
0	0
1	1
2	2
3	1 or 11
4	10
5	11 or 17
6	18
7	17

When using 2 bit-planes, the proposed matching criterion of BGCBPM gives a small value when the absolute difference is small and gives relatively large value in the opposite case. Since these values are much bigger than their absolute differences, the proposed algorithm can prune out the bad motion vectors effectively. Unlike the metric distributions of 2 bit-planes, those of 3 bit-planes show some multiple metric outputs (when absolute difference is 3 or 5) and some metric output gives relatively small value when their absolute difference is large (when the absolute difference is 3). However, as can be seen from the tables, these cases are relatively rare and the metric distributions clearly show the tendency that the proposed matching criterion of BGCBPM gives a small value when the absolute difference is small and vice versa.

Note that from (5), it appears that transforming the image frames into bit-inverted Gray codes requires (K-NTB) Boolean NOT operations more for each pixel compared with the typical Gray-coded BPMs. However, since the output of the XOR operation between two binary vectors **x** and **y** is the same as that of the XOR operation between ~**x** and ~**y** (where ~ means the component-wise NOT operation), the following identity is easily derived:

$$w_H(\mathbf{x},\mathbf{y}) = w_H(\sim\mathbf{x},\sim\mathbf{y}) \tag{6}$$

where w_H denotes the Hamming weight. Therefore, the bit-planes which only the Boolean XOR operations are involved with need not to be inverted.

Table 5: Computational complexity comparison of transformations (per pixel).

	TGCBPM	WTGCBPM	WC1BT	BGCBPM
XOR	K-NTB-1	K-NTB-1	-	K-NTB-1
NOT	-	-	-	1
Shift	-	-	1	-
Addition	-	-	16	-
Subtraction	-	-	1	-
Comparison	-	-	8	-

Table 6: Computational complexity comparison of matching (per pixel).

	TGCBPM	WTGCBPM	WC1BT	BGCBPM
XOR	N×N ×(K-NTB)	N×N ×(K-NTB)	N×N	N×N ×(K-NTB)
AND	-	-	-	2×N×N
Shift	(K-NTB-1)	-	-	2
Addition	N×N ×(K-NTB)	N×N ×(K-NTB)	N×N	3×N×N× K-NTB)+3
Compari-son	-	-	N×N	-
Multipli-cation	-	-	N×N	-

Only the (K-2)th Gray coded bit needs to be inverted, since only this bit-plane is involved with the Boolean AND operation in (5). The total operations of BGCBPM required for transformation of image frames and for matching compared with other recently proposed BPMs are in Table 5 and Table 6.

3 EXPERIMENTAL RESULTS

To demonstrate the superiority of the proposed algorithm, several experiments were carried out by comparing the ME accuracy of other BPM ME algorithms including WC1BT, TGCBPM, WTGCBPM, and the FSBMA using the measure of SAD. For WC1BT, the thresholds were set to $T_1 = 10$, $T_2 = 30$, $T_3 = 50$. The first 100 frames of 17 CIF (352 × 288) sequences are used as test sequences. All the searching processes were in spiral order.

Table 7 shows the average peak-to-peak signal to noise ratio (PSNR) results of the proposed BGCBPM algorithm with varying *NTB*s compared with other BPM based ME algorithms when the motion block size is 16×16 and the search range is ±16. We highlighted the PSNR values showing the best performance (except the FSBMA) in each sequence. The PSNR performances of the proposed algorithm with varying *NTB*s clearly show that the extension of the number of bit-planes from 2 to (K-*NTB*) enhances the ME accuracy. And compared with other BPM based ME algorithms, the proposed BGCBPM shows the best ME accuracy in terms of the PSNR. Compared with the recently proposed WC1BT, although they use multiplications in matching calculations and non-binary matching characteristic, their PSNR performances are worse than that of the proposed algorithm. And the PSNR difference between the proposed BGCBPM and the FSBMA is only 0.26dB, which is very small.

4 CONCLUSIONS

In this paper, a bit-inverted Gray coded BPM algorithm is proposed for low complexity motion estimation. Since the Gray-coded BPMs use only some of the first most significant bits of pixels, they are very similar to the quantized frame based ME and the actual distortion between two pixels in terms of the SAD is proportional to the absolute difference between these quantized symbols. To incorporate these facts into a BPM based ME, a transformation method which is a slight modification of the typical Gray-code mapping is proposed. And together with a transformation method, a corresponding extended bitwise operation-only matching criterion shows

Table 7: Average PSNR performance comparison of the algorithms when the motion block size is 16×16.

	WC1BT	TGCBPM (NTB=5)	WTGCBPM (NTB=5)	BGCBPM (NTB=6)	BGCBPM (NTB=5)	BGCBPM (NTB=4)	FSBMA
stefan	25.42	25.47	25.46	25.60	**25.71**	25.68	25.75
football	23.36	23.68	23.55	23.59	**23.95**	23.87	24.00
akiyo	42.66	42.37	42.56	42.09	42.61	**42.70**	42.84
foreman	32.43	32.51	32.68	31.99	32.83	**33.11**	33.43
mobile	23.77	23.78	23.68	23.81	**23.87**	23.86	23.92
hall	**34.09**	33.81	33.84	33.16	34.03	33.95	34.34
coastguard	29.40	29.37	29.40	28.09	29.49	**29.54**	29.62
container	**38.27**	37.66	37.66	37.67	37.70	37.99	38.33
bus	24.48	24.66	24.53	24.62	**24.84**	**24.84**	24.90
dancer	30.07	30.96	30.77	30.48	31.16	**31.66**	32.14
mother	39.55	39.25	39.48	37.48	39.49	**39.76**	40.12
tempete	27.38	27.51	27.46	27.44	**27.61**	**27.61**	27.70
table tennis.	28.27	28.18	28.37	28.32	28.62	**28.71**	28.87
flower	25.88	25.93	25.92	25.84	**25.98**	**25.98**	26.03
children	28.72	28.93	28.68	29.04	**29.17**	29.11	29.24
paris	30.50	30.52	30.48	30.49	**30.67**	30.65	30.71
news	36.68	36.92	36.89	36.79	37.04	**37.07**	37.33
Average	**30.64**	**30.68**	**30.67**	**30.38**	**30.87**	**30.95**	**31.13**

similar characteristics with the output of the SSD. Experimental results show that the proposed algorithm outperforms other BPM based ME algorithms while preserving the binary matching characteristic.

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