# Modified Constrained One-Bit Transform Based Fast Block Motion Estimation

Hwa-Yong Oh, Dong-Hwan Kim, Oğuzhan Urhan, *Member, IEEE* and Tae-Gyu Chang, *Member, IEEE*

**Abstract —** *Low-bit representation based motion estimation approaches such as one-bit transform, multiplication-free one-bit transform, and two-bit transform use matching criteria suitable for hardware. Thus, these techniques are more appropriate for consumer electronics devices which include hardware implementations in order to meet various constraints such as low-power and limited processing capability. The recently proposed constrained one-bit transform based motion estimation approach provides better results compared to other low-bit representation based approaches. Furthermore, it is shown in the literature that the performance of such approaches can be improved by employing some additional searches in the image domain starting from the best motion vectors found in the low-bit representation based motion estimation stage. This idea is applied to the constrained one-bit transform based motion estimation approach in this paper. Furthermore, a faster version of the constrained one-bit transform is also evaluated within this modification concept. Our experiments show that one of the proposed methods provides the best performance among methods sharing similar modification approaches whereas the other one enables the fastest implementation with small performance degradation*[1].

**Index Terms — Motion estimation, constrained one-bit transform, video coding.**

## I. INTRODUCTION

Block matching based motion estimation is an inevitable part of video coding standards such as H.261 [1], MPEG-2 [2], H.263 [3], and H.264/AVC [4] since it enables the exploitation of temporal redundancy between consecutive image frames. The optimal results for motion estimation can be obtained using a full search (FS) approach employing a minimum squared error (MSE) matching criterion. However, this stage requires a high computation and many methods have been developing to reduce the computational load. In software and hardware implementations some sparse search point approaches based on three step search [5], diamond search [6], and hexagonal search [7] might be used to speed up computation at the expense of some performance loss.

Some hardware implementation for variable block size motion estimation which is part of H.264/AVC is presented in [8-10] to enable real time processing. This hardware implementations use the sum of absolute difference (SAD) matching creation. We believe that low bit-representation based approaches can be an alternative to SAD based motion estimation since they use matching criteria that are very suitable for hardware realization. Some consumer electronics applications making use of such methods are presented in [11, 12].

One-bit transform (1BT) [13], two-bit transform (2BT) [14], and recently proposed multiplication-free one-bit transform (MF-1BT) [15], constrained one-bit transform (C-1BT) [16], and predictive hexagonal constrained-one bit transform (PHC-1BT) [17] based approaches use exclusive OR (XOR) based matching criteria instead of the commonly used SAD. These low-bit representation approaches enable faster hardware implementations with respect to classical SAD based approaches. However, they result in some performance degradation. The modified one-bit transform (M1BT) based approach presented in [18] proposes to use some additional search in the image domain around the motion vector found by the 1BT based approach to alleviate this drawback to some extent. A similar concept is employed in the modified two-bit approach (M2BT) [19] and adaptive modified two-bit approach (AM2BT) [20] for the 2BT based method and it is shown that the performance degradation can be alleviated to some extent by this way. In this work we implement a similar additional search scheme to the recently presented C-1BT and PHC-1BT based approaches. Our results show that the proposed schemes provide better results with respect to other methods sharing the similar idea.

## II. LOW-BIT REPRESENTATION BASED MOTION ESTIMATION APPROACHES

The 1BT based motion estimation approach initially applies a multi band-pass filtering to image frames and then compares the filtered frames with the originals. If the intensity value of a pixel in the original image frame is equal or greater than its filtered version the corresponding value in the binary image for this pixel becomes “1”, otherwise it takes a value of “0”. Next, the number of non-matching points (NNMP) creation is calculated as

$$NNMP(m,n)=\sum_{i=0}^{N-1}\sum_{j=0}^{N-1}\left\{B^{t}(i,j)\oplus B^{t-1}(i+m,j+n)\right\} \tag{1}$$

$$-s\le m,n\le s-1$$

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where $B^t$, $B^{t-1}$, $s$, and $\oplus$ represent binary one-bit images for frames $t$ and $t-1$, search range and Boolean XOR operation respectively. The candidate displacement $(m,n)$ that gives the lowest NNMP is assigned to be the block motion vector. If two candidates have the same NNMP value, the one with the lowest distance to the zero motion position is chosen as motion vector.

The kernel used in the 1BT approach has 25 non-zero component and thus requires floating point normalization for filtering. The MF-1BT method in [15] proposes a new diamond shaped kernel which has 16 non-zero components so that normalization can be carried out employing only integer shift operations. Since integer arithmetic is executed faster in both hardware and software implementations instead of floating point arithmetic [21], the MF-1BT approach can be performed within a shorter time interval with respect to 1BT.

The 2BT approach in [14] creates two bit-planes taking local mean and variance values into account and provides generally a better performance with respect to the 1BT and MF-1BT approaches. The C-1BT based approach in [16] introduces a constraining mask ( $CM$ ) which determines pixels to be used in the computation of matching creation. $CM$ is constituted as follows

$$CM^t(i,j)=\begin{cases}1, & \text{if } \left|I^t(i,j)-I_F^t(i,j)\right|\geq D\\ 0, & \text{otherwise}\end{cases} \tag{2}$$

where $I$ and $I_F$ show the original and filtered image frames. $D$ is a threshold which determines pixels to be included in the matching creation calculation. The pixels that have "1" in their $CM$ are considered as reliable and are used in the computation. The constrained number of non-matching points (CNNMP) is computed as [16]

$$CNNMP(m,n)=\begin{array}{l} {}^{N\ \ 1\,N\ \ 1} \quad CM^t(i,j)\,\mathrm{P}\,CM^{t\ \ 1}(i+m,j+n) \\ {}_{i=0\ \ j=0}\ \ \mathrm{e}\ \ B^t(i,j)\quad B^{t\ \ 1}(i+m,j+n)\end{array}\ , \tag{3}$$

$$s \quad m,n \quad s \quad 1$$

where P and e show Boolean OR and Boolean AND operations respectively.

The predictive hexagonal constrained one-bit transform (PHC-1BT) based method proposed in [17] aims to reduce computational load of C-1BT using a sparse search point scheme. Combination of sparse search algorithms with low-bit representation methods is rarely investigated. This approach applies predictive hexagonal search [22] with some improvements to the C-1BT based approach.

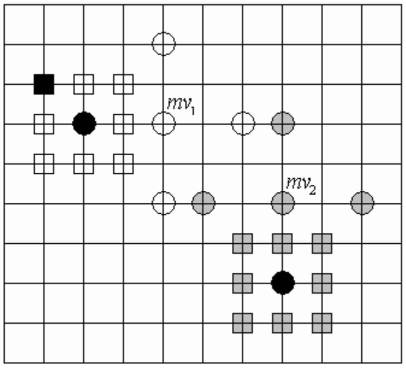

**Fig. 1. Multiple-candidate two-step search (M2SS) strategy.**

This method also uses a kernel which includes only 4 non-zero components. Therefore binary images used in the matching can be obtained faster with this method. This approach can reduce the number of average search points of up to 50 times, with nearly similar performance with respect to the C-1BT based method.

## III. PROPOSED METHOD

The modified one-bit transform (M1BT) method in [18] proposes to perform an additional search in the image domain to improve the performance of the 1BT method. In this work the distribution of motion vector differences between FS-SAD and 1BT results is examined. As a result of this examination it is found that motion vectors assigned by the 1BT approach are actually close to FS-SAD results and the 1BT performance can be improved if a small additional search is carried out. Thus, a multiple-candidate two-step search (M2SS) around the two best vectors found by 1BT is executed in the image domain. The M2BT approach in [19] follows a similar way and performs additional M2SS over motion vectors found by 2BT.

In this paper a similar modification concept is adopted and applied to the C-1BT [16] and PHC-1BT [17] approaches. Since the C-1BT approach provides better performance than the 2BT approach it is expected that the proposed modified constrained one-bit (MC-1BT) based approach will also provide improved performance. Furthermore, a combination with the PHC-1BT method enables fastest implementation among other known modified low-bit representation approaches. In the experimental results section it is shown that this scheme (i.e. MPHC-1BT) can provide nearly similar performance with significant reduction in computational load.

In the M1BT approach two sub-sampled versions of the minimum absolute error creation can be used. These two distortion measures are defined as

$$\begin{aligned} D1(mv_x,mv_y)&=\sum_{(i \bmod 2)=(j \bmod 2)}\left|I^t(i,j)-I^{t-1}(i+mv_x,j+mv_y)\right| \\ D2(mv_x,mv_y)&=\sum_{(i \bmod 2)=0,\ (j \bmod 2)=0}\left|I^t(i,j)-I^{t-1}(i+mv_x,j+mv_y)\right| \end{aligned} \tag{4}$$

TABLE I
RESULTS FOR THE “FOOTBALL” AND “TENNIS” SEQUENCES

| | | “Football” Sequence (frame size: $352\times240$ pels, 125 frames) | | | | “Tennis” Sequence (frame size: $352\times240$ pels, 125 frames) | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Method** | | **PSNR (dB)** | **% mv stage1** | **% mv stage2** | **% mv stage3** | **PSNR (dB)** | **% mv stage1** | **% mv stage2** | **% mv stage3** |
| SAD | | 22.88 | N/A | N/A | N/A | 29.45 | N/A | N/A | N/A |
| 1BT [13] | | 21.83 | N/A | N/A | N/A | 28.11 | N/A | N/A | N/A |
| 2BT [14] | | 22.08 | N/A | N/A | N/A | 28.46 | N/A | N/A | N/A |
| C-1BT [16] | | 22.10 | N/A | N/A | N/A | 28.71 | N/A | N/A | N/A |
| PHC-1BT [17] | | 21.66 | N/A | N/A | N/A | 28.14 | N/A | N/A | N/A |
| M1BT [18] | $T$=10 | 22.41 | 87.00 | 11.96 | 1.04 | 28.86 | 97.28 | 1.79 | 0.94 |
| | $T$ =7.5 | 22.60 | 77.69 | 18.63 | 3.68 | 29.02 | 95.77 | 2.80 | 1.43 |
| | $T$=5 | 22.77 | 61.11 | 27.21 | 11.68 | 29.20 | 90.86 | 6.65 | 2.49 |
| M2BT [19] | $T$=10 | 22.50 | 88.45 | 10.98 | 0.57 | 28.96 | 97.60 | 1.63 | 0.77 |
| | $T$=7.5 | 22.64 | 78.91 | 18.36 | 2.73 | 29.05 | 96.15 | 2.61 | 1.24 |
| | $T$=5 | 22.77 | 61.72 | 27.59 | 10.69 | 29.20 | 91.21 | 6.54 | 2.25 |
| MC-1BT | $T$=10 | 22.56 | 87.92 | 11.14 | 0.93 | 29.12 | 97.59 | 1.56 | 0.85 |
| | $T$=7.5 | 22.69 | 78.83 | 17.89 | 3.28 | 29.19 | 96.27 | 2.45 | 1.29 |
| | $T$=5 | 22.80 | 62.07 | 26.93 | 11.00 | 29.28 | 91.49 | 6.25 | 2.25 |
| MPHC-1BT | $T$=10 | 22.29 | 86.19 | 12.51 | 1.31 | 28.63 | 96.99 | 2.01 | 1.00 |
| | $T$=7.5 | 22.53 | 77.15 | 18.76 | 4.09 | 28.86 | 95.45 | 2.98 | 1.57 |
| | $T$=5 | 22.74 | 61.19 | 26.49 | 13.32 | 29.10 | 90.60 | 6.64 | 2.76 |

where $mv_x$ and $mv_y$ show the motion vector. We choose to use the $D1$ measure since its performance is better than $D2$.

In the proposed MC-1BT approach initially the image domain $D1$ measure is computed for the best motion vector found by C-1BT ( $mv_1$ ). If this value is lower than a pre-defined threshold ( $TH$ ) this point is accepted as final motion vector. A similar operation is performed for the second best motion vector found by C-1BT ( $mv_2$ ). If both errors are greater than the threshold then M2SS is executed. The search path of M2SS is shown in Figure 1.

Note that $mv_1$ and $mv_2$ are accepted as initial search centers of M2SS. Firstly, the image domain $D1$ error values of 10 circles including $mv_1$ and $mv_2$ are evaluated. Assume that the black filled circles give the minimum matching errors for each search center. Next, the second step is performed around these positions (black filled circles) over 16 points (squares in Fig. 1). The point giving the lowest matching error at this step (black filled square in Fig. 1) is chosen as final motion vector of the proposed MC-1BT approach. As an optional step full search can be carried out if the matching error is greater than $2\times TH$.

A similar modification is used for the PHC-1BT method to obtain results for the proposed MPHC-1BT approach.

## IV. EXPERIMENTAL RESULTS

We compare the proposed MC-1BT and MPHC-1BT approaches against the M1BT approach in [18], M2BT approach in [19], 1BT [13], 2BT [14], C-1BT [16], and PHC-1BT [17]. Performance evaluation is done using peak signal to noise ratio (PSNR) metric considering an open-loop scheme. Hence, the current frame is estimated using the previous frame and the estimation error between the original and estimated frames is considered. Blocks with a size of $16\times16$ pixels (i.e. macroblock level) with a search range of $s=16$ for the “Foreman”, “Football”, “Tennis”, “Coastguard”, “Mobile”, and “Garden” sequences are used in the experiments.

Table 1-3 show results of aforementioned sequences for various methods. Several thresholds are used for the modified approaches. The computed $D1$ errors are divided by the block size (i.e. $16\times16$ ) and then compared against the threshold value ( $T$ ) given in these tables. We investigated the modification phase in three stages, as in M2BT and AM2BT, to investigate the computational load in the image domain. If the motion vector decision is given directly at the $mv_1$ or $mv_2$ positions this case is referred to as stage-1. If this decision can be given after M2SS this case is referred as stage-2. If the decision is not given within these two stages, the full search result is considered as stage-3. The motion vector distribution corresponding to these stages gives an idea about the computational load of the introduced modification. However, since $mv_1$ and $mv_2$ may be close to each other, some search points in M2SS may overlap which can further decrease the number of average search points in the image domain.

If we evaluate the performance of proposed the MC-1BT approach according to these results it can be said that the proposed method slightly outperforms the M2BT approaches most of the time. Furthermore, the computational load of 2BT itself is quite high with respect to the C-1BT approach since it requires local mean and variance computations to obtain two bit planes which will be used in the matching step.

TABLE II
RESULTS FOR THE “FOREMAN” AND “COSTGUARD” SEQUENCES

| Method | | “Foreman” sequence (frame size: $352\times288$ pels, 300 frames) | | | | “Costguard” sequence (frame size: $352\times288$ pels, 300 frames) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **PSNR (dB)** | **% mv stage1** | **% mv stage2** | **% mv stage3** | **PSNR (dB)** | **% mv stage1** | **% mv stage2** | **% mv stage3** |
| SAD | | 32.09 | N/A | N/A | N/A | 30.48 | N/A | N/A | N/A |
| 1BT [13] | | 30.32 | N/A | N/A | N/A | 29.83 | N/A | N/A | N/A |
| 2BT [14] | | 30.70 | N/A | N/A | N/A | 29.94 | N/A | N/A | N/A |
| C-1BT [16] | | 30.86 | N/A | N/A | N/A | 29.98 | N/A | N/A | N/A |
| PHC-1BT [17] | | 30.66 | N/A | N/A | N/A | 30.13 | N/A | N/A | N/A |
| M1BT [18] | $T$=10 | 31.07 | 98.70 | 1.16 | 0.14 | 30.15 | 99.54 | 0.43 | 0.03 |
| | $T$ =7.5 | 31.21 | 97.69 | 1.94 | 0.37 | 30.18 | 98.46 | 1.45 | 0.09 |
| | $T$=5 | 31.45 | 94.40 | 4.58 | 1.02 | 30.28 | 93.28 | 6.33 | 0.39 |
| M2BT [19] | $T$=10 | 31.07 | 99.04 | 0.89 | 0.07 | 30.28 | 99.63 | 0.35 | 0.02 |
| | $T$=7.5 | 31.17 | 98.18 | 1.57 | 0.25 | 30.31 | 98.65 | 1.30 | 0.05 |
| | $T$=5 | 31.41 | 94.90 | 4.32 | 0.77 | 30.36 | 93.92 | 5.75 | 0.33 |
| MC-1BT | $T$=10 | 31.33 | 98.89 | 0.96 | 0.15 | 30.23 | 99.59 | 0.38 | 0.03 |
| | $T$=7.5 | 31.42 | 98.05 | 1.61 | 0.35 | 30.26 | 98.60 | 1.31 | 0.08 |
| | $T$=5 | 31.58 | 94.93 | 4.17 | 0.90 | 30.31 | 93.79 | 5.84 | 0.37 |
| MPHC-1BT | $T$=10 | 31.08 | 98.62 | 1.20 | 0.18 | 30.32 | 99.61 | 0.36 | 0.02 |
| | $T$=7.5 | 31.21 | 97.64 | 1.93 | 0.44 | 30.34 | 98.65 | 1.29 | 0.07 |
| | $T$=5 | 31.43 | 94.47 | 4.42 | 1.12 | 30.37 | 93.91 | 5.75 | 0.34 |

TABLE III
RESULTS FOR THE “MOBILE” AND “GARDEN” SEQUENCES

| Method | | “Mobile” sequence (frame size: $352\times240$ pels, 300 frames) | | | | “Garden” sequence (frame size: $352\times240$ pels, 115 frames) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **PSNR (dB)** | **% mv stage1** | **% mv stage2** | **% mv stage3** | **PSNR (dB)** | **% mv stage1** | **% mv stage2** | **% mv stage3** |
| SAD | | 23.94 | N/A | N/A | N/A | 23.79 | N/A | N/A | N/A |
| 1BT [13] | | 23.61 | N/A | N/A | N/A | 23.31 | N/A | N/A | N/A |
| 2BT [14] | | 23.66 | N/A | N/A | N/A | 23.43 | N/A | N/A | N/A |
| C-1BT [16] | | 23.69 | N/A | N/A | N/A | 23.38 | N/A | N/A | N/A |
| PHC-1BT [17] | | 23.70 | N/A | N/A | N/A | 23.37 | N/A | N/A | N/A |
| M1BT [18] | $T$=10 | 23.79 | 94.63 | 5.26 | 0.12 | 23.61 | 93.40 | 5.31 | 1.29 |
| | $T$ =7.5 | 23.82 | 86.30 | 13.04 | 0.66 | 23.67 | 83.46 | 14.46 | 2.08 |
| | $T$=5 | 23.85 | 67.95 | 26.96 | 5.08 | 23.71 | 64.55 | 29.29 | 6.16 |
| M2BT [19] | $T$=10 | 23.79 | 94.73 | 5.16 | 0.11 | 23.64 | 93.58 | 5.27 | 1.16 |
| | $T$=7.5 | 23.81 | 86.49 | 12.87 | 0.65 | 23.68 | 83.77 | 14..23 | 2.00 |
| | $T$=5 | 23.85 | 68.06 | 26.88 | 5.07 | 23.71 | 64.71 | 29.19 | 6.10 |
| MC-1BT | $T$=10 | 23.82 | 94.68 | 5.21 | 0.11 | 23.67 | 93.56 | 5.16 | 1.28 |
| | $T$=7.5 | 23.84 | 86.42 | 12.93 | 0.65 | 23.70 | 83.68 | 14.29 | 2.03 |
| | $T$=5 | 23.87 | 68.15 | 26.79 | 5.06 | 23.73 | 64.83 | 29.06 | 6.11 |
| MPHC-1BT | $T$=10 | 23.79 | 94.47 | 5.42 | 0.11 | 23.62 | 93.31 | 5.45 | 1.24 |
| | $T$=7.5 | 23.82 | 85.99 | 13.45 | 0.66 | 23.66 | 83.45 | 14.47 | 2.08 |
| | $T$=5 | 23.85 | 67.73 | 27.14 | 5.13 | 23.71 | 64.49 | 28.18 | 6.32 |

Therefore, MC-1BT is a good alternative to M2BT approach in terms of both, performance and computational load. The MC-1BT approach has a slightly higher computational load compared to the M1BT approach in the binary matching case. However, the MC-1BT approach provides better performance using fewer search points in the image domain. Thus, it also outperforms the M1BT approach.

The proposed MPHC-1BT approach has the lowest binary domain computational load among M1BT, M2BT and MC-1BT approaches since it provides a speed-up of up to 50 times with only a slight performance loss compared to the C-1BT approach. This method requires a little more computations in the image domain. However, its overall computational load is the lowest among other modified low bit representation methods. The MPHC-1BT approach has similar performance compared to the M1BT approach. Thus, it can be said that the proposed MPHC-1BT approach provides reasonable performance with significantly lower computation load among other modified methods.

## V. CONCLUSIONS

Two modified low bit representation based motion estimation methods are presented in this paper. The proposed MC-1BT approach provides the best performance with reasonable computational load compared to other existing methods. The secondly proposed MPHC-1BT method has the lowest overall computational load and provides an acceptable performance among other modified approaches. Experiments show the effectiveness of the proposed approaches clearly. Since these approaches use XOR based matching criteria suitable for hardware in the first phase, they are appropriate for hardware realization of motion estimation in related consumer electronics devices.

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