A Fast Block-Matching Motion Estimation Algorithm with Motion Modeling and Motion Analysis

Dong-Keun Lim and Yo-Sung Ho

Kwangju Institute of Science and Technology (K-JIST)
1 Oryong-dong, Puk-gu, Kwangju, 500-712, Korea
`{dklim, hoyo}@kjist.ac.kr`

Abstract. By modeling the block-matching algorithm as a function of the correlation of image blocks, we derive search patterns for fast block-matching motion estimation. The proposed approach provides an analytical support for the diamond-shape search pattern, which is widely used in fast block-matching algorithms. We also propose a new fast motion estimation algorithm using adaptive search patterns and statistical properties of the object displacement. In order to select an appropriate search pattern, we exploit the relationship between the motion vector and the block differences. By changing the search pattern adaptively, we improve motion prediction accuracy while reducing required computational complexity compared to other fast block-matching algorithms.

1 Introduction

In recent days, there has been an increasing demand for real-time video communication services, such as wireless or internet video conferences. Motion estimation has been widely used to find motion information in various video coding standards and plays an important role in video compression.

A block-matching algorithm (BMA) is adopted in most video coding standards, such as H.261, H.263, MPEG-1, MPEG-2 and MPEG-4, to estimate motion vectors. A brute-force BMA makes an exhaustive search for an optimal block displacement that minimizes a predefined cost function. The full search (FS) BMA requires very expensive computation. Therefore, various fast BMAs have been developed to reduce the computational burden [1-8]. Those fast BMAs employ different heuristic search patterns for improved trade-off between video quality and computational complexity.

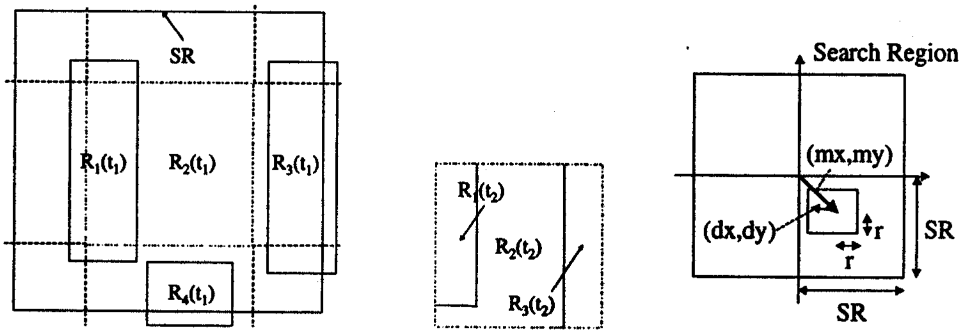
In this paper, we derive search patterns for fast block-matching motion estimation analytically, based on the correlation of image blocks. The derived patterns are verified with various test video sequences. The analysis presented in this paper supports the diamond shape search patterns, which are widely used in many fast BMAs [5-8]. We also propose an adaptive search algorithm, which changes search patterns for motion estimation based on statistical properties between the object displacement and block differences. Simulation results are presented to show effectiveness of the proposed motion search algorithm.

Y.-C. Chen, L.-W. Chang, and C.-T. Hsu (Eds.): PCM 2002, LNCS 2532, pp. 135-142, 2002.

2 Optimal Search Pattern

2.1 Problem Statement

Since the shape and the size of the search pattern in the fast BMA jointly determine the convergence speed and estimation performance, we analyze search patterns. In the block-matching algorithm, we calculate matching criteria between current and previous blocks in each search pattern. We reduce the displacement between checking positions in several steps to increase motion accuracy.



(a) At $t = t_1$ (Previous) (b) At $t = t_2$ (Current) (c) $(x, y)=(mx+dx, my+dy)$

Fig. 1. Block Region Diagram

If we assume that a block is partitioned with a limited number of regions of similar characteristics, each region can be represented by a certain value. In Fig. 1, $R_i(t_k)$ means the representative value of region R_i at time k. Let $OA_{(x,y)}(Cost(R_i, R_j))$ be an overlapped area with $Cost(R_i, R_j)$ when we match a block in the current frame and a block having (x,y) displacement in the search region(SR) in the previous frame.

In order to find the best matched position, we calculate the total cost, $TotalCost(x,y)$, at each candidate position (x,y) and decide a motion vector, $MV(mx,my)$.

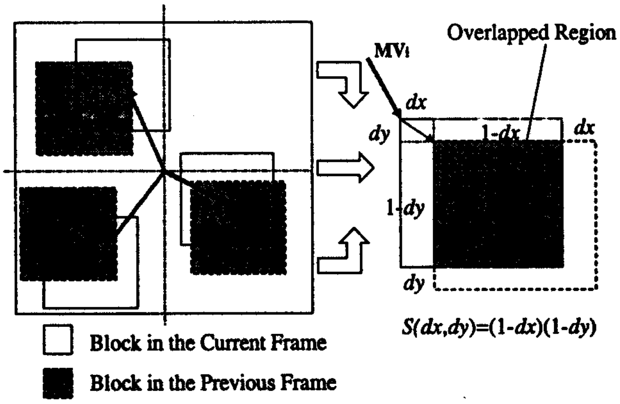
$$TotalCost(x,y) = \sum_{\substack{Ri \in Region(t=t1) \\ Rj \in Region(t=t2)}} OA_{(x,y)}(Cost(R_i, R_j)) \tag{1}$$

$$MV(mx,my) = \min_{(x,y)\in SR} TotalCost(x,y) \tag{2}$$

For a simple analysis, we consider an image block whose pixel values are uniform inside the block and the image block is uncorrelated to its background. In this analysis, we use correlation for the following matching criterion.

$$OA_{(x,y)}(Cost(R_i, R_j)) = \begin{cases} 0, & if\ i \neq j \\ 1, & if\ i = j \end{cases} \tag{3}$$

In Fig. 1(c), r is a small region of 4×4 pixels around the motion vector (mx,my). (dx,dy) indicates the displacement between the optimal search position and the current search position.



(a) (b)

Fig. 2. Correlation between Image Blocks.

Although we do not know the direction and the magnitude of the actual object movement, (mx,my) in Fig. 1(c) or MV_i in Fig. 2(a), we can derive analytic search patterns for motion estimation by investigating equi-correlation contours as a function of the distances, dx and dy, between checking positions in the search pattern.

2.2 Derivation of Analytic Search Pattern

The correlation $S(dx,dy)$ between the block and the search region can be calculated as the normalized area of the overlapped region, as shown in Fig. 2(b).

$$S(dx,dy) = (1-|dx|)(1-|dy|),\quad 0 \le |dx|,|dy| \le 1 \tag{4}$$

where $|dx|$ and $|dy|$ are normalized by the block size in the horizontal and vertical dimensions, respectively. For $|dx| \ge 1$ or $|dy| \ge 1$, we set $S(dx, dy)=0$.

Similar to the steepest descent algorithm, our search strategy is to find points of the minimal sum of absolute differences on the equi-correlation contours. In practice, we use surrounding motion vectors to predict the current motion vector (mx, my). Around this predicted position, we have small matching errors. We can derive the equi-correlation contours as a function of dx and dy as follows.

If we represent a position (dx,dy) in the block by the following linear relationship

$$dy = c \cdot dx,\quad c \in \Re \tag{5}$$

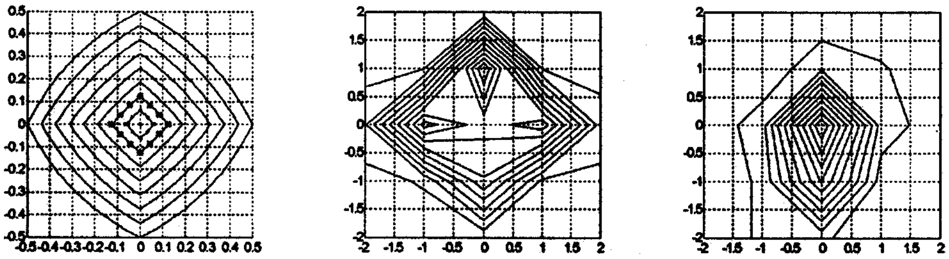
From Eq. (4) and Eq. (5), we can find locations of displacement (dx,dy) having the same correlation value.

$$dx = \frac{(c+1) \pm \sqrt{(c-1)^2 + 4c \cdot S(dx,dy)}}{2c} \tag{6}$$

By varying the value of c both in Eq. (5) and in Eq. (6), we can plot equi-correlation contours in Fig. 3(a). The resulting equi-correlation contours have the same characteristics as the search patterns used in the diamond search [4-5,8] and the advanced zonal search [6-8]. From the analytical equi-correlation contours in Fig. 3(a), we can generate various search patterns. By sampling checking positions from the continuous analytical equi-correlation contours, we chose discrete search points. The diamond shape can have different sizes and different choices of samples to optimize motion characteristics.

2.3 Experimental Results for Search Pattern

In order to verify the derived search patterns, we perform computer simulations on ITU-T test sequences of CIF and ITU-R 601 formats. In each simulation, the original image is used as a reference frame to generate a motion-compensated prediction image. For FS BMA, the block size is 16×16 and the search region is ±7. In other words, we normalize the values such that $0 < |dx|, |dy| < 7/16 \approx 1/2$.



(a) Analytical contours (b) MISS AMERICA (c) FOOTBALL

Fig. 3. Motion Distribution

While Fig. 3(a) indicates optimal search patterns for $S(dx,dy) < 1/2$, Fig. 3(b) and Fig. 3(c) show the real motion vector fields for MISS AMERICA and FOOTBALL, respectively, where the axes are normalized. We observe that the derived optimal search patterns and the experimental ones are all diamond-shaped, which implies that our derivation is valid for the optimal search pattern for BMA. To increase the motion estimation accuracy, we may increase the size of diamond shape and the number of checking positions, and modify the diamond shape with rounded sides.

3 Adaptive Motion Search

In teleconferencing video, most image blocks are regarded as stationary. Motion vectors for stationary image blocks are mostly around (0,0). In general, a large object displacement would produce a large block difference (BD) within the search region (SR). We exploit these characteristics for efficient motion search.

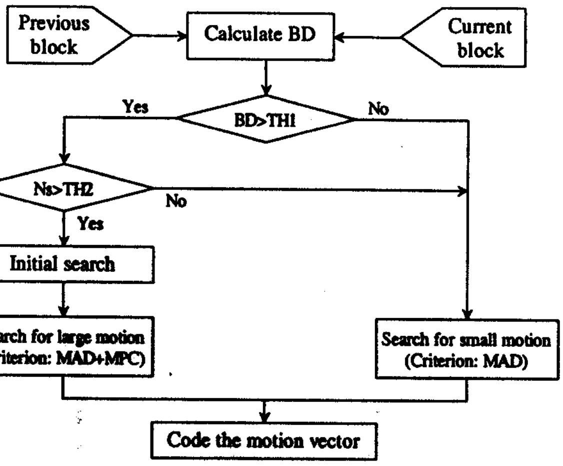
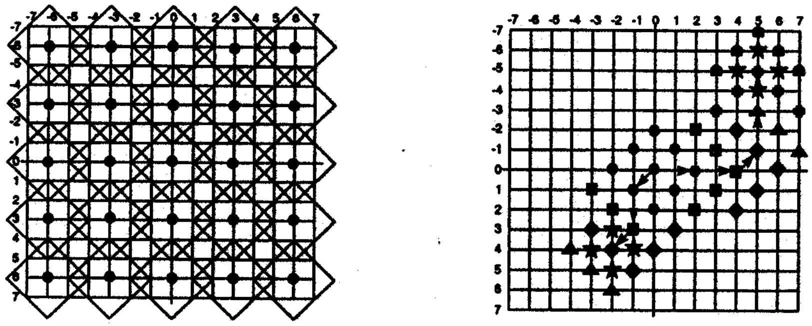


Fig. 4. Adaptive Motion Search Algorithm

Fig. 4 explains the overall procedure of the proposed adaptive motion search (AMS) algorithm, where *Ns* denotes the number of significant pixels in the block. The threshold values, TH1 and TH2, are determined experimentally.



(a) Initial Search Pattern (b) Next Stage Search Pattern

Fig. 5. Search Patterns for Large Motion

If the block difference is large, we use the initial search pattern, shown in Fig. 5(a). The initial search pattern consists of the uniform lattice that covers the search region. Once the minimum distortion position is selected in the initial search, other positions near this position are examined in the next stages. In Fig. 5(b), we show two diamond search examples [4-5], which explains two different search strategies. Depending on the last position of the minimum distortion, we add three or five new checking positions at each step. This procedure is repeated until we find the minimum distortion in the center of the search pattern or the boundary of search region. The final motion vector is the minimum distortion position among the one-pixel spaced positions around it.

If the block difference is small, the search region is limited to a small local region. The procedure for small motion is similar to that for large motion, while we start with neighboring 3×3 square pixel positions.

4 Simulation Results

Computer simulations have been performed on the monochrome test sequences of different image sizes including CIF and ITU-R 601. Quality of the motion-compensated prediction image is measured by the peak signal-to-noise ratio (PSNR).

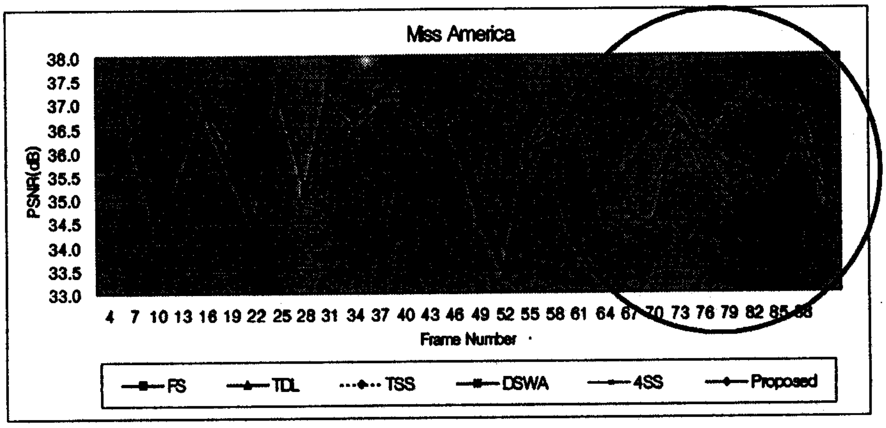


Fig. 6. Performance Comparisons for MISS AMERICA

Table 1. Average Performances of BMAs (MISA: Miss America, FB: Football)

Algorithm	PSNR(dB)		Average Number of Checking Points	
	MISA	FB	MISA	FB
Full Search	36.29	23.12	225.0	225.0
Three Step Search	35.78	21.77	25.0	25.0
4-Step Search	35.81	21.84	20.9	21.9
2-D Log Search	35.62	21.63	16.6	19.3
Dynamic Search	35.77	21.78	19.8	17.8
Adaptive Motion Search(AMS)	36.17	22.99	14.8	29.7

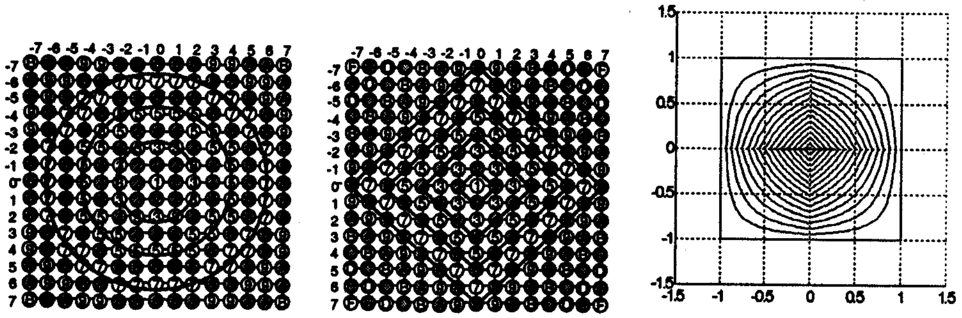
Note: Block Size =16×16, Search Region = ±7

Fig. 6 shows experimental results. The proposed AMS (Adaptive Motion Search) algorithm is compared with FS (full search), TDL (two-dimensional logarithmic search) [1], TSS (three-step search) [1], 4SS (four-step search) [2], and DSWA (dynamic search window adjust and interlaced search) [3] algorithms. From frame number 60 to 85 in Fig. 6, the proposed method provides good prediction while the others fail to estimate large motions. The result is also obvious in FOOTBALL sequence, since it has large motions.

The comparison with popular fast block-matching algorithms are summarized in Table 1, where we note that AMS(adaptive motion search) improves motion prediction accuracy and reduces the average number of checking position (CP).

5 Discussions and Analysis

Diamond search [4-5,8] and zonal search [6-8] have been used in the fast block-matching motion estimation algorithms in the MPEG-4 verification model [8]. Now zonal search was adopted as an informative annex in MPEG-2 IS software [11]. Zonal search can be performed with circular zonal search and diamond zonal search.



(a) Circular Zonal Search (b) Diamond Zonal Search (c) Derived Search Patterns

Fig. 7. Comparisons of Search Patterns

Fig. 7 shows the comparison of search patterns. In Fig. 3(a), we show the result for a limited search region to ±7, or 7/16 ≈ 0.5. By limiting the search region to ±15, or 15/16 ≈ 1, we can obtain the derived search pattern in Fig. 7. We can see that the search pattern changes from the diamond shape to the rectangular shape depending on the size of search region. This implies that the diamond shape is advantageous in a small motion, and the circular or the rectangular shape can be used for sequences of large motions.

In general search patterns used in fast block-matching algorithms, checking positions are located at the same distance from the center of the search region. It means that correlations in checking positions located in the same distance from the center of the search region may not always be the same value. Our definition of the search pattern considers the equi-correlation positions since matching criteria are not uniformly distributed according to the distance from the center of search area, but randomly distributed.

6 Conclusions

In this paper, we suggest an idea that the block-matching algorithm can be analyzed with a simplified model. Although our analysis is based on a simplified model, it provides some insights and justifications to the use of diamond search patterns in fast block-matching algorithms. Correlations in checking positions located in the same distance from the center of search region may not always be the same. The derived search pattern is optimal in the sense of equi-correlation positions. We also exploit the relationship between the motion vector and the frame difference of each block to select an appropriate search pattern in each block. As a result, we can improve motion prediction accuracy, while reducing required computational complexity compared to other fast block-matching algorithms.

Acknowledgements. This work was supported in part by the Korea Science and Engineering Foundation (KOSEF) through the Ultra-Fast Fiber-Optic Networks (UFON) Research Center at Kwangju Institute of Science and Technology (K-JIST), and in part by the Ministry of Education (MOE) through the Brain Korea 21 (BK21) project. We would like to thank Professor Ming-Ting Sun at University of Washington for helpful discussions.

References

1. Musmann, H., Pirsh, P., Grallert, H.: Advances in Picture Coding. Proc. IEEE, vol. 73, no. 4 (1985) 523-548
2. Po, L.M., Ma, W.C.: A Novel Four-step Search Algorithm for Fast Block Motion Estimation. IEEE Trans. Circuit and Syst. for Video Tech., vol. 6, no. 3 (1996) 313-317
3. Lee, L.W., Wang, J.F., Lee, J.Y., Shie, J.D.: Dynamic Search-window Adjustment and Interlaced Search for Block-matching Algorithm. IEEE Trans. Circuit and Syst. for Video Tech., vol. 3, no. 1 (1993) 85-87
4. Tham, J., Ranganath, S., Ranganath, M., Kassim, A.: A Novel Unrestricted Center-biased Diamond Search Algorithm for Block Motion Estimation. IEEE Trans. Circuit and Syst. for Video Tech., vol. 8 (1998) 369-377
5. Zhu, S., Ma, K.: A New Diamond Search Algorithm for Fast Block Matching Motion Estimation. IEEE Trans. Image Processing, vol. 92 (2000) 287-290
6. Tourapis, A., Au, O., Liou, M., Shen, G.: An Advanced Zonal Block based Algorithm for Motion Estimation. ICIP'99, vol. 2 (1999) 610-614
7. Tourapis, A., Au, O., Liou, M.: New Results on Zonal based Motion Estimation Algorithms-Advanced Predictive Diamond Zonal Search. ISCAS, vol.5 (2001) 183-186
8. Chiang, T., Sun, H.: Report of Ad hoc Group on Encoder Optimization, ISO/IEC/JTC1 /SC29 /WG11 MPEG99/ M5528 (1999)