High Efficiency and Low Complexity Motion Estimation Algorithm for MPEG-4 AVC/H.264 Coding

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Abstract

H.264/AVC has achieved significant rate-distortion efficiency by many useful video encoding and decoding tools, but the motion estimation process concerns greatly on computational complexity. In this work, we propose an efficient algorithm, Hierarchical Single Cross Search (HSCS), by using the precision initial search center and simple search strategy to finish the motion estimation. Experimental results indicate that the proposed method can obtain good performance. Through the proposed features, the coding performance can be improved significantly, and the computation complexity of the integer pixel motion estimation of H.264 is also decreased tremendously.

Key Words: Early Termination, H.264, JM9.2 Software, JVT, Motion Estimation, MPEG-4 Part10 Advanced Video Coding, UMHexagonS

1. Introduction

There are more and more applications on digital images and videos in recent years, and several coding and compression standards such as JPEG to JPEG-2000, MPEG-1 and MPEG-2 [1] to MPEG-4, H.261, H.262 [2], H.263 and recent H.264/AVC [2–10] were proposed. As far as "long-term" is concerned, H.264 is the latest standardization fruitful result that promises to outperform the earlier other standards, and providing better compression of video images [2,11,12]. Compared with the previous standard, some highlighted features of the new technique include motion estimation (ME) with variable block sizes and multiple reference frames motion compensation, spatial prediction for intra coding, small block-size (4 × 4) residual transform coding, adaptive and hierarchical block size transform, in-loop deblocking filter, weighted prediction, tree structure motion compensation, flexible slice size, SP/SI synchronization/switching pictures, …, etc. [12].

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In the H.264 reference software JM9.2 [10], the Unsymmetrical Multi-resolution Hexagon Search (UMHexagonS) algorithm is adopted to speed up the ME [13]. In order to solve the local minimum problem in the search process, the UMHexagonS algorithm uses the hybrid and hierarchical motion search strategies [13]. The hybrid search strategies exploit the irregularity of search patterns to find the best motion vector. However, the methods are hard to be used in the hardware implementation because of the inevitable hybrid searching resulted from the motion estimation processing [15].

In this paper, an efficient Hierarchical Single Cross Search (HSCS) algorithm for block motion estimation is proposed. The active research has focused on fast Block Matching algorithms for a long time [14–17]. The main idea is to choose the simple search pattern, and the prediction with the minimum Lagrangian cost among these prediction candidates can be chosen earlier as the search center step starts. Based on a common process of the initial search center predictor, our proposed algorithm makes use of a novel feature to achieve a superior performance.

This paper is organized as follows: Section II describes the UMHexagonS algorithm in the JM9.2 reference software. The proposed Explicit Single Pattern Search algorithms are illustrated in Section III. The simulation results and comparisons are discussed in Section IV, and Section V concludes this work.

2. Motion Estimation in H.264/AVC Video Coding

In the block-matching motion estimation, the motion vector is the displacement of a block with the minimum distortion from the reference block. The UMHexagonS block-matching algorithm determines the motion vector by identifying a block with the minimum distortion from a hybrid search strategies of the irregularity of search patterns in the search area [13]. In order to reduce the heavy computation load of motion estimation, several fast block-matching algorithms, such as two-dimensional logarithmic search, three-step search, four-step search, diamond search, conjugate direction search, and enhanced predictive zonal search have been proposed [14–19]. Although these approaches can reduce computational complexity, they are likely to fall into a local minimum in the search process.

To achieve the better coding efficiency and solve the "local-minimum" problem in the motion search process, UMHexagonS algorithm [13] is wisely conducted into two parts: the first part is initial search center prediction and the second part is hybrid UMHexagonS algorithm for integer pixel search.

2.1 Initial Search Center Prediction

Generally speaking, spatial and temporal predictions are the main mechanisms for motion estimation to find the motion vectors of the current block. These mechanisms generate four types of prediction means: Median Predictor, Up-Layer Predictor, Corresponding-Block Predictor, and Neighboring Ref-Frame Predictor. The general descriptions of these four predictions are described as follows [12]:

(1) Median Predictor: As Figure 1 shows, the median predictor is used in median prediction of motion vectors. The median value of the adjacent blocks on the left block (Block A), top block (Block B), and top-right block (Block C) of the current block (Block E) is used to predict the motion vector of the current block. The equation of the median predictor is described in equation (1).

$$\text{Median\_predictor} = \text{median value } [(x_A, y_A), (x_B, y_B), (x_C, y_C)] \quad (1)$$

(2) Up-Layer Predictor: In H.264/AVC a prediction for the current frame is created from the image samples that have already been encoded. Each frame is divided into one of the seven blocks (16 × 16, 8 × 16, 16 × 8, 8 × 8, 4 × 8, 8 × 4, 4 × 4) to select the best prediction mode for motion estimation and motion compensation. A hierarchical search order is adopted to determine the block mode. For example, the median predictor is used in mode 1, otherwise mode 1 is the up layer of mode 2 and mode 3; mode 2 and mode 3 are the up layers of mode 4; mode 4 is the up layer of mode 5 and mode 6, and mode 5 and mode 6 are the up layers of mode 7. The flow of the decision block mode is shown in Figure 2 and equation (2).

$$\text{UPLayer\_predictor} = \text{UPBlock\_MV} \quad (2)$$

(3) Corresponding-Block Predictor: In this prediction mode, the motion vector of the corresponding block in the last frame is used as one motion vector candidate, as shown in equation (3) and Figure 3.

$$\text{CP\_predictor} = \text{last\_frame\_mv} \quad (3)$$

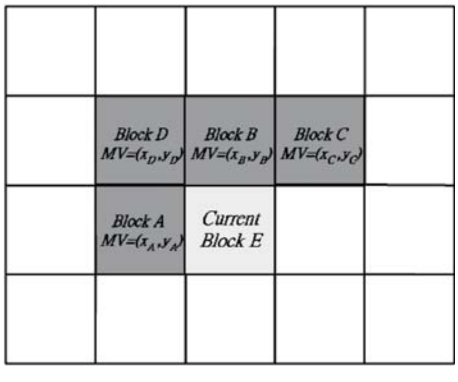

Figure 1. Spatial block location for the current frame.

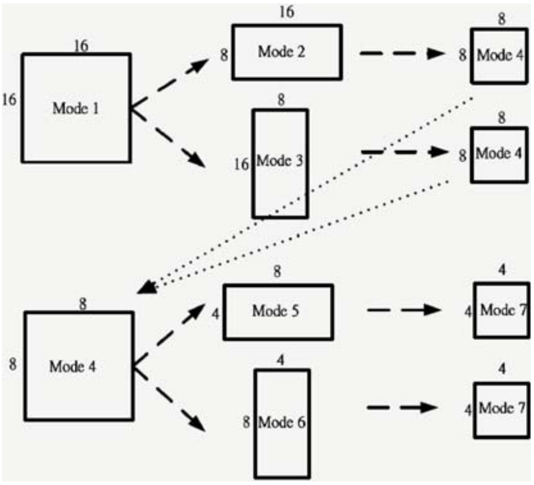

Figure 2. Hierarchical search order for the decision block mode.

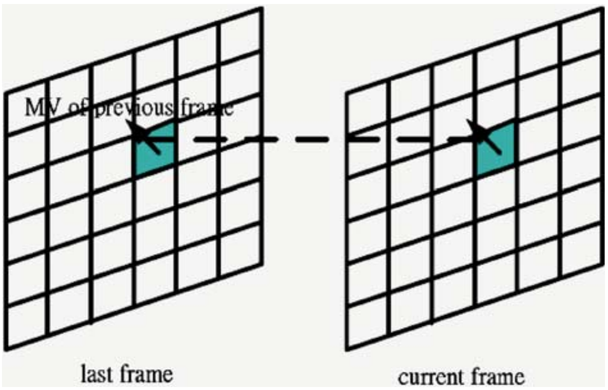

Figure 3. Temporal prediction of the last frames of the motion vector.

(4) Neighboring Ref-Frame Predictor: Multi-reference frames motion compensation is adopted in AVC to increase the prediction accuracy and coding efficiency. The current block's motion vector in reference frame t' can be predicted by scaling the current block's motion vector in the reference frame t' + 1, and equation (4) and Figure 4 show the approach.

$$NR\_predictor = \overrightarrow{MV_{NR}} \times \frac{t-t'}{t-t'-1} \tag{4}$$

2.2 Unsymmetrical Multi-Resolution Hexagon Search Algorithm

The optimum motion vector can be predicted accurately by UMHexagonS algorithm (as shown in Figure 5) [13]. There are three steps in the UMHexagonS search algorithm: the first step is Unsymmetrical-cross search; the second step is Uneven Multi-Hexagon-Grid Search, and Extended Hexagon-based Search is used at last. To find the optimum motion vectors in the search step, the UMHexagonS algorithm uses the hybrid and hierarchical motion search strategies. Obviously, the hybrid search strategies exploit the irregularity of search patterns to find the best motion vector. The irregularity may cause heavy computational overhead. This heavy computational load limits the performance of the ME speed and framework problem [13].

2.3 Early Termination with UMHexagonS Algorithm

Two goals are introduced for early termination. The first is the earlier the termination achieved the better, and the second is that the best matching position will not be

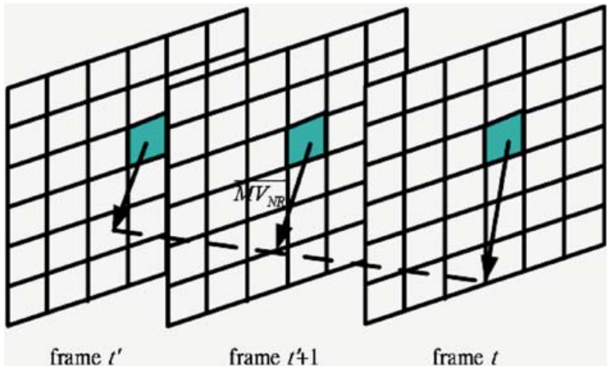

Figure 4. Temporal scaling prediction of the motion vector.

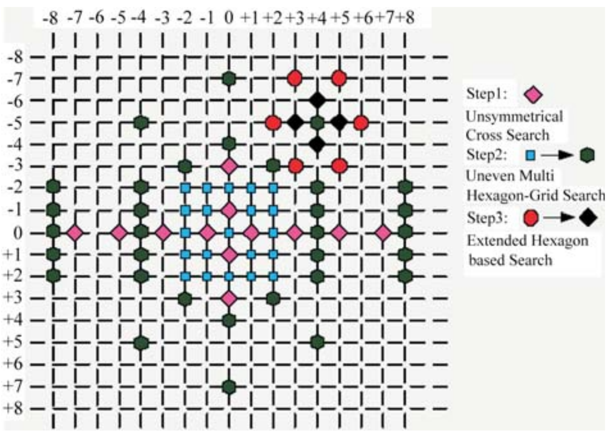

Figure 5. Prediction flow in the UMHexagonS algorithm.

missed or the termination motion vector will be very close to the best one. There are two main factors that determine the threshold of early termination: sum of absolute difference (SAD) and modulator factor. Similar to the initial search center prediction, it has four kinds of prediction modes for SAD prediction in the early termination algorithm [13,14].

Different skip policies will be used for termination by different threshold. Figure 6 is the whole flow chart of UMHexagonS algorithm by using the early termination method.

3. Proposed Algorithm for H.264/AVC Motion Estimation

In a typical initial search center prediction, the mechanisms generate four types of prediction means: Median Predictor, Up-Layer Predictor, Corresponding-Block Predictor, and Neighboring Ref-Frame Predictor. Although spatial and temporal predictions are the main mechanisms for motion estimation to find the initial search center of the current block, it still needs the irregularity of search patterns to refine the best motion vector, which performs around the many problems for complexity computation and framework [19].

3.1 Precision Initial Search Center

By the four types of initial search center prediction means [16], the proposed algorithm first determines the precision initial center of the search strategies. Because of the irregular sequences and the complexity of H.264, there are many factors to affect the prediction correlation such as playing speed, variable block size, quantization parameter, number of reference frame, …, etc. Therefore, there are different weightings for four initial search centers. For instance, when the block size is not equal to mode 1 (macroblock), compared with the median predictor, the up-layer predictor will be more important, which will become a reliable prediction. In this process, the predicted motion vector of each part is refined by the hierarchical single cross search algorithm to avoid the local-minimum problem for motion estimation. Hence, the motion vector and the prediction error between the local minimum problems of the initial search center can be considered and improved instead of the irregularity of search patterns (e.g. UMHexagonS). Figure 7 shows each refinement path of the initial search center. To reduce and consider every part of the local minimum effect, we use a hierarchical prediction process, which is performed around the initial search center candidate. Therefore, the optimum motion vector of each part can be refined for four

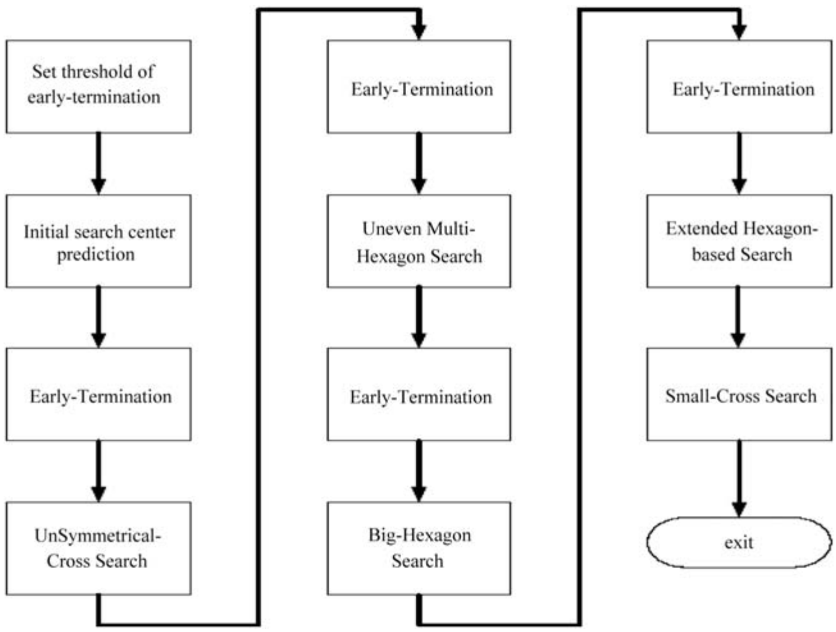

Figure 6. Flow chart of UMHexagonS algorithm and early termination.

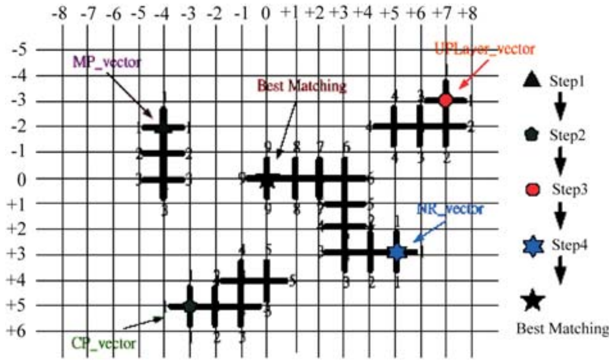

Figure 7. Four types of prediction means of the refinement.

different initial search centers by using the hierarchical refinement and single pattern search strategies. First, the mode decision is used since the inputs for different blocks are selectable. For mode 1 (macroblock), the median prediction is used to determine the initial search center and is refined by the single cross search, or for other block mode, the up-layer predictions are chosen and refined. Following the last step, if the corresponding block prediction is available for current frame, the corresponding block prediction is used to determine the initial search center and refine the motion vector by the single cross search again. Finally, similar to the corresponding block prediction, the neighboring ref-frame prediction is also based on the single cross strategy to avoid the local minimum problem in the initial search process. Therefore, we can find the neighboring search points of the initial search center for each part. The detailed procedure of the proposed precision initial search center (PISC) approach is shown in Figure 8.

3.2 Refining Motion Vector by Single Search Strategy

In the H.264/AVC standard, the newest way of performing motion estimation is to apply the so-called Unsymmetrical Multi-resolution Hexagon Grid block matching which consists of irregularity of hybrid search patterns to find the best motion vector. Although it is almost optimal, such an approach results in higher computational cost, due to more operations. A reduced complexity motion estimation technique, Hierarchical Single Cross Search (HSCS), is presented in this paper. It is based on the PISC and single cross search strategy to improve the computational complexity.

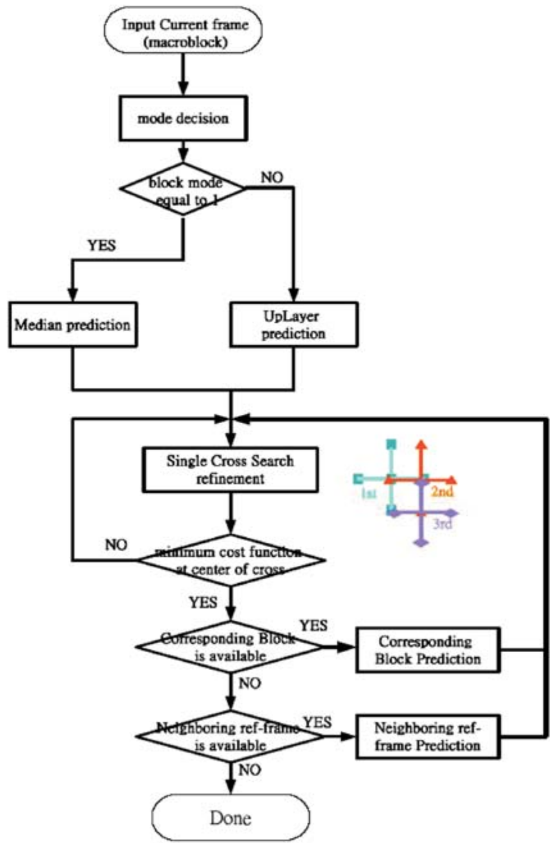

Figure 8. Flowchart of precision initial search center (PISC).

By using the precision initial search center determined in the first phase, HSCS starts searching the whole search area with a single cross until the minimum *MEcost* block lies in the center of the present search window. Even when the PISC coincides with the optimal solution, the Single-Cross still needs to evaluate as many as 5 points to verify the optimality, as indicated in Figure 9 [13]. The existence of local minimum is depicted in Figure 10. If the initial checking block is close enough to the global minimum, it will be very likely able to find the global

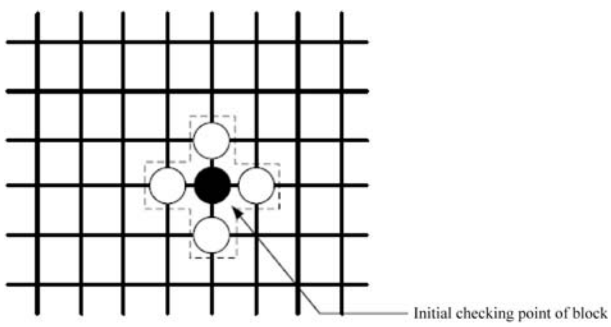

Figure 9. Small-cross search pattern.

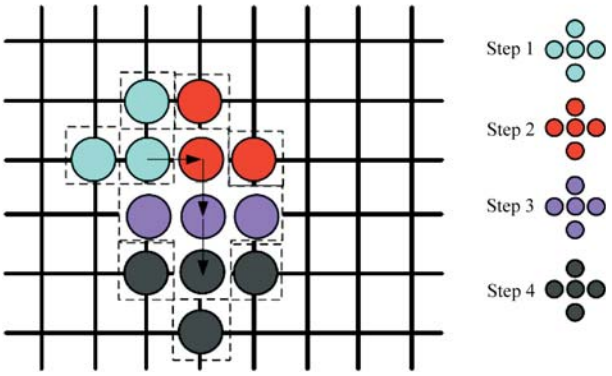

Figure 10. Single-cross search flow.

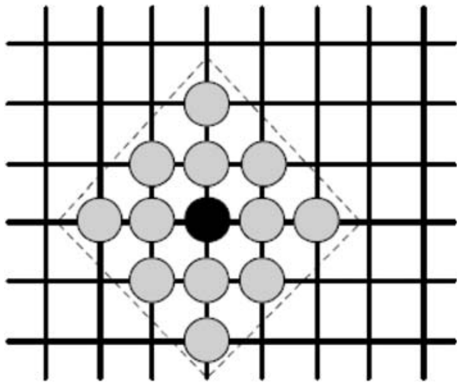

Figure 11. Diamond search pattern.

minimum through a local search. In our proposed algorithm, we only need to use a simple search strategy to find the best motion vector. Furthermore, the proposed HSCS scheme is not only accurate, but also it is more efficient to evaluate the candidate block.

3.3 Different Search Patterns for Single Search Strategy

Since many search shapes has been developed to find a good tradeoff between the video quality and the reduction of the computational load, we attempt to apply single search strategy from the well-known search pattern, and try to increase the video quality by increasing the number of search block in the search area. The choice of the patterns is driven by some practical and simple design in order to find the absolute minimum of the cost function. The most common plans of motion estimation algorithm are known as: cross form (Figure 10), diamond form (Figure 11), and rectangular form (Figure 12).

Based on a common search pattern of the motion estimation algorithm, our algorithm makes use of different plans to achieve single search strategies. Figure 13 shows the procedures of the proposed algorithm.

3.4 Classification and Comparison for Different Search Strategy

In a block matching motion estimation, an image is partitioned into blocks pixels, and the best match for these blocks is found inside a reference frame. To locate the best match, these fast algorithms use only a subset of the search area in order to reduce the total number of searches. Moreover, most of the existing fast algorithms

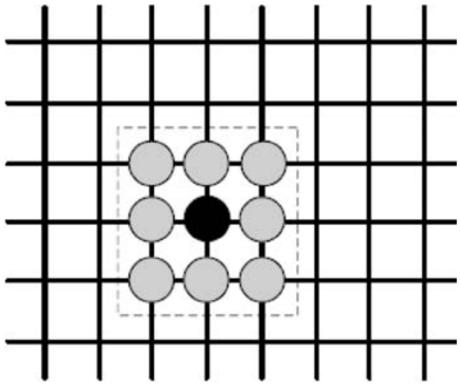

Figure 12. Rectangular search pattern.

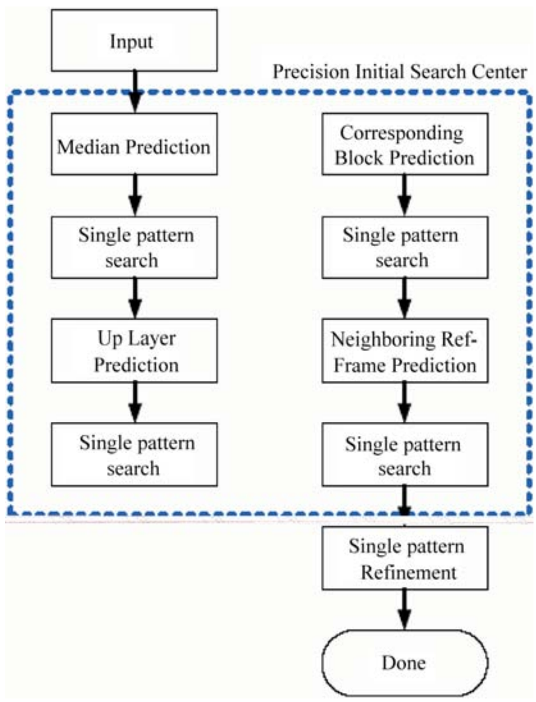

Figure 13. Procedures of the proposed HSCS algorithm.

focus on a hybrid pattern search strategy ME to improve the matching efficiency. However, those methods include some constraints, which are not applicable for hardware implementation [14]. In Table 1, we compare the property and nature to classify between hybrid and single search pattern. In our proposed algorithm, we only need to use a simple search strategy to find the best motion vector. Furthermore, the proposed PISC scheme is not only accurate, but also is more efficient to evaluate the candidate block.

4. Analysis and Judgment of the Experimental Results

The proposed HSCS algorithm is integrated within JM9.2 of the H.264 software for verification, the detail simulation environment is shown in Table 2.

We encode the sequences at 30 fps (common). The CABAC entropy code is used for all of the tests. The quantizer's values of I frame and P frame are 28 respectively, and B frame is of no use. The maximum search range is ±16 with 1~5 reference frames. In our experiment, we have evaluated sixteen sequences (QCIF 176 × 144 pixels, with 100 frames). Figure 14 shows the pictures of the motion for various sequences.

4.1 Objective Video Quality Evaluation

The experimental results show the HSCS algorithm and UMHexagonS algorithm in the objective video quality evaluation. The conventional objective image quality evaluation methods are based on mean square error (MSE) and peak signal to noise ratio (PSNR). The PSNR is measured by a logarithmic scale and depends on the MSE between the original and the encoded picture, and is defined as follows:

$$PSNR = 10\log_{10}\frac{255^2}{MSE}$$

Table 2. Simulation environment of JM9.2 reference software

Simulation Environment	Parameter setting
#IMAGE NUMBER	100
Quantization Parameter	28
Format	QCIF
#Number of reference frame	1 or 5
Search range	16
Variable block size	used
GOP	IPPPPP…………
Hardmard transform	used
Entropy coding	CABAC
YUV Format	4:2:0

Figure 14. Pictures of the motion for various sequence.

Table 1. Comparison of hybrid search and single search pattern

	Hybrid search pattern	Single search pattern
Advantage	♦ Perhaps more precise ♦ Easy to devise for various motion algorithm	♦ Easy to integrate with hardware ♦ Without early termination ♦ Regularity
Disadvantage	♦ Difficult to integrate with hardware ♦ Must exploit early termination to speed up ♦ Irregularity	♦ Local minimum problem ♦ More monotone applying to search strategy

MSE and PSNR can be calculated easily and quickly, and therefore are popular for video quality evaluation. Table 3 gives the comparisons of the PSNR measurements, and Table 4 calculates the difference of the PSNR measurements from the full search algorithm.

4.2 Experimental Results of Coding Bit-Rate

Table 5 gives the comparisons of the bit-rate measurements, and Table 6 calculates the difference of the bit-rate measurements.

4.3 Experimental Results of Motion Estimation Time

In our experiment, we have evaluated sixteen sequences QCIF type (176 × 144) with one hundred frames. In the experiment we compare the full search, UMHGS

Table 3. Average PSNR results obtained by different algorithms

	Full Search	UMHexagonS	UMHexagonS+ET	HSCS+cross	HSCS+rectangular	HSCS+diamond
	Y-PSNR (dB, average)					
akiyo	38.488	38.5	38.489	38.478	38.496	38.5
carphone	37.351	37.335	37.362	37.348	37.335	37.384
claire	39.807	39.775	39.754	39.725	39.776	39.78
coastguard	34.32	34.304	34.316	34.311	34.303	34.303
container	36.252	36.248	36.222	36.252	36.256	36.258
foreman	35.759	35.763	35.744	35.753	35.74	35.769
grandma	36.603	36.612	36.585	36.592	36.589	36.603
highway	37.881	37.856	37.819	37.804	37.841	37.85
miss_am	40.237	40.207	40.226	40.235	40.173	40.192
mobile	33.538	33.535	33.526	33.527	33.519	33.536
mthr_dotr	36.459	36.471	36.451	36.469	36.475	36.453
news	36.788	36.82	36.795	36.804	36.802	36.808
salesman	35.642	35.657	35.644	35.643	35.661	35.657
silent	36.029	36.004	36.022	36.033	36.01	36.016
suzie	37.4	37.381	37.39	37.379	37.387	37.406
trevor	36.558	36.537	36.524	36.517	36.536	36.516

Table 4. Average PSNR difference from the full search algorithm

	UMHexagonS	UMHexagonS+ET	HSCS+cross	HSCS+rectangular	HSCS+diamond
	PSNR Difference from Full search				
akiyo	0.012	0.001	-0.01	0.008	0.012
carphone	-0.016	0.011	-0.003	-0.016	0.033
claire	-0.032	-0.053	-0.082	-0.031	-0.027
coastguard	-0.016	-0.004	-0.009	-0.017	-0.017
container	-0.004	-0.03	0	0.004	0.006
foreman	0.004	-0.015	-0.006	-0.019	0.01
grandma	0.009	-0.018	-0.011	-0.014	0
highway	-0.025	-0.062	-0.077	-0.04	-0.031
miss_am	-0.03	-0.011	-0.002	-0.064	-0.045
mobile	-0.003	-0.012	-0.011	-0.019	-0.002
mthr_dotr	0.012	-0.008	0.01	0.016	-0.006
news	0.032	0.007	0.016	0.014	0.02
salesman	0.015	0.002	0.001	0.019	0.015
silent	-0.025	-0.007	0.004	-0.019	-0.013
suzie	-0.019	-0.01	-0.021	-0.013	0.006
trevor	-0.021	-0.034	-0.041	-0.022	-0.042

Table 5. Coding bit-rate results obtained by different algorithms

	Full Search	UMHexagonS	UMHexagonS+ET	HSCS+cross	HSCS+rectangular	HSCS+diamond
	Bit-rate (bits/s)					
akiyo	27876	27998	28003	28111	27878	28241
carphone	89722	89225	89482	89383	89234	89026
claire	30073	30002	30000	29731	29892	29865
coastguard	225845	225480	225549	225402	225086	224998
container	35368	35853	35439	35731	35856	35807
foreman	102773	102667	102530	101770	282609	102031
grandma	33519	33553	33426	33279	250896	33571
highway	61474	61934	62321	63790	248406	62491
miss_am	30775	30641	30924	30787	31027	30708
mobile	395016	391891	392686	391994	392122	392810
mthr_dotr	78191	77870	77895	78066	78284	78149
news	72382	72041	72012	71995	72216	72098
salesman	54170	54034	54050	54235	54199	54010
silent	76675	76692	76524	77371	76762	76980
suzie	87408	87478	87463	87120	87343	87487
trevor	123288	123370	122669	123130	123077	122738

Table 6. Coding bit-rate difference from the full search algorithm

	UMHexagonS	UMHexagonS+ET	HSCS+cross	HSCS+rectangular	HSCS+diamond
	Bit-rate Difference from Full search (bits/s)				
akiyo	122	127	235	2	365
carphone	-497	-240	-339	-488	-696
claire	-71	-73	-342	-181	-208
coastguard	-365	-296	-443	-759	-847
container	485	71	363	488	439
foreman	-106	-243	-1003	-1263	-742
grandma	34	-93	-240	-428	52
highway	460	847	2316	1226	1017
miss_am	-134	149	12	252	-67
mobile	-3125	-2330	-3022	-2894	-2206
mthr_dotr	-321	-296	-125	93	-42
news	-341	-370	-387	-166	-284
salesman	-136	-120	65	29	-160
silent	17	-151	696	87	305
suzie	70	55	-288	-65	79
trevor	82	-619	-158	-211	-550

algorithm, and the proposed HSCS algorithm. Table 7 gives the comparisons of the ME time measurements, and Table 8 calculates the variation of the bit-rate measurements. Compared with JM9.2, HSCS provides an efficient motion estimation method for sixteen different video sequences. The experimental results show that the proposed algorithm can more effectively stop the search processes in all kinds of the videos accurately.

4.4 Rate Distortion Curve

In our experiments, we have evaluated six sequences (QCIF 176 × 144 pixels, with 100 frames), “Akiyo”, “Coastguard”, “Container”, “Foreman”, “News”, and “Silent”. These sequences have been selected to highlight dif-

Table 7. Coding ME Time results obtained by different algorithms

	Full Search	UMHexagonS	UMHexagonS+ET	HSCS+cross	HSCS+rectangular	HSCS+diamond
	ME time (ms)					
akiyo	140725	50302	11749	10119	13520	17889
carphone	142490	59862	22929	16589	22692	29230
claire	138934	50448	12682	11061	14180	19176
coastguard	140550	77107	40692	19912	27491	37116
container	137841	58620	13416	11474	14245	20392
foreman	140198	62598	28443	18352	25137	33238
grandma	139960	54694	14314	10595	14216	20257
highway	141899	61825	17489	14568	20510	26406
miss_am	143055	55578	13833	12432	16412	21449
mobile	141465	68434	36521	15927	20796	28325
mthr_dotr	141871	56966	20883	14515	18029	24308
news	140634	54768	16053	11070	14438	20770
salesman	140132	55618	15750	10261	15254	20043
silent	139396	55673	18418	13455	17965	25694
suzie	141841	66738	27763	19207	26589	35240
trevor	140410	63256	24864	15500	21661	28483

Table 8. Coding ME time variation from the full search algorithm

	UMHexagonS	UMHexagonS+ET	HSCS+cross	HSCS+rectangular	HSCS+diamond
	ME Time Variation from UMHexagonS search (%)				
akiyo	0%	-77%	-80%	-73%	-64%
carphone	0%	-62%	-72%	-62%	-51%
claire	0%	-75%	-78%	-72%	-62%
coastguard	0%	-47%	-74%	-64%	-52%
container	0%	-77%	-80%	-76%	-65%
foreman	0%	-55%	-71%	-60%	-47%
grandma	0%	-74%	-81%	-74%	-63%
highway	0%	-72%	-76%	-67%	-57%
miss_am	0%	-75%	-78%	-70%	-61%
mobile	0%	-47%	-77%	-70%	-59%
mthr_dotr	0%	-63%	-75%	-68%	-57%
news	0%	-71%	-80%	-74%	-62%
salesman	0%	-72%	-82%	-73%	-64%
silent	0%	-67%	-76%	-68%	-54%
suzie	0%	-58%	-71%	-60%	-47%
trevor	0%	-61%	-75%	-66%	-55%

ferent kind of motions. “Coastguard” and “Foreman” have large motion activities. “Container” and “Silent” contain medium motion activities. “Akiyo” and “News” consist of relatively small motions. In the experiment we compare the UMHexagonS and the proposed HSCS algorithm, the maximum search range is ±16 with 1 or 5 reference frames. Figures 15 to 16 show the experimental results of the motion estimation algorithms for the rate distortion curve.

The results of our algorithm are almost the same as that of JM9.2 software. According to the experimental results shown in the rate-distortion curve, it indicates that the motion object blocks can be found accurately for all the video sequences. For example, “Coastguard” has the most motion activities in sixteen of the different video sequences, and the

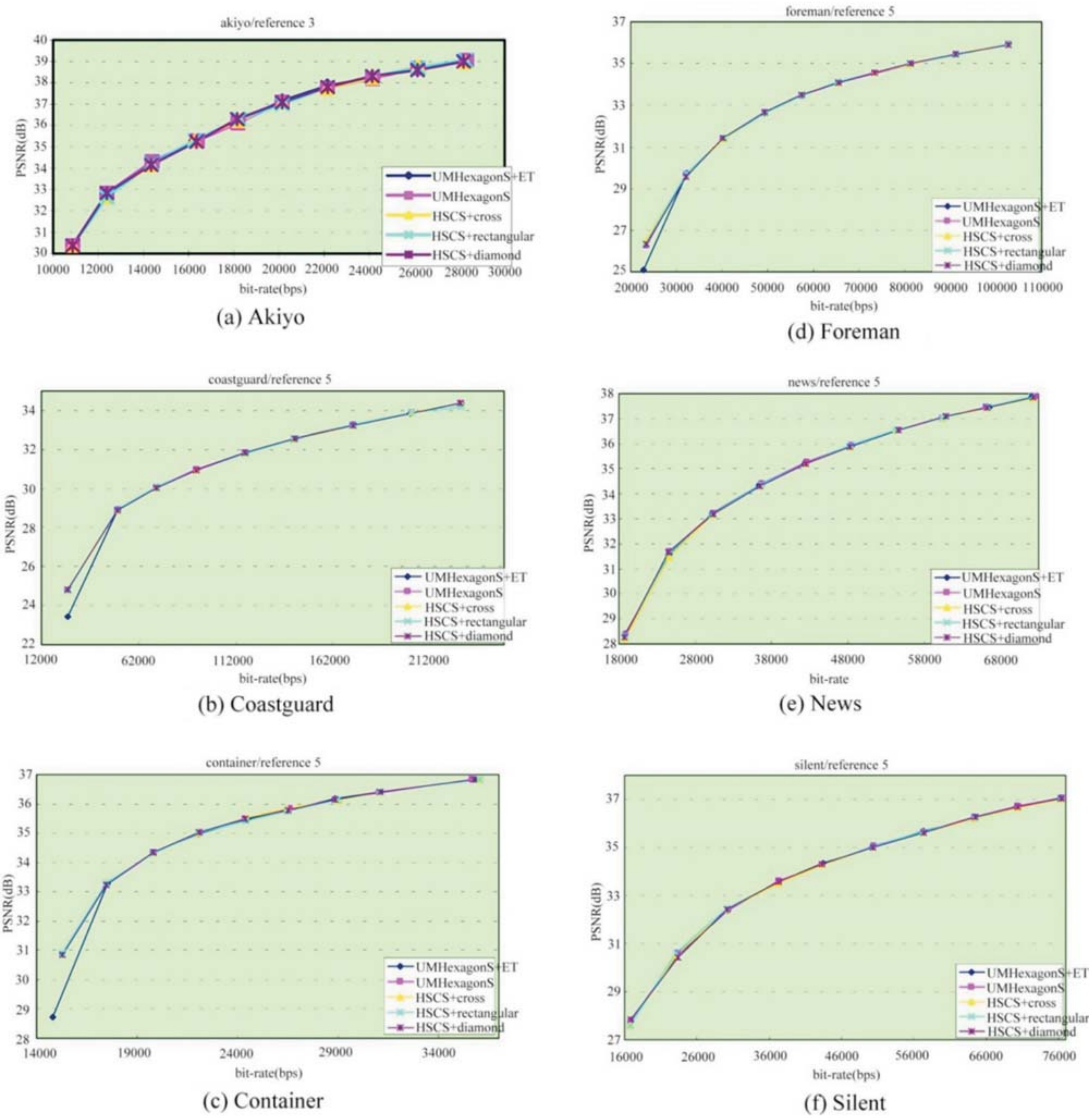

Figure 15. Rate distortion curve for 5 reference frames.

result of the rate-distortion curve is almost the same as that of the JM9.2 software. Obviously, the HSCS algorithm can accurately predict the motion vector for various motion blocks. The results indicate that the proposed approach can predict motion pictures for all kinds of video accurately.

4.5 Subjective Video Quality Evaluation

Figure 17 shows the experimental results of the full search, UMHexagonS, and HSCS algorithms in the subjective video quality evaluation respectively. These sequences have been selected to have high motion activities in all directions and with clear motion qualities.

As Figure 18 shows, the sequences are coded using a constant bit rate (250,000 bps) to find the effects of the different coding algorithms on image quality. The experimental results show that the proposed algorithm can

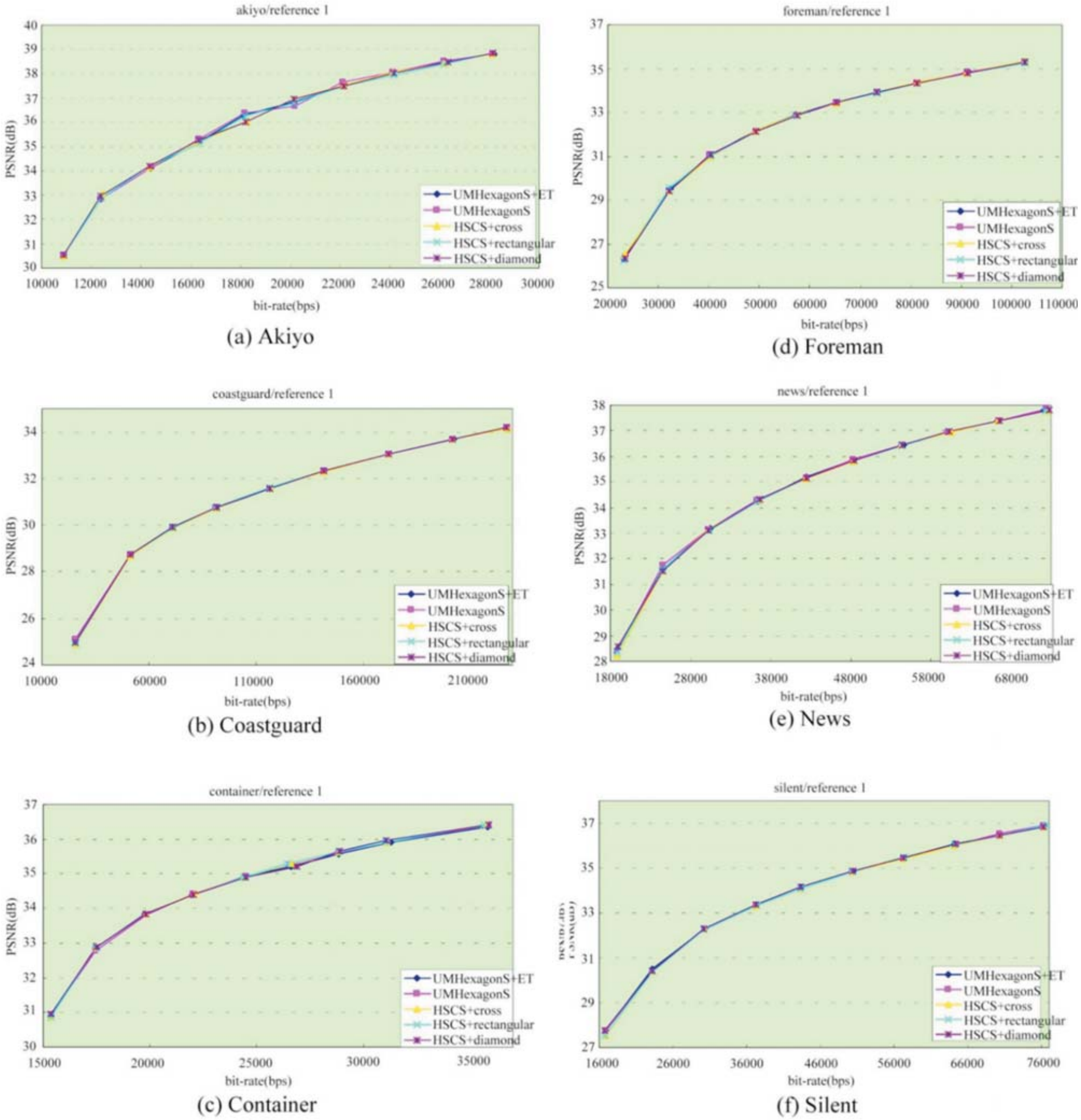

Figure 16. Rate distortion curve for 1 reference frame.

more effectively stop the search processes in all kinds of the video accurately, and the subjective video quality evaluations are almost the same.

5. Conclusion

H.264 is one of the most advanced video compression techniques. In H.264 standard, Motion Estimation takes most of the execution time. This paper tries to find some new algorithms to improve the Motion Estimation block coder. A description of the proposed algorithm and the analysis of the results have been illustrated in this paper. The accurate motion estimation method, HSCS, for successive motion pictures is presented in this paper. By finding more precision initial search center, the method can refine the motion vector of the cur-

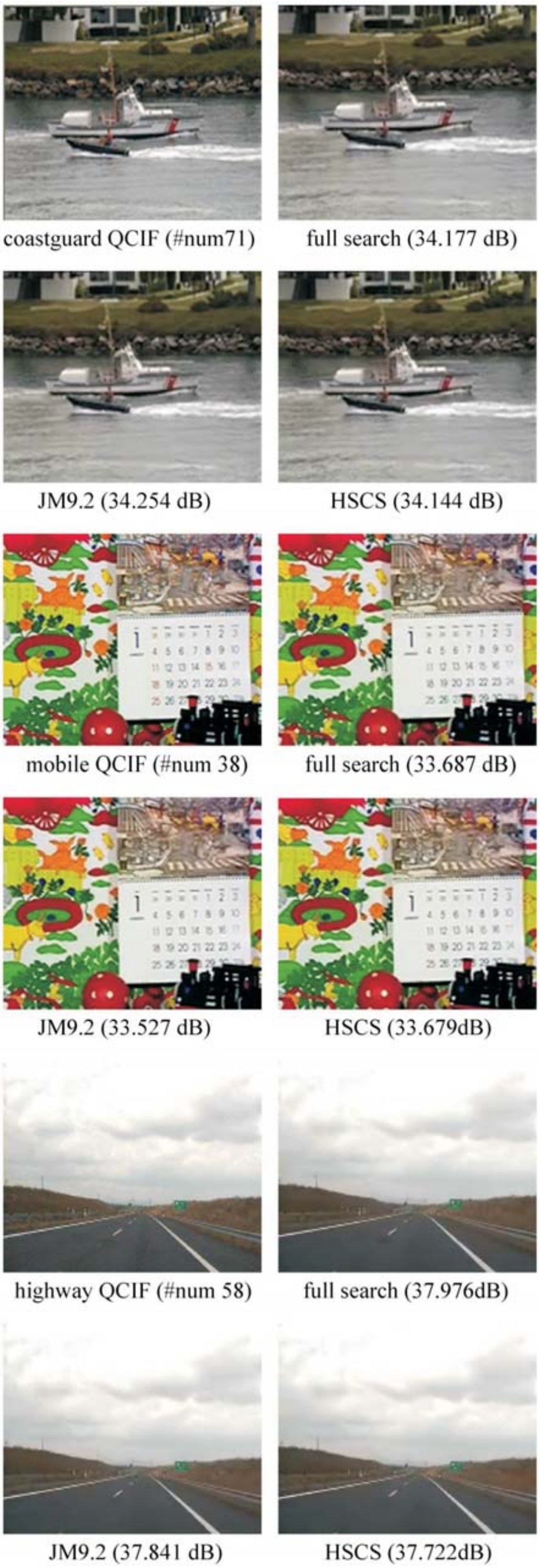

Figure 17. Subjective quality evaluation of coastguard, mobile and highway for three different algorithms.

Figure 18. Subjective quality evaluation of foreman (CIF) for three different algorithms.

rent blocks. Furthermore the coding performance can be improved efficiently, and the computation complexity of the integer pixel motion estimation of H.264 is also tremendously decreased. Experimental results indicate that the proposed method works better than other algorithms.

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