ETRI Journal, Volume 40, Number 2, April 2018
https://onlinelibrary.wiley.com/journal/22337326

Motion-Vector Refinement for Video Error Concealment Using Downhill Simplex Approach

Do-Hyun Kim, Young-Jin Kwon, and Kyoung-Ho Choi

In error-prone wireless environments, it is difficult to realize video coding systems that are robust to various types of data loss. In this paper, a novel motion-vector refinement approach is presented for video error concealment. A traditional boundary-matching approach is exploited to reduce blocky effects along the block boundary. More specifically, a downhill simplex approach is combined with a boundary-matching approach to fine-tune the motion vectors, reducing the blocky effects along the prediction unit block boundary, and minimizing the computational cost. Extensive simulations are performed, and the results obtained verify the robustness and effectiveness of the proposed approach.

Keywords: Block boundary errors, Downhill Simplex, Optimization, Video error concealment.

I. Introduction

High-efficiency video coding (HEVC) emerged as a new video coding standard in January 2013, targeting ultra high-definition TV (HDTV) and various multimedia services, and has doubled the coding efficiency compared with H.264/AVC [1]–[3]. In H.264/AVC, the size of a coding block ranges from 4 × 4 to 16 × 16. However, in HVEC, this range is extended to 4 × 4 to 64 × 64. In addition, the number of angular predictions in intra coding is increased from 9 in H.264/AVC to 33 in HEVC. In HEVC, a slice is a sequence of the largest coding units (LCUs), and it is usually defined as 64 × 64. The size of an LCU is 16 times greater than that of a macro block in H.264/AVC. As a result, the loss of a slice implies that a large region of an image is missing, which makes it difficult to use error-concealment techniques employed in previous standards, which are designed only for small lost blocks [4].

Owing to advances in multimedia streaming technologies, popular multimedia services are being deployed in vehicles for driver/passenger safety and entertainment purposes [5]. Furthermore, vehicles are becoming intelligent more rapidly than initially anticipated, and in-vehicle wireless technologies have become current issues in the automotive industry. The use of various wireless network technologies, such as ZigBee, UWB, and wireless LANs, has been considered to determine their potential as alternatives to exiting in-vehicle wired networks [6]–[8]. In wireless environments, including in-vehicle wireless networks, it is difficult to develop video coding and decoding systems that are robust to various types of data loss. A compressed bit stream is sensitive to transmission errors from predictive coding and variable-length coding techniques involved in the data-compression process. In addition, video data and communication

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Manuscript received Apr. 24, 2017; revised Sept. 25, 2017; accepted Dec. 8, 2017.

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https://doi.org/10.4218/etrij.2017-0078

pISSN: 1225-6463, eISSN: 2233-7326

channels are time varying, and thus it is difficult to determine the optimal coding parameters during the coding and decoding process. In noisy environments, bit errors and packet losses can occur. While bit errors can be fixed using error-correction mechanisms, an error-concealment process is required for packet losses [9].

The compression ratio of HEVC is 50% higher than that for H.264/AVC, meaning that the packet loss significantly affects the quality of the decoded bit stream. According to a recent study, if the packet loss rate is higher than 3% in an HEVC bit stream, viewers may be dissatisfied with the resulting image [10]. Thus, a robust error-concealment approach is essential to successfully deploy video streams for various multimedia services. Many approaches that focus on ways to estimate the motion vectors of lost blocks have been proposed for video-error concealment. Motion vectors of lost blocks can be estimated using methods that involve motion vectors of collocated blocks or surrounding blocks, the simplest of which is a motion-vector extrapolation approach that is based on the idea that the motion vector of a missing block is an extension of the motion vector of the previous frame [11]. In addition, a B-splice function is used to interpolate the motion vector of a lost block using neighboring blocks [12]. Motion-vector extrapolation with partition information has been proposed as an extension of [8], and is based on the idea that the motion vector of a missing coding unit (CU) is an extension of the motion vector of a collocated block in the previous frame, and the size of the collocated block is crucial to determine the motion vector of a lost block [13]. It was reported that the CU depths and prediction unit (PU) partitions of the blocks in a current frame are highly correlated with the collocated values in the previous frame [14]. Using the partition information of a collocated block, the misalignment along the same object is reduced, which is based on the idea that the same object is within the same partition. More weight is given to a block with a larger partition than one with a smaller partition. Furthermore, an optimization framework was proposed to find the best motion vector, minimizing a mismatch in the spatiotemporal boundary [15]. Recently, residual errors in CUs have been exploited in HEVC error concealment [4]. Residual errors are the difference in the PU values after the prediction, and are coded using an integer transform. For instance, residual errors are calculated after motion estimation. A large residual errors indicates that the motion estimation is insufficient to show the correct motion of the current PU. More specifically, blocks with large residual errors are merged, and new motion vectors are assigned. A new motion vector is obtained by calculating the average motion vector of the surrounding reliable blocks.

In this paper, a novel error-concealment technique for the HEVC standard is proposed for error-prone wireless environments, and the proposed technique is an extended version of our previous work [16]. With the proposed technique, a downhill simplex approach is exploited to simultaneously fine-tune the estimated motion vectors and minimize blocky effects along the block boundary. The contributions of the present paper can be summarized as follows. First, a novel error-concealment approach is presented for HEVC in wireless IP networks, and it considers the block types, block residual errors, and boundary-mismatch errors. Second, HEVC error concealment is formulated as an optimization problem in the proposed approach. Finally, a downhill simplex approach is presented to fine-tune the motion vectors and minimize the blocky effects along the block boundary. In other words, in the proposed optimization framework, the best motion vector is found to minimize the mismatching errors along the block boundary.

The remainder of this paper is organized as follows. In Section II, the proposed error-concealment approach is presented based on the block-boundary matching. A detailed description of the proposed downhill simplex approach for motion-vector refinement is then presented. In Section III, exhaustive simulation results are presented. Finally, Sections IV and V present a discussion and some concluding remarks, respectively.

II. Downhill Simplex Approach for Video Error Concealment

1. Error Detection in Decoder

In error-prone wireless IP networks, video packets can be lost owing to network traffic jams or other networking problems. When a packet loss occurs, a decoder can send a re-transmission request via a transmission control protocol (TCP). However, with live video-transmission services, the user datagram protocol (UDP) is used to satisfy the real-time requirements. In this case, lost packets cannot be resent, and error-concealment operations have to be applied on the decoder side. For HEVC, the error-concealment process on the decoder side can be started by the detection of the missing slice numbers.

In HEVC, a picture is divided into coding tree units (CTUs) and the size of the CTUs is 64 × 64, 32 × 32, 16 × 16, or 8 × 8, depending on the coding parameters. Each region is also called a CU. A sequence of CTUs is called a slice, and a picture can be divided into any number of slices. A simple error-detection process is as follows. An encoded bit stream is a sequence of network abstraction layer (NAL) units. The decoding process is started by the location of 0x00000001, which denotes the starting point of a NAL unit. Right after locating 0x00000001, the sequence parameter set (SPS), picture parameter set (PPS), and supplemental enhancement information (SEI) can be loaded by locating 0x000001. The picture data, which are the data immediately before the next 0x00000001, are then loaded after the loading of all parameters is achieved. Finally, the image, which consists of a single slice or several slices, is loaded. In the decoder, it is possible to monitor the number of starting and ending CTUs of a slice in the image, which means that the loss of the slice can be detected.

2. Procedure for New Motion Vector Search

By detecting a slice loss during the decoding process, the error-concealment process is started. The proposed error-concealment process is shown in Fig. 1. The entire process can be described as follows:

- As a slice loss is detected, block partition information from the previous frame is used based on an assumption that the CU partition and PU segmentation of the previous frame are highly correlated with the current frame.
- If a block is intra-coded, the motion vector of the missing block is set to zero, that is, $\mathbf{MV}_x = \mathbf{MV}_y = 0$. For an inter-coded block, the motion vector of the collocated block is used for the missing block. A temporarily concealed frame is then created.

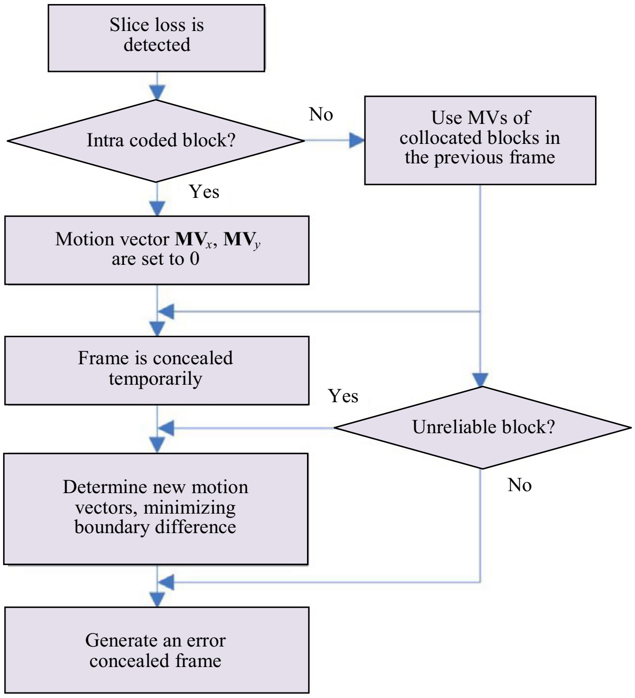

Fig. 1. Block diagram of the proposed error-concealment approach for HEVC.

- If a block is not intra-coded, the residual errors of the collocated block in the previous frame are calculated using (1):

$$E = \sum_{(i,j)\in b_{m,n}} |r_Y(i,j)|, \tag{1}$$

where $r_Y(i,j)$ is the residual value of the Y component in the previous frame. If the residual error E exceeds a given threshold, the block is considered unreliable. Refer to [4] for further details.

- With the proposed approach, if a block is unreliable or intra-coded, a new motion vector is assigned. Motion vectors of intra-coded and unreliable blocks are adjusted by calculating the difference in the boundary of the surrounding PU blocks.
- Motion vectors of intra-coded blocks, $\mathbf{MV}_x = \mathbf{MV}_y = 0$, and unreliable blocks are used as the initial motion vectors for the PU blocks to be concealed.
- A search region $\boldsymbol{S}$ is defined as shown in Fig. 2(b). All motion vectors within the search region are evaluated. For each motion vector, a newly concealed image is generated. The boundary difference between the concealed image and the surrounding blocks is then calculated.
- Among all motion vectors, a motion vector $\mathbf{MV}_{\text{min}}$ that results in the minimum boundary difference is chosen as a new motion vector. In Fig. 2(a), initial motion vector $\mathbf{MV}_{\text{init}}$ is a motion vector of a collocated block. The initial motion vector is used to conceal a lost PU block. Then, as can be seen in Figs. 2(b) and (c), a search region $\boldsymbol{S}$ is defined around the initial motion vector $\mathbf{MV}_{\text{init}}$, and a new motion vector is searched. A motion vector with the minimum boundary difference is found, and it is used to conceal the lost PU block, as shown in Figs. 2(d) and (e).
- To evaluate the motion vectors within a given search region effectively, an optimization framework is presented in the proposed approach.
- A cost function is defined using mismatch errors along the PU block boundary, and a downhill simplex optimization is applied to find a new motion vector by perturbing the initial motion vector. With this step, the motion vector is further refined to minimize the mismatch errors along the block boundary.

3. Downhill Simplex Approach for Motion-Vector Refinement

In Section II, a new motion-vector search procedure is described. In the proposed approach, a motion vector in a

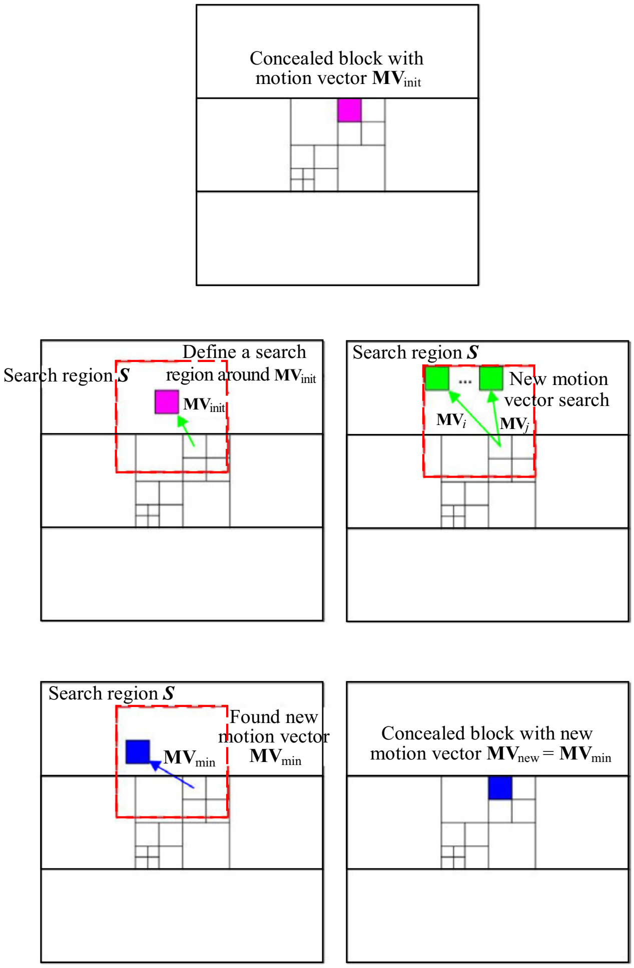

Fig. 2. Motion-vector search in a defined search region $\boldsymbol{S}$: (a) Initially concealed frame, (b) reference frame with a given search region, (c) motion vector search in the reference frame within a given search region, (d) found a new motion vector with minimum boundary difference, and (e) concealed frame with a new motion vector $\mathbf{MV}_{\text{new}}$.

collocated block is used as the initial motion vector. However, to find a motion vector with a minimum boundary difference, it is necessary to check all motion vectors in a given search region, as indicated in Fig. 2(c). With the proposed approach, an optimization framework based on a downhill simplex is presented to reduce the computational cost.

Downhill simplex is an optimization technique that is based on a simplex, and it does not require derivative operations during the optimization process [17], [18]. By choosing the initial simplex, that is, an object with $n + 1$ vertices (n = the number of variables), a downhill simplex algorithm is started, and the vertex with the highest function value is replaced with a new vertex. During the search procedure, reflection, expansion, contraction, and shrinkage operations are applied until a local minimum point is reached. After assigning the initial motion vector, the motion vector is fine tuned. Many applications, including computer vision and video processing, have been reported to solve the nonlinear optimization problems by using a downhill simplex technique [19], [20].

In the proposed approach, the downhill simplex approach is adopted to estimate the motion vector more accurately, minimizing errors in the block boundary. In the proposed approach, an optimization problem is formulated. To minimize the boundary mismatching, a cost function $f(\mathbf{MV}_{x\text{init}}, \mathbf{MV}_{y\text{init}}, \mathrm{d}x, \mathrm{d}y)$ is defined as

$$f(\mathbf{MV}_{x\text{init}}, \mathbf{MV}_{y\text{init}}, \mathrm{d}x, \mathrm{d}y) = \sum_{\text{forall} I_{\text{in}}, I_{\text{out}} \in B} |I_n(\mathbf{MV}_{x\text{init}} + \mathrm{d}x, \mathbf{MV}_{y\text{init}} + \mathrm{d}y) - I_{\text{out}}|, \tag{2}$$

where $\mathbf{MV}_{x\text{init}}$, $\mathbf{MV}_{y\text{init}}$, and I_{out} denote the initial motion vector in the x and y directions, and pixels outside of the block boundary, respectively. In addition, $I_{\text{in}}(\mathbf{MV}_{x\text{init}}, + \mathrm{d}x, \mathbf{MV}_{y\text{init}} + \mathrm{d}y)$ indicates pixels inside the block generated using the estimated motion vector, and B denotes a set containing all pixels along the block boundary. By determining values of dx and dy that minimize the cost function defined in (2), an optimal motion vector for the block can be determined.

III. Experiment Results

For the implementation, HM3.4 was used, and various HEVC sequences were tested. Packet loss rates of 12.5%, 18.75%, and 25% were tested. For the PSNR (dB) calculation, the same experiment was conducted for 50 frames, and the average PSNR was obtained. For the performance comparison, 1) pixel copies of collocated blocks, and 2) motion-compensated error concealment (MCEC), which uses a pixel replication for intra blocks and the same motion vector of the collocated blocks for the inter-coded blocks, were used. The performance of the proposed approach compared with other methods is shown in Table 1. The overall performance of the proposed approach is better than that of the other approaches, as shown in Table 1. As the packet-loss rate is increased, the PSNR of all of the methods is decreased. However, the proposed approach also showed a good performance under a high packet loss.

In addition, the performance of the downhill simplex approach was compared with the full search method. More specifically, the size of the search window for the full search method was changed from 5 to 125, and the corresponding PSNR was compared with the results of the downhill simplex approach. As shown in

Table 1. PSNR comparison of test sequences.

Sequence	Method	Packet loss rate (%)		
		12.5	18.7	25
Basketball-Drill	Pixel copy	26.7	25.3	24.1
	MCEC	37.0	35.5	33.5
	Proposed approach	37.8	36.4	33.7
Keiba	Pixel copy	22.2	19.3	17.7
	MCEC	33.6	31.4	28.4
	Proposed approach	34.2	31.2	28.7
Race-Horses	Pixel copy	22.2	19.0	17.6
	MCEC	33.8	31.8	29.7
	Proposed approach	34.0	32.1	30.0

Table 2, the PSNR of the downhill simplex approach was similar with the result of the full search method, while also reducing the computational complexity.

According to the simulation, the PSNR was increased as the size of the search window was increased, as shown in Table 2, where a 12.5% packet loss is assumed. For small search windows, for example, 5 × 5, the PSNR was not increased much because the motion of the block was outside of the search window. In addition, according to the simulations, the performance was not increased significantly as the search window size was higher than 65. Further, the size of the search window had to be increased carefully owing to the computational requirements. It was found that an optimal motion vector with the lowest boundary difference is close to the initial motion vector. For various threshold values of the block reliability measure, the performance of the proposed approach was compared with the full search method. As shown in Table 2, the performance of the proposed approach was good for various threshold values.

For a subjective evaluation of the proposed approach, concealed frames are shown in Figs. 3 and 4. In Fig. 3, concealed frame no. 4 is shown. In the simulation, it was assumed that whole slices were missing and that the whole frame was concealed using MCEC and the proposed approach. As indicated by the small boxes around the face and tail (in Figs. 3(b) and 3(c)), the concealed results that were obtained using the MCEC method were corrupted by blocky effects. However, the concealed frame shown in Fig. 3(c) was much smoother around the block boundary. The proposed approach appears to show a better visual quality around the block boundary.

Another example of concealed images using the proposed approach is shown in Fig. 4. The body line and leg of the horse, as indicated inside the small box, are better concealed in Fig. 4(c) than in Fig. 4(b). However, some parts around the saddle in Fig. 4(c) are poorly concealed when compared with the MCEC method. It can be explained that for a homogeneous PU block, the proposed approach showed a good performance.

However, for a non-homogeneous PU block, the performance may be lower when compared with the homogeneous PU block. Although the boundary of the PU block was similar, the inside of the PU block may be different from the error-free block. According to simulations, the proposed approach shows a slightly better performance than the MCEC method because the MCEC approach is based on the motion vectors of collocated blocks. However, when the motion vectors of collocated blocks are not reliable, it is likely that the recovered motion vector will also not be reliable. In the proposed

Table 2. Performances of various search windows and thresholds.

Sequences	Threshold for block reliability measure	PSNR					
		Downhill simplex	Search window size (Full search method)				
			5	25	45	65	125
Race-Horses	2,500	33.8	33.5	33.8	34.1	34.2	34.3
	2,800	34.0	33.5	33.8	34.1	34.2	34.3
	3,000	34.0	33.5	33.8	34.3	34.3	34.3
	3,400	34.4	33.2	33.5	33.8	33.9	33.9
	3,800	34.3	33.2	33.5	33.9	33.9	34.0
Basketball-Drill	2,500	37.7	37.3	38.0	38.5	38.7	39.0
	2,800	37.8	37.3	38.0	38.5	38.8	39.0
	3,000	37.8	37.3	38.0	38.5	38.8	39.0
	3,400	37.9	37.4	38.2	38.6	38.8	39.1
	3,800	38.0	37.4	38.2	38.7	38.9	39.2

Fig. 3. (a) Example of an error-free image of “Race-Horses” (frame no. 4), (b) error-concealed image generated using the MCEC method, and (c) error-concealed image generated using the proposed approach. The concealed regions shown in the small boxes in (c) are smoother than the concealed regions shown in (b).

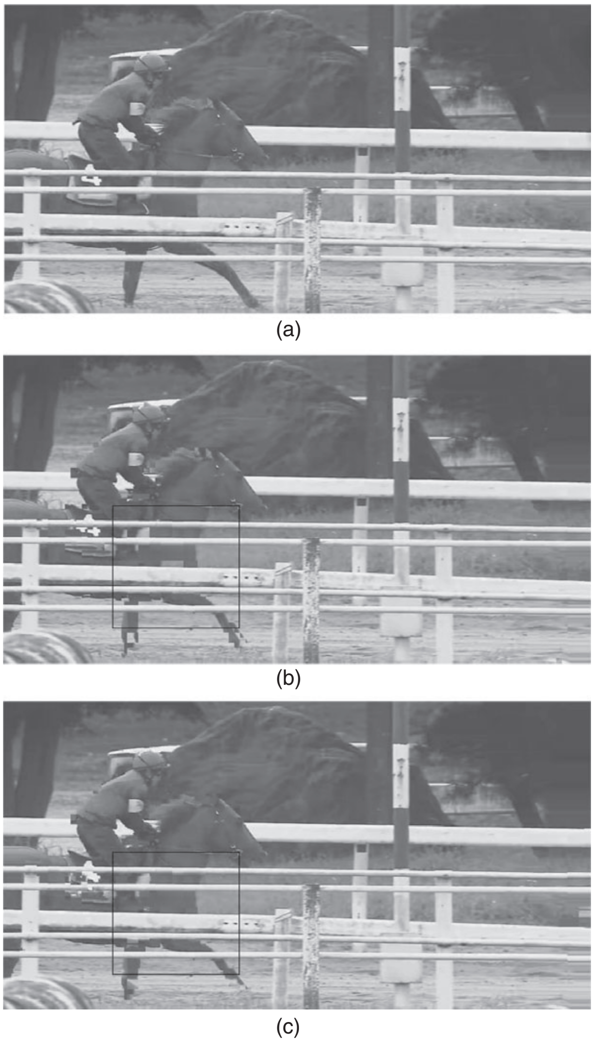

Fig. 4. (a) Example of an error-free image of “Keiba” (frame no. 20), (b) error-concealed image generated using the MCEC method, and (c) error-concealed image generated using the proposed approach.

approach, the motion-vector refinement is applied for the unreliable blocks to fine tune motion vectors, reducing errors along the block boundary with additional computational cost compared with the MCEC method. In Table 3, a computational analysis of the downhill simplex approach is shown compared with the full search method. The number of comparisons used to calculate the difference between the inside and outside of the PU block boundary in the downhill simplex approach is compared with that of the full search method. As shown in Table 3, if the size of the search window is 25, the number of boundary comparisons is 625, which means that the boundary comparison shows all motion vectors within a given search window. As the size of the search window is increased, the number of boundary comparisons is exponentially increased. On the contrary, the number of average iterations for the downhill simplex is 20 for each PU block. In addition, in our implementation, the average number of boundary comparisons for each iteration with the proposed approach is 5, requiring an average of 100 boundary comparisons, as shown in Table 3.

For instance, the comparison ratio of the downhill simplex compared with that for a full search is only 16% for a search window size of 25. The advantage of the downhill simplex approach is the reduction of the computational complexity. The search procedure for locating a motion vector with the minimum boundary difference in the proposed downhill simplex approach is shown in Fig. 5.

Each pixel in Fig. 5 indicates the value of the cost function described in (2). Each pixel value is the sum of the boundary differences along a concealed PU block, which is scaled to 255 for the display. In our simulation, an initial simplex is

Table 3. Computational analysis for full search vs. downhill simplex.

Full search (A)		Downhill simplex (B)		Comparison ratio % (= B/A)
Size of search window	Number of boundary comparison	Average iteration	Number of boundary comparison	
25	625	20	100	16.0
45	2,025			4.94
65	4,225			2.37

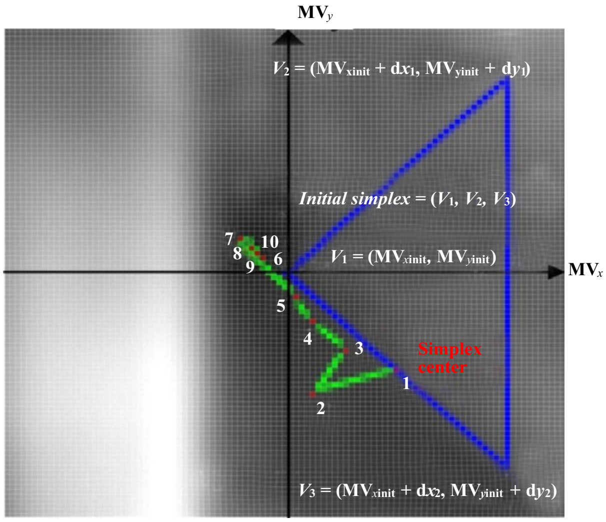

Fig. 5. Graphical view of the proposed downhill simplex search using (2), which shows the initial simplex denoted as (V_1, V_2, V_3), which represent the three corners of the triangle, and simplex centers are indicated by red dots for all iterations.

defined as V_1 = ($\mathbf{MV}_{x\text{init}}$, $\mathbf{MV}_{y\text{init}}$), V_2 = ($\mathbf{MV}_{x\text{init}}$ + dx_1, $\mathbf{MV}_{y\text{init}}$ − dy_1), and V_3 = ($\mathbf{MV}_{x\text{init}}$ +dx_2, $\mathbf{MV}_{y\text{init}}$ + dy_2), where $\mathrm{d}x_1 = \mathrm{d}y_1 = \mathrm{d}x_2 = \mathrm{d}y_2 = 40$. Simplex centers, which are marked as red dots, indicate the center points of each simplex without a vertex with the highest cost value. It can be seen that for all iterations, the center of the simplex moves to the global minimum, which is denoted as 10.

IV. Discussions

For video-error concealment, spatial, temporal, and spatiotemporal techniques have been used in previous studies. The basic idea of these techniques is that blocks close to each other are positively correlated either spatially or temporally. In spatial error-concealment approaches, information on the neighboring blocks is used for the block recovery. Blurring is likely to occur as the block size is increased up to 64 × 64 in HEVC. For temporal-error concealment, scene continuity is assumed, and the motion information of the collocated or neighboring blocks is used. However, blocky effects also occurred along the block boundary. In this paper, a traditional boundary-matching approach is again considered to reduce the blocky effects along the block boundary. However, it is time consuming to calculate the difference along the block boundary. Thus, a downhill simplex approach was adopted to reduce the computational complexity of the proposed approach. We believe that the proposed downhill simplex can be combined with other error-concealment algorithms, and can be used to reduce the blocky effects along the block boundary.

To determine a motion vector for a lost block with the best boundary matching, a full search or a three-step search method [21] may be used within a given search window. A proper search window has to be chosen, and a large search window is necessary in HEVC owing to its larger block size compared with the previous standards. Thus, the downhill simplex approach was applied to the proposed approach to identify a motion vector with the minimum computational cost. For the downhill simplex approach, an initial simplex has to be chosen. In addition, a poorly chosen initial simplex can make the algorithm stuck at the local minimum, which is a weak point of the downhill simplex approach.

With the proposed approach, a block-reliability measure was used to determine the reliability of the collocated blocks. Depending on the threshold value, blocks are classified as either reliable or unreliable. If the threshold value is low, many blocks are considered as unreliable and used for motion-vector refinements. Depending on the applications, and whether or not the scenes are dynamic, the threshold value should be chosen carefully.

V. Conclusions

This paper proposed a novel video error-concealment approach that combines the block reliability with the boundary-difference minimization along the block boundary. More specifically, a downhill simplex approach was adopted to minimize the computational complexity of the boundary matching and fine-tune the motion vectors. Intra-coded blocks or unreliable blocks were chosen for motion-vector refinements. The initial motion vectors for intra-coded blocks were considered as zeros, and the motion vectors of the collocated blocks were used for the initial motion vectors of unreliable blocks. According to the simulation results, the proposed approach shows good performance based on both subjective and quantitative evaluations. However, the best boundary matching does not always guarantee the best motion vector of a lost block. The proposed downhill simplex approach may be combined with other error-concealment approaches to reduce mismatches along the block boundary. For future research, the selection of the initial simplex can be investigated to avoid detecting a local minimum.

Acknowledgements

This work was supported by an Electronics and Telecommunications Research Institute (ETRI) grant funded by the Korean government (17ZS1600, Development of advanced digital cockpit system for smart car).

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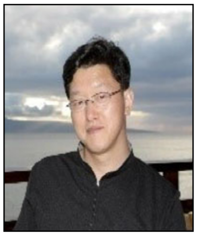

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https://doi.org/10.4218/etrij.2017-0078