PAPER

Error Concealment Based on Motion Vector Recovery Using Optical Flow Fields

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SUMMARY Compressed video bitstreams are very sensitive to transmission errors. If we lose packets or receive them with errors during transmission, not only the current frame will be corrupted, but also errors will propagate to succeeding frames. Therefore, we need various mechanisms to protect data and reduce the effects of transmission errors. Error concealment is a data recovery technique that enables the decoder to conceal the effects of transmission errors by predicting the lost or corrupted video data from the previously reconstructed error free information. Motion vector recovery and motion compensation with the estimated motion vector is a good approach to conceal the corrupted macroblock data. In this paper, we show that it is reasonable to use the estimated motion vector to conceal the lost macroblock by providing macroblock distortion models. After we propose a new motion vector recovery algorithm based on optical flow fields, we compare its performance to those of conventional error concealment methods.

key words: *MPEG-2 video compression, error concealment, motion vector estimation, optical flow*

1. Introduction

In recent years, video compression standards have been generated to transmit an enormous amount of digitized video data efficiently over a band-limited channel. In particular, the MPEG-2 video coding standard [1] successfully achieves high compression ratios using a hybrid algorithm of motion compensation (MC) and discrete cosine transform (DCT). The MPEG-2 video compression algorithm employs the prediction structure to reduce the temporal and spatial redundancies. In addition, it uses the variable length code (VLC) to reduce statistical redundancy. Therefore, the coded video bitstreams are compact but highly sensitive to information loss and channel errors.

Transmission of compressed video data consists of several steps to transport the compressed video data from the transmitter to the receiver. First of all, digitized video data are compressed by a specific video coding standard adopted for a given application. The compressed bitstream is segmented into fixed or variable length packets for easy transmission and multiplexed with other data types, such as audio and data. The multiplexed packets are then sent over the transmission channel after channel encoding using forward error correction (FEC). The received transmission packets, which may include transmission errors, undergo channel decoding and demultiplexing to get depacketized bitstreams. Finally, the resulting bitstreams are entered to the video decoder to reconstruct the original video data.

In order to obtain reconstructed pictures of acceptable visual quality, we need appropriate data protection and error reduction methods. Since the channel coding and decoding cannot completely eliminate transmission errors, we need error resilience coding techniques to protect compressed video data against error prone environments. Several error resilient coding methods have been proposed to deal with this problem [3]. Error concealment is a data recovery technique using spatial and temporal redundancies existing in the video sequence. It is decoder-based and requires no changes on the bitstream syntax and transport technology.

Error concealment can be categorized into two classes: spatial-domain error concealment and temporal-domain error concealment. The spatial-domain error concealment algorithms interpolate the lost area using spatially neighboring image data [4]–[7]. These approaches assume the existence of statistical correlation between neighboring image blocks. Therefore, if the corrupted block and its surrounding neighbors belong to homogeneous regions, they reproduce a good approximation for the lost macroblocks (MBs). Also, some people consider error concealment techniques based on DCT coefficients recovery [8], [9]. On the other hand, the temporal-domain error concealment schemes utilize previously decoded image data to recover the lost MBs [10]–[13]. They estimate motion vectors (MVs) of the lost MBs to compensate for the lost MBs.

In this paper, we address the problem of error concealment in packet-based transmission of MPEG-2 coded video bitstreams over a noisy channel. In order to show the importance of using estimated MV for the lost MB, we analyze MB distortion including quantization, error propagation, and error concealment noises. Based on the proposed MB distortion models, we show that motion compensation with the estimated MV is reasonable for temporal-domain error concealment. After reviewing the conventional MV recovery algorithms, we

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propose a new motion vector recovery algorithm using optical flow fields.

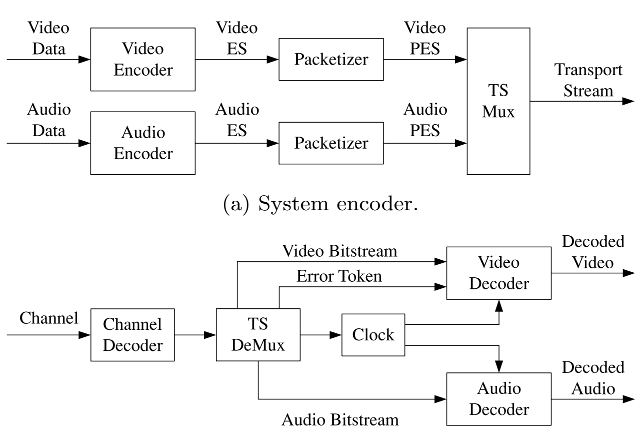
The organization of this paper is as follows. In Sect. 2, we summarize the MPEG-2 video coding and transmission system for evaluation of the error concealment algorithms. We then introduce the error detection algorithm used in our system. Section 3 shows the importance of the estimated MV in concealing the lost MB. In Sect. 4, we review the demerits and merits of the conventional MV recovery algorithms. In Sect. 5, we introduce optical flow fields and propose a new MV recovery algorithm using optical flow fields. Section 6 presents simulation results and performance comparisons of different error concealment algorithms. Finally, conclusions are drawn in Sect. 7.

2. System Configuration

Due to imperfect communication channels, it is nearly impossible to design a completely error free transmission system. As shown in Fig. 1, the MPEG-2 system standard [2] describes a general approach which defines a transport stream (TS) packet transmission system considering noisy channels. Like a TS packet, packetization is the most common way to localize errors in the bitstream. The elementary stream (ES) is the output of each source encoder. Each ES is packetized into packetized ES (PES) before transmission. After multiplexing, TS packets are transmitted over the communication channel. The TS packet consists of 188 bytes, including 4-byte header information. The TS packet header contains a 1 bit transport-error-indicator field, which indicates whether or not the received TS packet has uncorrectable bit errors. If TS DeMux detects transmission errors, it sends an error token to the video decoder.

As shown in Fig. 2, the MPEG-2 video coding algorithm adopts DCT, motion estimation and motion compensation (ME and MC), and VLC to reduce spatial, temporal, and statistical redundancies, respectively. If a variable length codeword is corrupted during transmission, the decoder will fail to determine the original length of the codeword and may lose synchronization. When the decoder loses synchronization, it searches forthcoming bits for an error-free synchronization codeword and then restarts the decoding process. If the video decoder receives a damaged packetized bitstream with an error token, the damaged packet is thrown out and treated as a lost packet because there is no way to be certain how many bits within the damaged packet are healthy. The MPEG-2 places synchronization codewords at the beginning of a sequence, a group of pictures (GOP), a frame, and a MB slice. Because the MB slice is the smallest unit of re-synchronization, we lose horizontal MB strips from the first erroneous MB to the beginning of the next MB slice.

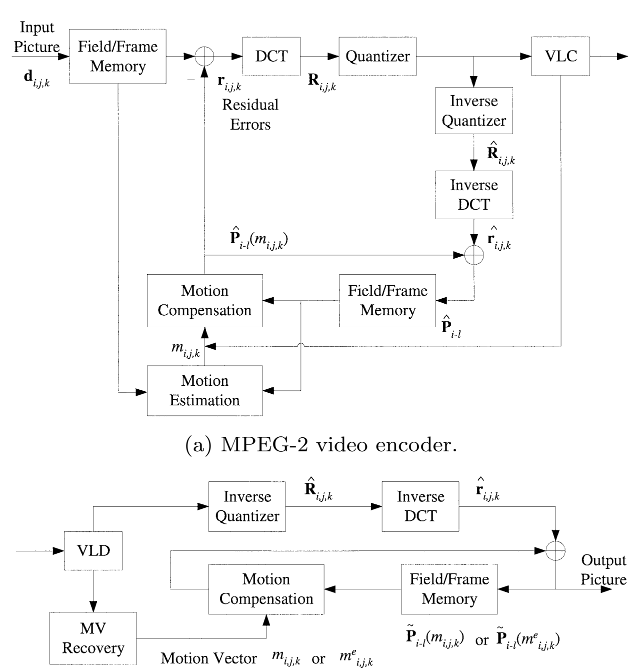
Error concealment is largely dependent upon the ability of the system to detect errors, since error concealment operations are applied to the corrupted MBs. As stated above, because the damaged packetized bitstream is thrown out and treated as lost, we can obtain the MB position where an error occurs by checking the MB address (MBA), which defines the absolute position of the MB. In our system, whenever we decode correctly received bitstreams, we store the last decoded MBA. If we receive an error token from TS DeMux, the address (recorded as MBA + 1) is the initial position of erroneous MBs.



(a) System encoder.

(b) System decoder.

Fig. 1 MPEG-2 TS system for noisy channel.



(a) MPEG-2 video encoder.

(b) Modified MPEG-2 video decoder.

Fig. 2 Modified MPEG-2 video codec.

3. Importance of MV Recovery of the Lost MB

It is desirable to analyze the end-to-end MB distortion to determine the important parameters for error concealment at the video decoder. To show the importance of using estimated MV of the lost MB for temporal-domain error concealment, we derive simple form of MB distortion according to MB coding mode.

The MPEG-2 video codec is shown in Fig. 2, where $\{i,j,k\}$ indicates the k-th MB in the j-th slice of the i-th frame and bold characters are 2-D MB data. As well, $\mathbf{r}_{i,j,k}$ denotes residual errors, $\mathbf{R}_{i,j,k}$ is the DCT transformed data of the residual errors, $\hat{\mathbf{R}}_{i,j,k}$ is the quantized data of $\mathbf{R}_{i,j,k}$, $m_{i,j,k}$ represents an MV, and $\hat{\mathbf{P}}$ and $\tilde{\mathbf{P}}$ indicate reference frames that are stored in frame memory for motion estimation (ME) and MC at the encoder and the decoder, respectively, where i is the coding order. $\hat{\mathbf{P}}$ and $\tilde{\mathbf{P}}$ are different because some parts of the reference frame might be concealed at the decoder.

Let $S_{i,j}$ be the event that the j-th slice of the i-th frame is corrupted. Then, we can define the slice error probability by

$$\begin{aligned} Pr(S_{i,j}) &= \sum_{n=1}^{T_{i,j}} {}_{T_{i,j}}C_n P_b^n (1-P_b)^{T_{i,j}-n} \\ &= 1-(1-P_b)^{T_{i,j}} \qquad (1) \\ & i=1,2,\cdots,N, \text{ and } j=1,2,\cdots,J \end{aligned}$$

where P_b is bit error probability, $T_{i,j}$ is the total number of bits of the j-th slice of the i-th frame, J is the number of the MB slices of the frame, and N is the total number of frames.

The distortion $\mathbf{e}^I_{i,j,k}$ for the intra-coded MB can be represented by

$$\begin{aligned} \mathbf{e}^I_{i,j,k} &= E\big[(\mathbf{d}_{i,j,k}-\hat{\mathbf{d}}_{i,j,k})^2\big](1-Pr(S_{i,j})) \\ &\quad + E\big[(\mathbf{d}_{i,j,k}-\tilde{\mathbf{d}}_{i,j,k})^2\big]Pr(S_{i,j}) \qquad (2) \end{aligned}$$

In Eq. (2), if we receive corrupted MB data, concealed data, $\tilde{\mathbf{d}}_{i,j,k}$, replaces quantized MB data, $\hat{\mathbf{d}}_{i,j,k}$, according to error concealment. If we assume that the quantization and concealment noises are uncorrelated, the second term in Eq. (2) can be decomposed into

$$\begin{aligned} E\big[(\mathbf{d}_{i,j,k}-\tilde{\mathbf{d}}_{i,j,k})^2\big] &= E\big[(\mathbf{d}_{i,j,k}-\hat{\mathbf{d}}_{i,j,k})^2\big] \\ &\quad + E\big[(\hat{\mathbf{d}}_{i,j,k}-\tilde{\mathbf{d}}_{i,j,k})^2\big] \qquad (3) \end{aligned}$$

With Eq. (3), we can rewrite Eq. (2) as

$$\begin{aligned} \mathbf{e}^I_{i,j,k} &= E\big[(\mathbf{d}_{i,j,k}-\hat{\mathbf{d}}_{i,j,k})^2\big] \\ &\quad + E\big[(\hat{\mathbf{d}}_{i,j,k}-\tilde{\mathbf{d}}_{i,j,k})^2\big]Pr(S_{i,j}) \qquad (4) \end{aligned}$$

In order to obtain small distortion $\mathbf{e}^I_{i,j,k}$ in the I-frame, $\tilde{\mathbf{d}}_{i,j,k}$ is recovered by spatial interpolation methods because the I-frame is coded without the MV information. In the case of the P-frame and B-frame, we estimate the MV for the lost MB and compensate for the lost MB with this estimated MV to reduce intra-coded MB distortion.

The distortion $\mathbf{e}^P_{i,j,k}$ for the inter-coded MB can be expressed as

$$\begin{aligned} \mathbf{e}^P_{i,j,k} &= E\big[\{(\mathbf{r}_{i,j,k}+\hat{\mathbf{P}}_{i-l}(m_{i,j,k})) \\ &\quad - \tilde{\mathbf{P}}_{i-l}(m^e_{i,j,k})\}^2\big]Pr(S_{i,j}) \\ &\quad + E\big[\{(\mathbf{r}_{i,j,k}+\hat{\mathbf{P}}_{i-l}(m_{i,j,k})) \\ &\quad - (\hat{\mathbf{r}}_{i,j,k}+\tilde{\mathbf{P}}_{i-l}(m_{i,j,k}))\}^2\big](1-Pr(S_{i,j})) \end{aligned} \qquad (5)$$

where i is the current frame number. If we receive corrupted MB data, we estimate the MV for the lost MB using previous reference frames and compensate with the estimated MV to reconstruct the lost MB, as shown in the first term of Eq. (5). In order to estimate MV of the lost MB in the P-frame, l is 1 or M where M is the number of frames between the I-frame and the P-frame or successive P-frames. For the B-frame, l is a value between 1 and $M-1$. This means that we use the closest reference frame from the corrupted frame to estimate MV of the lost MB.

In order to separate meaningful terms, if we assume that the concealment noise and the quantization noise of the residual errors are uncorrelated, the first term of Eq. (5) can be rearranged as

$$\begin{aligned} &\big(E\big[\{\hat{\mathbf{r}}_{i,j,k}+\hat{\mathbf{P}}_{i-l}(m_{i,j,k})-\tilde{\mathbf{P}}_{i-l}(m^e_{i,j,k})\}^2\big] \\ &\quad + E\big[(\mathbf{r}_{i,j,k}-\hat{\mathbf{r}}_{i,j,k})^2\big]\big)Pr(S_{i,j}) \qquad (6) \end{aligned}$$

If we use another assumption that the mismatch noise between the reference frame of the encoder and the reference frame of the decoder and the quantization noise of the residual errors are uncorrelated, the second term of Eq. (5) can be represented as

$$\begin{aligned} &\big(E\big[\{\hat{\mathbf{P}}_{i-l}(m_{i,j,k})-\tilde{\mathbf{P}}_{i-l}(m_{i,j,k})\}^2\big] \\ &\quad + E\big[(\mathbf{r}_{i,j,k}-\hat{\mathbf{r}}_{i,j,k})^2\big]\big)(1-Pr(S_{i,j})) \qquad (7) \end{aligned}$$

Using Eq. (6) and Eq. (7), we can rewrite Eq. (5) as

$$\begin{aligned} \mathbf{e}^P_{i,j,k} &= E\big[(\mathbf{r}_{i,j,k}-\hat{\mathbf{r}}_{i,j,k})^2\big] \\ &\quad + E\big[\{\hat{\mathbf{P}}_{i-l}(m_{i,j,k})-\tilde{\mathbf{P}}_{i-l}(m_{i,j,k})\}^2\big] \\ &\quad \cdot (1-Pr(S_{i,j})) + E\big[\{\hat{\mathbf{r}}_{i,j,k}+\hat{\mathbf{P}}_{i-l}(m_{i,j,k}) \\ &\quad - \tilde{\mathbf{P}}_{i-l}(m^e_{i,j,k})\}^2\big]Pr(S_{i,j}) \qquad (8) \end{aligned}$$

Inter-coded MB distortion includes quantization noise, mismatch noise between reference frames, and error concealment noise. It is difficult to manipulate the first term to improve the performance of error concealment since it is quantization noise of the residual errors. If there is no mismatch noise in the reference frames, we can remove the second term. As shown in this series of equations, if we can estimate an accurate MV for the lost MB, we can reduce the distortion, $\mathbf{e}^P_{i,j,k}$.

4. Conventional MV Recovery Algorithms

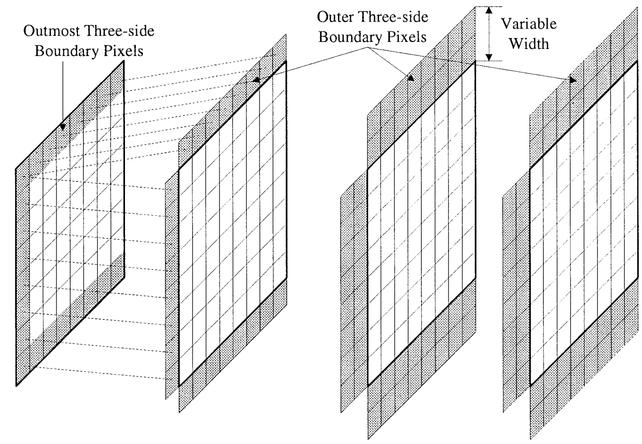
One of the difficult problems in error concealment techniques is limitation of available information. In order to conceal the lost MB, we can only use the upper and lower MBs, with respect to the lost MB, considering the high correlation of neighboring MBs. In addition, if the corrupted area is wider than a single MB row, the problem becomes more difficult.

The simplest method is to replace the erroneous MBs by the spatially coinciding MBs in the previous frame. This means that the lost MV is considered as zero with an assumption that no motion has occurred between the previous reference frame and the current frame. The use of zero MV produces a reasonably good approximation in small and slow motion areas. However, we cannot expect good results in large and fast motion areas. Therefore, we need different approaches to conceal the corrupted areas more effectively. Estimating MVs for the lost MBs and compensating them with the estimated MVs is one way to improve performance of error concealment operations.

In order to estimate MV for the lost MB, we can exploit vertically neighboring MVs of the lost MB. MV of the lost MB can be obtained by taking the average value (AVG) of MVs of the vertically adjacent MBs [10]. In this scheme, if vertically adjacent MBs have corresponding MVs, we can obtain good reconstruction quality of the lost MB. However, if only one or none of the vertical neighbors has a valid MV, quality of the reconstructed image is not satisfactory. Therefore, the coding mode of MBs adjacent to the lost MB is very important when taking the average value. In other words, if an adjacent intra-coded MB of the lost MB has MV, we can obtain good performances. In order to overcome this problem, a modified average algorithm has been proposed [11].

The boundary matching algorithm (BMA) [12] exploits the fact that adjacent pixels in the image have high spatial correlations. Within the default search range (SR), BMA calculates the squared sum of differences (SSD) between the outer one pixel boundary line of the top, left, and below sides of the lost MB in the current frame and the outmost boundary pixels of the target block in the previous reference frame, as shown in Fig. 3(a). BMA chooses MV of the lost MB among a set of candidate MVs which produces the smallest SSD, and replaces the lost MB with the target block data that has the smallest total SSD. However, this technique has some limitations. Using only one pixel boundary line on the three sides to find the target block data is not sufficient in some cases. Furthermore, the left boundary pixels are not available to recover MVs when successive MBs have been lost.

The decoder motion vector estimation algorithm (DMVE) [13] aims to accurately estimate MVs for the lost MBs using a variable extension width. This means that DMVE uses several outer pixel boundary lines (one to eight) of the lost MB in the current frame and the previous reference frame to calculate SSD, as shown in Fig. 3(b). In this algorithm, the variable extension width is an important parameter in the ME process. If the extension width is increased, the computation time will be increased. Therefore, this algorithm entails a considerable amount of processing complexity compared to BMA. In addition, the MV estimation process already includes an error concealment mismatch since the left boundary pixels are used for SSD calculation.



(a) BMA. (b) DMVE.

Fig. 3 Boundary matching algorithm.

BMA and DMVE demonstrate improved performance compared to that of AVG. However, if the corrupted areas are wider than a single MB row, neither works well. This means that we cannot use both the top and below boundary pixels in the ME process because successive slice errors have occurred. In order to resolve this problem, we propose a new MV recovery algorithm using optical flow fields.

5. A Proposed Error Concealment Algorithm

Optical flow is the distribution of apparent velocities of movement for bright patterns in the image. Optical flow is very similar to the true motion because it arises from relative motion of the objects and the viewer. In order to obtain the optical flow fields, we use a simple algorithm proposed by Horn and Schunch [14], [15].

5.1 Optical Flow Constraint

We will derive an equation that relates the change in image brightness at a point to the motion of the brightness pattern [14]. Let $E(x, y, t)$ be the intensity at time t at the image point (x, y). Then, if $u(x, y)$ and $v(x, y)$ are the x and y components of the optical flow fields at that point, we expect that the intensity will be the same at time $t+\delta t$ at the point $(x+\delta x, y+\delta y)$, where $\delta x = u\delta t$ and $\delta y = v\delta t$. That is,

$$E(x,y,t) = E(x+\delta x, y+\delta y, t+\delta t) \tag{9}$$

for a small time interval δt.

If brightness varies smoothly with x, y, and t, Eq. (9) can be rearranged to get Eq. (10) using the Taylor series and chain rule for differentiation.

$$\begin{aligned} &E_x u + E_y v + E_t = 0 \\ &E_x = \frac{\partial E}{\partial x},\ \ E_y = \frac{\partial E}{\partial y},\ \ E_t = \frac{\partial E}{\partial t} \end{aligned} \tag{10}$$

E_x, E_y, and E_t are the partial derivatives of image brightness with respect to x, y and t, respectively. The above equation is called the optical flow constraint. This single constraint is not sufficient to determine both u and v.

The optical flow fields at each point in the image cannot be computed independently of neighboring points without introducing additional constraints. Horn and Schunck [15] suggested a smoothness constraint which minimizes the magnitude squares of the of optical flow velocity's gradient

$$\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2 \text{ and } \left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 \tag{11}$$

In order to determine the optical flow fields, we need to solve the double integral composed of both the optical flow and smoothness constraints.

$$\begin{aligned} \epsilon = \iint &\big[(E_x u + E_y v + E_t)^2 \\ &+ \alpha^2(u_x^2 + u_y^2 + v_x^2 + v_y^2)\big] dxdy \end{aligned} \tag{12}$$

The minimization is accomplished by finding suitable values for the optical flow velocity (u, v). Using a calculus of variation method and an approximation of Laplacian, we can have

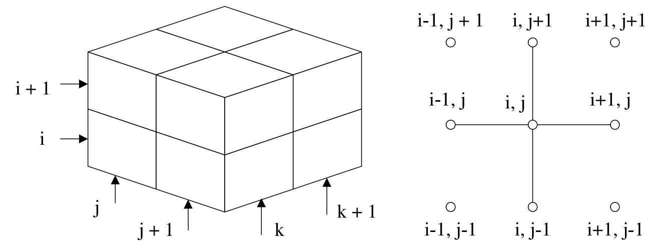
$$\begin{aligned} (\alpha^2 + E_x^2 + E_y^2)(u - \bar{u}) &= -E_x(E_x\bar{u} + E_y\bar{u} + E_t) \\ (\alpha^2 + E_x^2 + E_y^2)(v - \bar{v}) &= -E_y(E_x\bar{v} + E_y\bar{v} + E_t) \end{aligned} \tag{13}$$

The term α^2 plays a significant role only for areas where the brightness gradient is small, preventing haphazard adjustments to the estimated optical flow velocity occasioned by noise in the estimated derivatives.

5.2 Proposed Motion Vector Recovery Algorithm

Optical flow fields can be computed by a new set of velocity estimates (u^{n+1}, v^{n+1}) from the estimated derivatives and the average of the previous velocity estimates (u^n, v^n) as Eq. (14).

$$\begin{aligned} u^{n+1} &= \bar{u}^n - E_x(E_x\bar{u}^n + E_y\bar{v}^n + E_t)/(\alpha^2 + E_x^2 + E_y^2) \\ v^{n+1} &= \bar{v}^n - E_y(E_x\bar{u}^n + E_y\bar{v}^n + E_t)/(\alpha^2 + E_x^2 + E_y^2) \end{aligned} \tag{14}$$



(a) Partial derivatives. (b) Local averages.

Fig. 4 Relationship of time and space.

where n is the iteration number, and $\bar{u}$ and $\bar{v}$ are the local average values of the velocity.

The relationship of space and time to obtain partial derivatives and local averages of temporary optical flow velocities is shown in Fig. 4. We can estimate the derivatives of the brightness from the discrete set of image intensities. Each of the estimates is the average of four differences taken over adjacent measurements in the cube, as shown in Eq. (15).

$$\begin{aligned} E_x \approx \frac{1}{4}\{&E_{i,j+1,k} - E_{i,j,k} + E_{i+1,j+1,k} - E_{i+1,j,k} \\ &+ E_{i,j+1,k+1} - E_{i,j,k+1} + E_{i+1,j+1,k+1} - E_{i+1,j,k+1}\} \\ E_y \approx \frac{1}{4}\{&E_{i+1,j,k} - E_{i,j,k} + E_{i+1,j+1,k} - E_{i,j+1,k} \\ &+ E_{i+1,j,k+1} - E_{i,j,k+1} + E_{i+1,j+1,k+1} - E_{i,j+1,k+1}\} \\ E_t \approx \frac{1}{4}\{&E_{i,j,k+1} - E_{i,j,k} + E_{i+1,j,k+1} - E_{i+1,j,k} \\ &+ E_{i,j+1,k+1} - E_{i,j+1,k} + E_{i+1,j+1,k+1} - E_{i+1,j+1,k}\} \end{aligned} \tag{15}$$

The local average values $\bar{u}$ and $\bar{v}$ are defined as follows

$$\begin{aligned} \bar{u}_{i,j,k} = &\frac{1}{6}\{u_{i-1,j,k} + u_{i,j+1,k} + u_{i+1,j,k} + u_{i,j-1,k}\} \\ &+ \frac{1}{12}\{u_{i-1,j-1,k} + u_{i-1,j+1,k} + u_{i+1,j-1,k} + u_{i+1,j+1,k}\} \\ \bar{v}_{i,j,k} = &\frac{1}{6}\{v_{i-1,j,k} + v_{i,j+1,k} + v_{i+1,j,k} + v_{i,j-1,k}\} \\ &+ \frac{1}{12}\{v_{i-1,j-1,k} + v_{i-1,j+1,k} + v_{i+1,j-1,k} + v_{i+1,j+1,k}\} \end{aligned} \tag{16}$$

In order to recover MV of the lost MB, we can use the optical flow fields of correctly decoded neighboring MB data. As shown in Fig. 5, we obtain optical flow fields of the optical flow region (OFR) with Eq. (14). As shown in Fig. 4, the calculation of the optical flow fields is based on only two frames: the current frame and the previous reference frame. Then, we take an average of the optical flow fields within the MV estimate block (MVEB) that comes in touch with the lost MB. The average value is used as MV of the lost MB. In this algorithm, although two successive MB slice data may be lost, we can obtain relatively well estimated MVs for the lost MBs. MVs of the first MB row of the corrupted

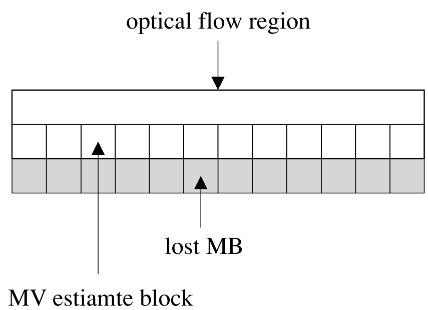


Fig. 5 MV recovery based on optical flow fields.

Table 1 PSNR values of the MV recovery algorithms.

	FOOTBALL	BICYCLE	BALLET	FLOWER GARDEN	TRAIN
Original	32.59	26.57	29.12	26.36	24.88
AVG	30.62	24.55	28.41	24.90	22.95
BMA	31.25	23.37	28.53	25.11	23.39
	31.17	23.14	28.50	25.00	23.36
DMVE	31.23	23.30	28.52	25.12	23.38
	31.15	23.11	28.31	24.93	23.00
OFA	31.75	25.21	28.87	25.36	23.14

Table 2 Comparison of computational complexity.

	(−) operation	(+) operation	(×) operation
BMA	50×50×16×3 = 120000	50×50×15×3 = 112500	50×50×16×3 = 120000
OFA	32×16×3×4 +32×2 = 6208	32×16×3 +32×16×4 +32×6×2 = 3968	32×16×3×3 +32×16×3×12 +32×4×2 = 23296

areas can be estimated using OFR at the top region of the lost MBs and the second row can be obtained with the bottom region of the lost MBs.

6. Simulation Results

In order to evaluate the performance of the error concealment algorithms, five different 4:2:0 CCIR 601 test sequences have been used: FOOTBALL, BICYCLE, BALLET, FLOWER GARDEN, and TRAIN. They have been coded by the MPEG-2 encoder at 5 Mbps at 30 frames/sec. We use the restricted slice structure, N is equal to 12 (the number of frames in a GOP), and $M = 3$. The GOP structure implies that if some errors occur in the I-frame, the effects of data corruption propagate through all other frames within GOP including the corrupted frame. Similarly, an error of the P-frame may affect neighboring P-frames and B-frames, while errors of the B-frame can be isolated. Therefore, it is desirable to develop error concealment algorithms for the reference frames to prevent error propagation. In this paper, we lose one TS packet in the first P-frame, and conceal the corrupted MBs using the different error concealment algorithms.

Computer simulations have been performed to compare described temporal-domain error concealment algorithms: AVG [10], BMA [12], DMVE [13], and the newly proposed OFA. In order to estimate MV for the lost MB, conventional MV recovery algorithms use $[-25, 24]$ SR with a full search algorithm, which is referred to as a block matching algorithm. While BMA uses a one pixel boundary line, DMVE can exploit variable pixel boundary lines, i.e., from one to eight. From the simulation, we found that DMVE produces the best results when it uses two pixel boundary lines.

To calculate the optical flow of OFR, initial velocity estimates of optical flow, $(\bar{u}, \bar{v})$, are zeros. When we compute the local average of velocity lie outside the OFR at the boundary of OFR, we simply copy velocities from adjacent points. For iterative solution, we iterate until the solution has stabilized. In addition, we set α value as 1 from the simulation and the size of MVEB is the same as that of MB.

Table 1 summarizes the peak-signal-to-noise ratio (PSNR) of the reconstructed P-frames for the five test sequences. OFA produces higher PSNR values than any other methods except for TRAIN. BMA and DMVE demonstrate similar performances. In addition, OFA yields good performance when we cannot use the bottom boundary pixels of the lost MBs, as shown in the second row of each algorithm.

Table 2 compares the computational complexity of different error concealment algorithms. We count the numbers of (−), (+), and (×) operations to estimate MV for the lost MB. In the case of BMA, we need 120000 (−) and (×) operations and 112500 (+) operations to determine the smallest SSD except for a sorting operation. Computational complexity of DMVE is roughly twice than that of BMA. In the case of OFA, however, we have to calculate the partial derivatives just one time. In addition, we calculate the local averages, $\bar{u}$ and $\bar{v}$, and the temporary velocity estimates, u^n and v^n, in each iteration, respectively. While MV recovery methods based on motion estimation with the full search algorithm result in a big burden on computation time, OFA requires fewer iterations to obtain the optical flow in OFR.

When we compare performances of error concealment algorithms, we need to test the subjective picture quality of reconstructed frames. Figure 6 shows concealed P-frames obtained by various error concealment algorithms with the BICYCLE sequence. As shown in Fig. 6(c), the concealed P-frame by AVG has some block spots. Figure 6(d) and Fig. 6(e) are obtained by BMA and DMVE. In these reconstructed pictures, we can observe abrupt changes of luminance values in the MB slice boundaries, which is quite annoying to human viewing. The results clearly show that P-frame reconstructed with OFA has smooth MB boundaries. When compared with the other test sequences, we obtain good results using OFA.

(a) Original frame.

(b) Corrupted frame.

(c) Frame concealed with AVG.

(d) Frame concealed with BMA.

(e) Frame concealed with DMVE.

(f) Frame concealed with OFA.

Fig. 6 Subjective quality comparison.

In the case of the FOOTBALL sequence, although objects movement is not homogenous in the motion area, OFA provides better picture quality than any other algorithms. For the BALLET sequence, it is difficult to recover the corrupted MBs with each algorithm because the MB size representing the cloth of both ballet dancers is relatively large. For the FLOWER GARDEN and TRAIN sequences, each algorithm produces similar subjective picture qualities. From the objective and subjective quality tests, we have observed that OFA provides the best results.

7. Conclusion

In this paper, we have proposed a new error concealment technique for digital television applications. Since MPEG-2 video compressed bitstreams are very sensitive to transmission errors, we need a mechanism to mitigate the effects of transmission errors on the decoded picture quality. Error concealment algorithms attempt to reduce the visual degradation in the reconstructed video sequence. In this paper, we have reviewed the merits and demerits of conventional MV recovery algorithms and proposed a new MV recovery algorithm based on the optical flow fields to improve the performance of error concealment operations. Simulation results demonstrate that the proposed algorithm has better results than the other methods, and is less computationally complex.

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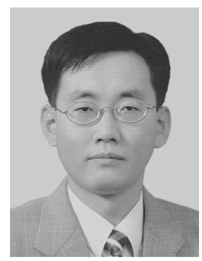

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