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Error Concealment Using Motion Field Interpolation

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Abstract

In the context of block-based video coding, two error concealment algorithms are presented. The first algorithm is based on bilinear motion field interpolation (BMFI). For each pel in a damaged block, the algorithm recovers a motion vector using bilinear interpolation of neighbouring motion vectors. This vector is then used to conceal the damaged pel. A reduced complexity version of this algorithm is also presented. The second algorithm uses overlapped motion compensation to combine the first algorithm with a boundary matching error concealment algorithm. Simulation results show that at low error rates the first algorithm outperforms other concealment techniques, but its performance starts to deteriorate with increasing error rate. The second algorithm, however, maintains a superior performance regardless of the error rate. Simulation results within an H.263 codec are also presented.

1. Introduction

Fast growing multimedia services have generated a great interest in transmitting digital video over a wide range of communication channels. However, practical communication channels are not error free, although the loss mechanism may vary from medium to medium (e.g. multi-path fading in wireless channels or network congestion in ATM networks). Since the transmitted video is often highly compressed, to meet bandwidth requirements, it is very sensitive to channel errors and the quality of the reconstructed video can be severely degraded.

There are three main approaches available to combat the effect of channel errors. The first approach is error detection and correction using structured codes such as the Hamming code. This approach increases the bit rate because it works by adding redundancy to the data. The second approach is to modify the video encoder so that the produced compressed stream is more resilient to channel errors. This may require modifications to existing video coding standards. The third approach is error concealment which provides a subjectively acceptable approximation of the original data by exploiting the high temporal and spatial correlation of video sequences. This approach requires no change to the encoder and no increase in the bit rate. It is particularly attractive for very low bit rate applications.

In this paper we propose a temporal error concealment method based on bilinear motion field interpolation (BMFI). The paper is organised as follows. Section 2 briefly reviews a number of temporal error concealment methods and discusses their drawbacks. Section 3 describes the BMFI error concealment method and highlights its main advantages. Section 4 discusses ways of reducing the complexity of the BMFI method. Section 5 shows how to use overlapped motion compensation to combine the BMFI method with a boundary matching method to achieve a more robust error concealment method. Section 6 presents the results of testing the proposed algorithms. Finally, section 7 gives some concluding remarks.

2. Temporal Error Concealment

Temporal error concealment methods exploit the high temporal correlation of video sequences and conceal corrupted blocks in the current frame using blocks from a previously reconstructed frame. This can be expressed as follows:

$$\hat{\mathbf{B}}_c(\mathbf{x}) = \mathbf{B}_r(\mathbf{x}+\mathbf{d}) \tag{1}$$

where $\mathbf{B}_r$ is a block in a previously reconstructed frame used to produce an approximation, $\hat{\mathbf{B}}_c$, of the damaged block, $\mathbf{B}_c$, in the current frame, $\mathbf{x}$ is the spatial co-ordinates of the top-left corner of the damaged block, and $\mathbf{d}$ is the spatial displacement between $\mathbf{B}_c$ and $\mathbf{B}_r$.

When the motion information, $\mathbf{d}_m$, of the damaged block is available then the concealment displacement is set to $\mathbf{d} = \mathbf{d}_m$. In practice, however, this information is usually lost or erroneously received. This is due to the fact that most video coding standards use variable length codes (VLC) and differential encoding. Thus, an error in a

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code-word will usually lead to loss of synchronisation at the decoder, and all blocks (including their motion information) up to the next synchronisation point will be completely lost. Most temporal error concealment methods will, thus, attempt to recover the lost or erroneously received motion vector before applying Eq.1.

Replacement of the damaged motion vector with **0** is usually employed [1, 2]. This method is referred to as temporal replacement (TR). It works well for stationary and quasi-stationary areas (e.g. background) but will fail for fast moving areas.

Another approach is to replace the damaged motion vector with the average or the median of the vectors of directly neighbouring blocks [1, 2]. This method works well for areas with smooth motion where there is a high correlation between the motion vectors of neighbouring blocks. It will fail for areas with unsmooth motion (e.g. objects moving in different directions).

A boundary matching algorithm with side match distortion measure (BMSMD) has also been used to select a suitable replacement from a set of candidate motion vectors [3, 4]. This can be explained as follows. For each candidate motion vector, motion compensation (Eq.1) is used to produce an approximation of the damaged block. Since the pels in a video frame are highly correlated, then the quality of this approximation can be measured using the continuity across the block boundaries. Such continuity is well represented by the side match distortion (SMD) measure which is defined as the sum of absolute (or squared) differences across the boundaries of the concealed block. The candidate motion vector that achieves the minimum SMD is chosen as the recovered motion vector. The set of candidate motion vectors is usually selected from the motion vectors of neighbouring blocks. The main advantage of this method is that the recovered motion vector is selected based on a distortion measure. The method will fail for areas with unsmooth motion and also for areas with low spatial correlation (e.g. at the boundaries of objects).

3. Error Concealment Using Bilinear Motion Field Interpolation (BMFI)

As already described in section 2, temporal error concealment is achieved using two processes: motion information recovery followed by motion compensation. Thus, if the performance of either or both processes can be improved then the performance of the temporal error concealment method will also be improved.

In recent years motion field interpolation (MFI) has been used in the field of motion compensation [5, 6]. It has been reported to give some improvement over conventional translational motion compensation models. Its main advantage is that it provides a smoothly varying motion field which reduces blocking artefacts and compensates for more types of motion (e.g. rotation or scaling).

In MFI, motion information is available at a number of nodal or control points. The motion vector at any other point can then be approximated by interpolating the motion vectors of the surrounding control points. Thus, motion information recovery is inherent in this method.

The above features (i.e. better motion compensation performance and inherent motion information recovery) makes MFI a very attractive choice for temporal error concealment.

Bilinear motion field interpolation (BMFI) is the most widely used MFI method. It can be described as follows. Assume that $\mathbf{V}_{TL}$, $\mathbf{V}_{TR}$, $\mathbf{V}_{BL}$ and $\mathbf{V}_{BR}$ are respectively the motion vectors at the top-left, top-right, bottom-left, and bottom-right corners of a block, then the motion vector $\mathbf{v}(x, y)$ at any point $p(x, y)$ within the block can be estimated using the following bilinear interpolation equation:

$$\begin{aligned}\mathbf{v}(x, y) = &(1-x_n)(1-y_n)\mathbf{V}_{TL} + x_n(1-y_n)\mathbf{V}_{TR} \\ &+ (1-x_n)y_n\mathbf{V}_{BL} + x_n y_n \mathbf{V}_{BR}\end{aligned} \tag{2}$$

and

$$x_n = \frac{x - x_L}{x_R - x_L} \quad , \quad y_n = \frac{y - y_T}{y_B - y_T} \tag{3}$$

where x_L and x_R are respectively the x-coordinates of the left and right borders of the block, and y_B and y_T are respectively the y-coordinates of the bottom and top borders of the block.

The above equation (Eq.2) assumes that the motion information at the four corners of the block is available. Such information is not provided by current video coding standards. We, therefore, modify the above equation to become:

$$\mathbf{v}(x, y) = \frac{(1-x_n)\mathbf{V}_L + x_n\mathbf{V}_R + (1-y_n)\mathbf{V}_T + y_n\mathbf{V}_B}{2} \tag{4}$$

where $\mathbf{V}_L$, $\mathbf{V}_R$, $\mathbf{V}_T$, and $\mathbf{V}_B$ are respectively the motion vectors of the blocks to the left, to the right, above and below the current block.

When used for error concealment, Eq.4 is used to recover one motion vector per pel of the damaged block (compare with the methods in section 2 where only one motion vector is recovered per damaged block). Each pel is then compensated (or concealed) individually. In this case, motion compensation may require accessing a pel at a non-sampling coordinate in the previously reconstructed frame. Again, bilinear interpolation of the pels at surrounding sampling coordinates is employed.

4. Reduced Complexity BMFI

One of the main disadvantages of BMFI is its high computational complexity. A direct implementation of equations 3 and 4 requires $12N^2$ addition/subtractions and $12N^2$ multiplications/divisions for an $N \times N$ block. This complexity can be reduced using a number of methods.

One method is to calculate the normalised coordinates, x_n and y_n, off-line and store them in a look-up table. This reduces the complexity to $8N^2$ additions/subtractions and $6N^2$ multiplications/divisions.

Another method is to use a line scanning technique. That is, once $\mathbf{v}(x, y)$ is computed, then the motion vector of the next pel in the row can be calculated using:

$$\mathbf{v}(x+1, y) = \mathbf{v}(x, y) + \frac{\mathbf{V}_\mathrm{R} - \mathbf{V}_\mathrm{L}}{N} \tag{5}$$

Note that the second term is a constant and needs to be calculated only once per block. A similar expression can also be derived for the next pel in the column, i.e. $\mathbf{v}(x, y+1)$. This technique reduces the complexity to about (N^2 + 4) additions/subtractions and about 4 multiplications/divisions per block. Thus, this method achieves a much reduced complexity.

A point to note here is that BMFI will only be used for damaged blocks. Thus, it will not increase the complexity of the decoder considerably.

5. A Combined BMFI and BMSMD Error Concealment Method

The BMFI error concealment method provides a smoothly varying motion field within the concealed block. Although this is an attractive feature of the method, it may cause severe degradation if the motion within the damaged block was purely translational. Moreover, the technique is highly dependent on neighbouring motion vectors and may, therefore, fail if those vectors are not available. On the other hand, the BMSMD method is less dependent on neighbouring vectors, because it uses only the one which minimises a distortion measure, but it can fail if the motion within the damaged block was not purely translational or if the actual motion vector is not close to any of the neighbouring vectors. We, therefore, propose to combine the two methods to produce a more robust error concealment method.

Let $\hat{\mathbf{v}}^\mathrm{i}(x, y) = (\hat{d}_\mathrm{x}^\mathrm{i}, \hat{d}_\mathrm{y}^\mathrm{i})$ be the recovered vector, at pel $p_\mathrm{c}(x, y)$ of the damaged block, using BMFI, and let $\hat{\mathbf{V}}^\mathrm{s} = (\hat{d}_\mathrm{x}^\mathrm{s}, \hat{d}_\mathrm{y}^\mathrm{s})$ be the recovered vector of the damaged block using BMSMD, then pel $p_\mathrm{c}(x, y)$ can be approximated (or concealed) as follows:

$$\hat{p}_\mathrm{c}(x, y) = \frac{1}{2}\left[p_\mathrm{r}(x + \hat{d}_\mathrm{x}^\mathrm{i}, y + \hat{d}_\mathrm{y}^\mathrm{i}) + p_\mathrm{r}(x + \hat{d}_\mathrm{x}^\mathrm{s}, y + \hat{d}_\mathrm{y}^\mathrm{s})\right] \tag{6}$$

where p_r refers to pels in a previously reconstructed frame. In other words, the damaged block is concealed using the average of two blocks: the one produced by BMFI and that produced by BMSMD. This is a form of overlapped motion compensation [7].

6. Simulation Results

Three QCIF test sequences were used in this simulation: FOREMAN (176×144 @ 30 f.p.s., 300 frames), TUNNEL (176×144 @ 25 f.p.s., 250 frames), and TABLE TENNIS (176×120 @ 30 f.p.s., 300 frames). The block size was set to 16×16 and motion was estimated using full-pel exhaustive search block matching with a maximum motion displacement of ±15. To simulate the effect of transmission over practical communication channels, errors were introduced randomly. It is assumed that the concealment process is supported by an appropriate transport format which helps to identify lost or damaged blocks at the decoder. The original previous frame is used during the concealment process. The assumption that this frame is available at the decoder was adopted to mask the effect of temporal error propagation on the results. It was further assumed that there is no spatial error propagation (i.e. fixed length codes and no differential encoding).

Five temporal error concealment algorithms were considered: temporal replacement (TR), average vector (AV), BMSMD, BMFI, and combined BMFI & BMSMD (COMBINED). In each case, the motion vectors of the four neighbouring blocks (left, right, above and below) were used in the motion information recovery process. Whenever a neighbouring motion vector is not available (e.g. damaged, or does not exist as in border blocks) it is set to **0**. For the BMSMD, the sum of absolute differences was used in the side match distortion calculations.

Table 1. *Comparison between different error concealment algorithms with a block error rate of 20%. The PSNRs are for damaged blocks only and averaged over the whole sequence.*

	Average PSNR (dB)		
	FOREMAN	TUNNEL	TABLE
TR	28.40	28.68	29.40
AV	29.85	28.57	29.50
BMSMD	30.78	29.69	30.90
BMFI	31.25	29.79	30.80
COMBINED	31.84	30.80	31.70

Table 1 compares the performance of the five algorithms when applied to the three test sequences with a block error rate of 20%. In general, TR and AV have comparable results, although AV is slightly better. The proposed BMFI algorithm has a very comparable performance to that of the BMSMD. In general, both algorithms provide about 1 ~ 2 dB improvement over TR and AV. The best performance is achieved by the proposed COMBINED algorithm. It provides about 0.8 ~ 1 dB improvement over BMSMD and BMFI, and about 2 ~ 3 dB improvement over TR and AV.

To investigate the effect of the block error rate on the performance, the five algorithms were tested using the FOREMAN sequence with a block error rate of 10% ~ 50% in increasing steps of 10%. The results are illustrated in figure 1.

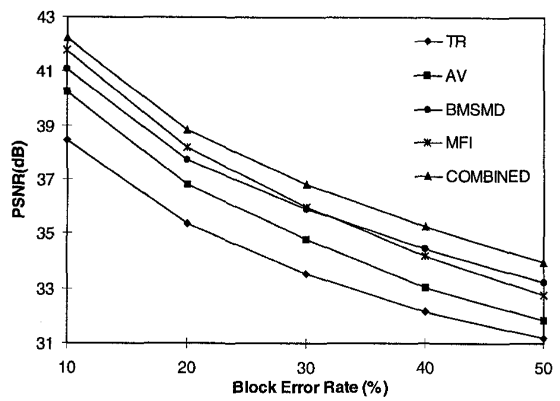
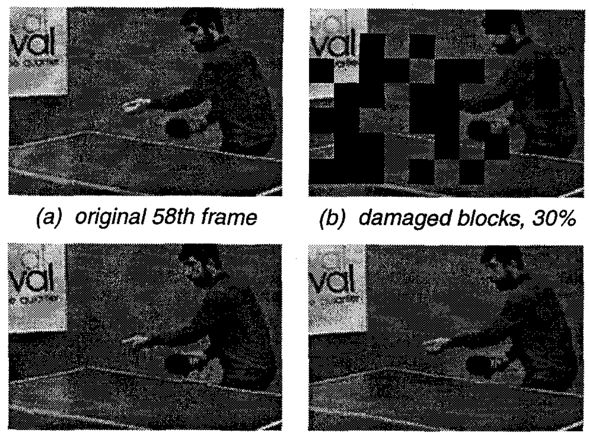


Figure 1. *Comparison between different error concealment algorithms when applied to the FOREMAN sequence with different block error rates. The PSNRs are for whole frames and averaged over the sequence.*

As expected, the quality of the concealed video sequence deteriorates with increasing block error rate. Over the considered block error rate range, the TR algorithm has the worst performance and the proposed COMBINED algorithm has the best performance. A very interesting point to note here is that at low block error rates the proposed BMFI algorithm outperforms the BMSMD algorithm. As the block error rate increases the performance of the BMFI algorithm deteriorates and becomes inferior to that of the BMSMD algorithm. This is due to the fact that the BMFI algorithm is highly dependent on the neighbouring motion vectors. Therefore, as the block error rate increases, more of those neighbouring vectors are in error and the performance starts to deteriorate. This effect can be reduced using interleaving techniques such as the simple odd-even block interleaving scheme adopted in [8].

The above observations indicate that an efficient way to utilise the proposed algorithms is as follows. At low block error rates, the BMFI algorithm is employed. When the block error rate exceeds a threshold, the more complex COMBINED algorithm is invoked.

Figure 2 shows the subjective quality of the 58th frame of TABLE TENNIS with a block error rate of 30% when concealed using BMSMD and the proposed COMBINED algorithm. The superior performance of the COMBINED algorithm is immediately evident from the good concealment of the left hand of the player.



(a) original 58th frame *(b) damaged blocks, 30%*

(c) concealed using BMSMD *(d) concealed using COMBINED*

Figure 2. *Subjective quality of concealed 58th frame of TABLE TENNIS with a block error rate of 30%.*

The proposed COMBINED algorithm was also tested within an H.263 codec. In this case, some of the assumptions made in the previous simulations were relaxed. For example, the previously decoded (and possibly damaged) frame was used in the concealment of the current frame. This will result in temporal error propagation. Spatial error propagation will also occur since the H.263 uses VLC and differential encoding.

At the decoder, errors were detected using a set of error-checking conditions derived from the structure and the constraints imposed on the H.263 video bitstream syntax. Examples of such error-checking conditions are when an invalid codeword is detected, when the number of decoded DCT coefficients within a block is invalid, when decoded motion vectors are out of range, or when decoded quantisation parameter is out of range. When an error is detected, the decoding process is stopped, the decoder then searches for the next synchronisation point and decoding is resumed again. All macroblocks between the point where the error was detected and the synchronisation point are marked as corrupted macroblocks. In this simulation the H.263 option to insert synchronisation codewords at the start of each GOB was switched on. All other optional modes were switched off.

The H.263 encoder was used to encode the FOREMAN sequence at a bit rate of 24 kbits/s. The resulting compressed sequence has a frame rate of 8.13 f.p.s. and includes 75 frames. This sequence was corrupted with a random bit error rate of 10^{-3}. The H.263 decoder was used to decode the corrupted sequence. Two error concealment algorithms, BMSMD and COMBINED were used to conceal corrupted macroblocks. Figure 3 compares the performance of the two algorithms. The PSNRs are for the luminance components and calculated with reference to the original sequence. On average, the BMSMD algorithm achieves a PSNR of 19.76 dB whereas the COMBINED algorithm achieves a PSNR of 20.11 dB.

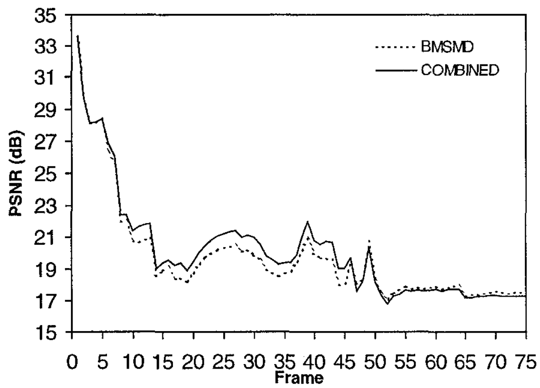


Figure 3. *Comparison between BMSMD and COMBINED when used to conceal an H.263 encoded 24 kbits/s FOREMAN sequence corrupted with a 10^{-3} bit error rate. The PSNRs are for the luminance component.*

Figure 4 compares the performance of the two algorithms in terms of the subjective quality of the decoded 25th frame of the sequence. Again, the superior performance of the COMBINED method is immediately evident.

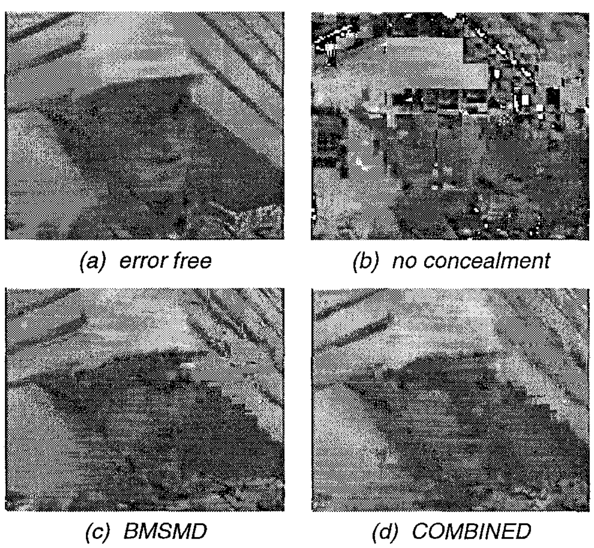


Figure 4. *Subjective quality of decoded and concealed 25th frame of the H.263 encoded 24kbits/s FOREMAN sequence corrupted with a 10^{-3} bit error rate.*

7. Conclusions

When transmitted over practical communication channels, compressed video suffers severe degradations. One approach to combat the effect of channel errors is error concealment. This is an attractive choice for very low bit rate applications because it does not increase the bit rate. In this paper, two error concealment algorithms were proposed. The first approach, BMFI, is based on bilinear motion field interpolation. The second approach, COMBINED, uses a form of overlapped motion compensation to combine BMFI with a boundary matching error concealment algorithm, BMSMD. At low error rates, the BMFI outperforms the BMSMD algorithm. However, as the error rate increases, the performance of the BMFI deteriorates. The COMBINED algorithm is more robust as it maintains its superior performance regardless of the error rate.

Possible ways to reduce the complexity of the BMFI algorithm and also to improve its performance at high error rates were discussed. An efficient way to utilise the proposed algorithms at the decoder was recommended. Simulation results within an H.263 codec were also presented.

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