Multiple Reference Motion Compensation: A Tutorial Introduction and Survey

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Abstract

Motion compensation exploits temporal correlation in a video sequence to yield high compression efficiency. Multiple reference frame motion compensation is an extension of motion compensation that exploits temporal correlation over a longer time scale. Devised mainly for increasing compression efficiency, it exhibits useful properties such as enhanced error resilience and error concealment. In this survey, we explore different aspects of multiple reference frame motion compensation, including multihypothesis prediction, global motion prediction, improved error resilience and concealment for multiple references, and algorithms for fast motion estimation in the context of multiple reference frame video encoders.

Contents

1

Introduction

Digital video compression has matured greatly over the past two decades. Initially reserved for niche applications such as videoconferencing, it began to spread into everyday life with the introduction of the Video CD and its accompanying Motion Pictures Experts Group MPEG-1 digital video compression standard in 1993 [51]. Home use became widespread in 1996, when the digital video/versatile disk (DVD) with MPEG-2 compression technology was introduced [48, 52]. Digital video compression also facilitated cable and IP-based digital TV broadcast. At the same time, the increase in Internet bandwidth fueled an unprecedented growth in Internet video streaming, while advances in wireless transmission made mobile video streaming possible.

An example video sequence consisting of two frames is shown in Figure 1.1. A frame contains an array of luma samples in monochrome format or an array of luma samples and two corresponding arrays of chroma samples in some pre-determined color sub-sampling format. These samples correspond to pixel locations in the frame. To compress these two frames, one can encode them independently using a still image coder such as the Joint Photographic Experts Group (JPEG) [50] standard. The two frames are similar (*temporally correlated*), hence more

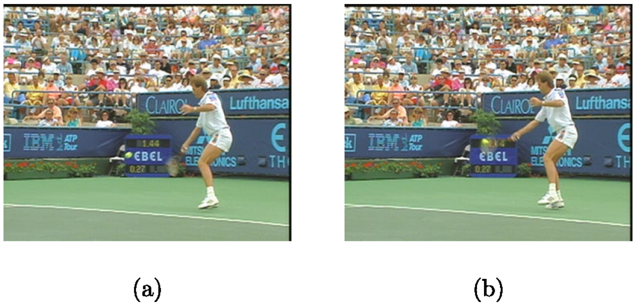
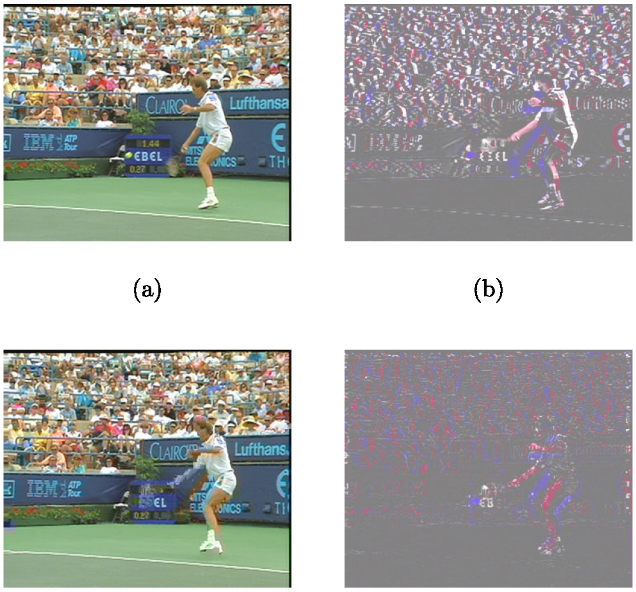


Fig. 1.1 The previous (a) and the current (b) frame of the video sequence.

compression can be obtained if we use the previous frame to help us compress the current frame. One way to do this is to use the previous frame to *predict* the current frame, and then to encode the difference between the actual current frame and its prediction. The simplest version of this process is to encode the difference between the two frames (i.e., subtract the previous frame from the current frame and encode that difference). In this case, the entire previous frame becomes the *prediction* of the current frame. Let i and j denote the spatial horizontal and vertical coordinates of a pixel in a rectangularly sampled grid in a raster-scan order. Let $f_n(i,j)$ denote the pixel with coordinates (i,j) in frame n. Let $\hat{f}_n(i,j)$ denote the predicted value of this pixel. The prediction value is mathematically expressed as $\hat{f}_n(i,j) = f_{n-1}(i,j)$. This technique is shown in the first row of Figure 1.2. For sequences with little motion such a technique ought to perform well; the difference between two similar frames is very small and is highly compressible. In Figure 1.1(b) for example, most of the bottom part of the tennis court will be highly compressed since the difference for these areas will be close to zero. However, there is considerable motion in terms of the player and camera pan from one frame to the next and the difference will be non-zero. This is likely to require many bits to represent.

1.1 Motion-Compensated Prediction

The key to achieving further compression is to *compensate* for this motion, by forming a better prediction of the current frame from some



(a) (b)

(c) (d)

Fig. 1.2 Motion compensated prediction. The top row shows the prediction which is the unaltered previous frame (a) and the resulting difference image (b) that has to be coded. The bottom row shows the equivalent prediction (c) and difference image (d) for motion compensated prediction. The reduction of the error is apparent.

reference frame. A frame is designated as a reference frame when it can be used for motion-compensated prediction. This prediction of the current frame, and subsequent compression of the difference between the actual and predicted frames, is often called *hybrid coding*. Hybrid coding forms the core of video coding schemes from the early compression standards such as ITU-T H.261 [103] and ISO MPEG-1 to the most recent ISO MPEG-4 Part 2 [53], SMPTE VC-1 [82], China's Audio Video Standard (AVS) [29], ITU-T H.263 [104], and ITU-T H.264/ISO MPEG-4 Part 10 AVC coding standards [1, 84].

When a camera pans or zooms, this causes *global motion*, meaning that all or most of the pixels in the frame are apparently in motion in some related way, differing from the values they had in the previous frame. When the camera is stationary but objects in the scene move, this is called *local motion*. To compensate for local motion, a frame is typically subdivided into smaller rectangular blocks of pixels, in which motion is assumed to consist of uniform translation. The translational motion model assumes that motion within some image region can be represented with a vector of horizontal and vertical spatial displacements. In *block-based* motion-compensated prediction (MCP), for each block b in the current frame, a *motion vector* (MV) can be transmitted to the decoder to indicate which block in a previously coded frame is the best match for the given block in the current frame, and therefore forms the prediction of block b. Let us assume a block size of 8×8 pixels. The MV points from the center of the current block to the center of its best match block in the previously coded frame. MVs are essentially addresses of the best match blocks in the reference frame, in this case the previous frame. Let $\mathbf{v} = (v_x, v_y)$ denote the MV for a block in frame n. For the pixels in that block, the motion-compensated prediction from frame $n - 1$ is written as $\hat{f}_n(i,j) = f_{n-1}(i + v_x, j + v_y)$. If the MV is $\mathbf{v} = (0,0)$, then the best match block is the co-located block in the reference frame. As Figure 1.1 shows, parts of the tennis court at the bottom part of the frame appear static, so the best match is found with the $(0,0)$ MV. However, there is substantial motion in the rest of the frame that can only be modeled with *non-zero* MVs.

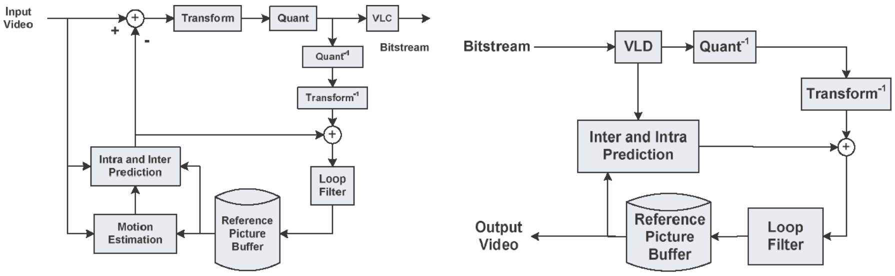
MVs or, in general, *motion parameters* are determined by doing a motion search, a process known as *motion estimation* (ME), in a reference frame. Assuming a search range of $[-16, +16]$ pixels for each spatial (horizontal and vertical) component, $33 \times 33 = 1089$ potential best match blocks can be referenced and have to be evaluated. The MV $\mathbf{v}$ that minimizes either the sum of absolute differences (SAD) or the sum of squared differences (SSD) between the block of pixels f in the current frame n and the block in the previous frame $n - l$ that is referenced by $\mathbf{v} = (v_x, v_y)$ may be selected and transmitted. Let b denote a set that contains the coordinates of all pixels in the block. The SAD and SSD are written as:

$$SAD = \sum_{(i,j) \in b} |f_n(i,j) - f_{n-l}(i + v_x, j + v_y)| \tag{1.1}$$

$$SSD = \sum_{(i,j) \in b} (f_n(i,j) - f_{n-l}(i + v_x, j + v_y))^2 \tag{1.2}$$

To form the MCP of the current frame, the blocks that are addressed through the MVs are copied from their original spatial location, possibly undergoing some type of *spatial filtering* (more on that in Section 3.5), to the location of the blocks in the current frame, as shown in Figure 1.2(c). This prediction frame is subsequently subtracted from the current frame to yield the *motion-compensated difference frame* or, in more general terms, the *prediction residual* in Figure 1.2(d). Obviously, if the MCP frame is very similar to the current frame, then the prediction residual will have most of its values close to zero, and hence require fewer bits to compress, compared to coding each frame with JPEG or subtracting the previous frame from the current one and coding the difference. One trade-off is an increase in complexity since ME is costly. The prediction residual is typically transmitted to the decoder by transforming it using a discrete cosine transform (DCT), rounding off the coefficients to some desired level of precision (a process called quantization) and sending unique variable-length codewords to represent these rounded-off coefficients. Along with this difference information, the MVs are transmitted to the decoder, requiring some additional bit rate of their own. For content with sufficient temporal correlation, the overall bit rate requirements are much less than without the use of MCP.

A diagram of a hybrid codec is illustrated in Figure 1.3. The decoder uses the MVs to obtain the motion compensated prediction blocks from some previously decoded reference frame. Then, the decoded prediction



(a) (b)

Fig. 1.3 Hybrid video (a) encoder and (b) decoder.

residual block is added to the MCP block to yield the current decoded block. This is repeated until the entire frame has been reconstructed. The reconstructed frame at the decoder may not be identical with the original one, because of the quantization used on the residual blocks.

Note that MCP for a block is also known as *inter prediction* since inter-frame redundancy is used to achieve compression. When combined with coding of the prediction residual it is called *inter-frame* coding. When a block is encoded independently of any other frame, this is known as *intra-frame* coding. Usually, intra-frame coding involves some kind of *intra-frame prediction* or *intra prediction*, which is predicting a block using spatial neighbors. This might involve using the DC coefficient of a transform block as a prediction of the DC coefficient of the next transform block in raster-scan order (as in JPEG). Or it might involve prediction of each pixel in a block from spatial neighbors using one of several possible directional extrapolations (as in H.264). In general, inter-frame coding enables higher compression ratios but is not as error resilient as intra-frame coding, since, for inter-frame coding, decoding the current frame depends on the availability of the reference frame. Video frames (or equivalently pictures) that use intra-frame coding exclusively to encode all blocks are called *intra-coded* or *I-coded frames*, while frames that allow the use of either intra-frame or inter-frame coding from some reference frame are known as *P-coded frames*. P-coded frames have been traditionally constrained to reference past frames in display order (as in the early standards H.261, H.263, MPEG-1, MPEG-2, and MPEG-4 Part 2). Finally, *B-coded frames* allow bi-directional prediction from one past and one future frame in display order in addition to intra-frame or inter-frame coding. Note that referencing future frames in display order generally involves transmitting frames out of order. For example, frame 3 can be encoded after frame 1 and then frame 2 can be encoded making reference to both frames 1 and 3. A simple illustration is shown in Figure 1.4. Note that B-coded frames were further extended in H.264/MPEG-4 AVC [1] to provide for a more generic form of bi-prediction without any restrictions in direction. Detailed information on bi-predictive coding is found in Section 4.1.

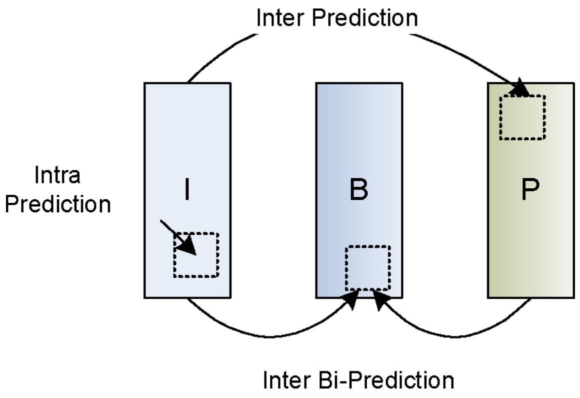


Fig. 1.4 An example of different prediction schemes.

1.2 Outline

Block-based MCP traditionally made use of a single previous frame as a reference frame for motion-compensated prediction, while for B-coded frames a single future frame was used jointly with the previous frame in display order to produce the best prediction for the current frame. However, motion search does not have to be limited to one frame from each prediction direction. Temporal correlation can be often nontrivial for temporally distant frames. In this article, the term multiple-reference frame motion compensation encompasses any method that uses combinations of more than one reference frame to predict the current frame. We also discuss cases where reference frames can be synthesized frames, such as panoramas and mosaics, or even composite frames that are assembled from parts of multiple previously coded frames. Finally, we note that we wish to decouple the term reference frame from that of a decoded frame. While a decoded frame can be a reference frame used for MCP of the current frame, a reference frame is not constrained to be identical to a decoded frame. The first treatise of the then state-of-the-art in multiple-reference frames for MCP is [109]. This work is intended to be somewhat broader and more tutorial. The article is organized as follows. Section 2 describes background, mosaic, and library coding, which preceded the development of modern multiple-reference techniques. Multiple-frame motion compensation is treated in

Section 3, while the almost concurrent development of multihypothesis prediction, often seen as a superset of multiple-reference prediction, is investigated in Section 4. The commercialization and rapid deployment of multiple-reference predictors has been hampered by the increased complexity requirements for motion estimation. Low complexity algorithms for multiple-frame motion search are covered in Section 5. The uses of multiple references for error resilience and error concealment are discussed in Sections 6 and 7, respectively. An experimental evaluation of some of the advances discussed in this work is presented in Section 8. This survey is concluded with Section 9. Appendix A provides the reader with additional information on rate-distortion optimization and Lagrangian minimization. Note that this work disregards the impact of each prediction scheme on decoder complexity.

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