# Frame Rate Converter With Pixel-Based Motion Vectors Selection and Halo Reduction Using Preliminary Interpolation

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Abstract—A new two-image-based method for frame rate conversion is proposed to reduce blocking, halo, and flickering artifacts. For blocking effects, a pixel-based motion vector (MV) selection is suggested based on neighboring block-based motion vectors. For halo reduction, after a preliminary image interpolation, MV at each pixel is re-estimated using the interpolated intensities and the MV of the current pixel and its neighbors constrained in adaptive sliding windows. Experimental results showed that the proposed method outperforms objectively and subjectively in comparison with some existing interpolation techniques.

*Index Terms*—Frame rate converter (FRC), halo reduction, intensity adaptive windowing, motion adaptive windowing, pixel-based motion vector selection, real-time processing.

# I. INTRODUCTION

N RECENT years, frame rate up-conversion (FRUC) or simply frame rate conversion (FRC) has become an important technique for various film/video conversions, temporal video formats coding and technology displays. Many motion estimation (ME) and motion-compensated interpolation (MCI) algorithms, forming the basis of typical FRC solutions, have been proposed for motion judder reduction [1]–[6]. Hierarchical block matching motion estimation was presented in [1] and [4] for complexity reduction over classical block matching motion estimation (BME). The FRC methods can be further classified into two approaches. The first approach estimates the motion vector (MV) between the previous and the current frame and then generates the desired interpolated frames [1]-[5]. The second approach working in the decoding enhancement context utilizes the received MV provided by various image compression standards such as MPEG1 and MPEG2 [6]-[9].

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Among various ME techniques, the block-matching algorithm (BMA) frequently used in temporal prediction coding is the most popular for low computation and ease of implementation [10]. Considering that a single motion vector is invariably assigned to a given block in a reference image, BMA can give rise to various artifacts such as blocking effect, but also to holes and overlapped areas in the interpolated image, when remapping the obtained MV. Various algorithms have been proposed to reduce these artifacts [2], [3]. For avoiding holes and overlaps phenomena, block-based bi-directional ME (BDME) proposed in [11], [12] is a capable solution. BDME estimates a bidirectional motion vector of the reference block in the interpolated image using geometrical similitude relationship between the previous and the current input image. It provides an MV for each pixel or block in the interpolated image. In order to reduce blocking artifacts, overlapped block motion compensation (OBMC) was suggested [3], [5]. OBMC can be incorporated in motion compensated interpolation (MCI) by appropriately combining interpolated results from neighboring block MV. A similar approach was generalized with weighted-adaptive MCI [13] in which the weighting or accuracy function was determined by using predicted ME errors. In [14], the suggested MCI was based on median filtering of various pixel intensity candidates which were obtained from neighboring block motion vector trajectories passing through the interpolated pixel location. The re-sampling of the MV field in smaller blocks to smooth motion vectors was also proposed [15]. The benefit of such an approach is to increase MV field resolution.

The halo effect caused by erroneous estimated MV in occlusion regions is also an important artifact in FRC [2]. Existing halo reduction algorithms can be classified into two categories using two or more successive input frames. Multiple-framebased analysis [19]-[23] can provide greater potential for efficient halo reduction. However, in the present case, a two-framebased solution [2], [4]–[14] is preferred for cost consideration. Most FRC algorithms with an emphasis on halo-artifact reduction are based, respectively, on two aspects: covered or uncovered (C/U) area detection and adaptive forward and backward MCI while assuming that estimated forward or backward MVs are adequate for image interpolation. Covered and uncovered area detection is provided generally by forward and backward prediction errors or MV boundaries. However, in occlusion regions, motion-compensated prediction models are not necessarily valid, since none of the classical forward, backward, and bidirectional ME between two existing images can correctly estimate the true MV. Therefore, C/U area detection provided by

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associated prediction errors can be difficult to approximate with practical accuracy. In a teleconference application, where the background is stationary, the C/U detection as shown in [2] can be based solely on foreground MV. However, in more generic applications, weighted-adaptive MCI or median filtering MCI has been proposed [19] to blur the halo artifact in the detected C/U area. Recently, in classified occlusion regions, median MV filtering [16] in a spiral scanning from the left-top and clockwise direction was suggested for re-estimated MV [9].

Frame-based iterative techniques and object-based segmentations are software-oriented concepts for artifact reduction [5], [17], [18] but generally, their hardware implementation is rather difficult and becomes another challenge altogether for a realtime FRC.

In this paper, a new image interpolation scheme is proposed to overcome the difficulties outlined previously. The suggested scheme is based mainly on MV estimation and processing between two adjacent frames. Thanks to recent advances in ASIC technology, after conventional BMA, a pixel-based MV selection (MVS) is performed in order to avoid blocking artifacts. For halo reduction, which requires both occlusion area detection and adequate ME, the problem is addressed in a fundamentally different way. Based on the notion of consistency between MV and intensity of adjacent pixels, a methodology using a sliding shape adaptive window (SAW), as used in [30], with local segmentation in three pixel groups, is proposed for removing the need for explicit C/U detection. For a sharp image interpolation, a generic adaptive MCI is introduced which considers the forward, backward interpolations and also the interpolated image position.

Section II of the paper presents in detail the proposed method. In Section III, experimental results are given and discussed. Section IV presents the final word on the techniques described in this paper.

## II. PROPOSED FRAME RATE CONVERSION

The system block diagram illustrated by Fig. 1, accepts an existing progressive image  $I_n(\boldsymbol{x})$ , and its picture delay version  $I_{n-1}(\boldsymbol{x})$  as inputs and provides at the output an interpolated image  $I_{n-\alpha}(\boldsymbol{x})$ . Alpha,  $\alpha$ , a fractional value, is the normalized distance between the existing image  $I_n(\boldsymbol{x})$  and the desired interpolated image  $I_{n-\alpha}(\boldsymbol{x})$ ; meanwhile,  $\boldsymbol{x}$  in bold character denotes the vector representing the current pixel coordinates in column and row.

This section covers the details of the proposed FRC which is composed mainly of the block-based ME, pixel-based motion vector selection (MVS), halo consideration MV refinement (HMVR), and MCI.

### A. Block-Based ME and Pixel-Based MV Selection

The smoothness in MV field is an interesting property which has been exploited in several ways. Particularly, BMA for ME is an economical example of this technique which assumes pixels in a block should share the same MV. However, this assumption is no longer valid around moving object boundaries. Recently, a ME with variable block sizes [25] and a MV interpolation for smaller block sizes [15] have been proposed in order to increase the MV field resolution. Pixel-based MV is desirable;



Fig. 1. Proposed FRC.

however, the classical optical flow process [26], [27] usually requiring several iterations makes it impractical for real-time applications. Particularly, for pixel-based FRC, Vatolin and Grishin proposed other designs [31]. In the present FRC, the proposed pixel-based ME is composed of two steps. The first one is the well-known BMA followed by a second estimation or a selection of neighboring block MV for each pixel in the interpolated image. Moreover, in order to anticipate the image interpolation in occlusion regions, forward and backward MV estimations will be performed independently in BMA. Ideally, in non-occlusion regions, the forward and backward MVs are collinear and their sum is equal to zero; it would be equivalent to BDME's results. In occlusion regions, this property will no longer be valid; it could thus yield a method for occlusion detection.

Suppose forward motion vector (F) indicates the displacement of a given image block W of dimension  $W \times W$  in image  $I_{n-1}$ , with respect to a matched block in image  $I_n$ . Backward motion vector (B) indicates the displacement of a given block in image  $I_n$  to a matched block in image  $I_{n-1}$ . If u represents the current block location, u = Integer[x/W], the MV F(u) and B(u) minimize, respectively, the mean of absolute differences errors MADF(u) and MADB(u) for the exhaustive full search in a given search zone SZ

$$MADF(\boldsymbol{u}) = \min_{\boldsymbol{F}} \frac{1}{n(\boldsymbol{R})} \\ \cdot \sum_{\boldsymbol{y} \in \boldsymbol{R}} |I_{n-1}(\boldsymbol{u}W + \boldsymbol{y}) - I_n(\boldsymbol{u}W + \boldsymbol{y} + \boldsymbol{F})| \quad (1)$$
$$MADB(\boldsymbol{u}) = \min_{\boldsymbol{B}} \frac{1}{n(\boldsymbol{R})} \\ \cdot \sum_{\boldsymbol{y} \in \boldsymbol{R}} |I_{n-1}(\boldsymbol{u}W + \boldsymbol{y} + \boldsymbol{B}) - I_n(\boldsymbol{u}W + \boldsymbol{y})| \quad (2)$$

in which  $\mathbf{R}$  denotes the current window region,  $n(\mathbf{R})$  is the region size, and  $\mathbf{y}$  are the coordinates of pixels within



Fig. 2. Illustration of forward MV used in MVS calculation.

the window **R**. The  $MADF(\mathbf{u})$ ,  $MADB(\mathbf{u})$  and the corresponding MVs can be associated to a small window **W** centralized inside the reference region **R**. Usually, the window **W** size is  $W \times W = 8 \times 8$ . The implemented search zone **SZ** is apt to detect displacements of  $\pm 24$  columns by  $\pm 20$  rows for standard definition TV (SDTV).

If the block-based MVs F(u) or B(u) are projected by following their linear trajectories, holes/covered areas (respectively, no/multiple MV) are an inevitable phenomenon produced in the interpolated image. In order to avoid this effect, as well as blocking artifacts, a MV Selection is used to provide for each pixel in the interpolated  $\alpha$ -plane two dense MV fields corresponding to its own selected forward and backward MVs, MV  $F_s(x)$  and MV  $B_s(x)$ , respectively. Let u be the coordinates of the current block W; u = Integer[x/W]. Let p be coordinates of a block in a square of neighboring blocks of the current one u. The square size of neighboring blocks could be a function of  $\alpha$  and the MV length; however, a fixed dimension  $5 \times 5$  can be used for implementation.

In a given  $\alpha$ -plane, the pixel-based forward MV  $F_s(x)$  is selected as one of the associated block-based Forward MV F(p)estimated in image  $I_{n-1}$ . As illustrated by Fig. 2, the MV F(p)is directly transferred from  $I_{n-1}$  to  $I_{n-\alpha}$ , i.e., it maintains the same spatial coordinates from frame to frame.  $F_s(x)$  minimizes the following weighted error forward WEF(x; p)

$$WEF(\boldsymbol{x};\boldsymbol{p}) = a_{\rm f}(\boldsymbol{p})[(1-c) \cdot MLEF(\boldsymbol{x};\boldsymbol{p}) + c \cdot MADF(\boldsymbol{p})] + b_{\rm f}(\boldsymbol{p}). \quad (3)$$

The obtained minimum error is denoted by

$$MWEF(\boldsymbol{x}) = \min_{\boldsymbol{F}(\boldsymbol{p})} WEF(\boldsymbol{x}; \boldsymbol{p})$$
  
= WEF(\boldsymbol{x}; \boldsymbol{p})|\_{\boldsymbol{F}(\boldsymbol{p}) = \boldsymbol{F}\_{\boldsymbol{S}}(\boldsymbol{x})}  
$$\boldsymbol{F}_{\boldsymbol{S}}(\boldsymbol{x}) = \arg\min WEF(\boldsymbol{x}; \boldsymbol{p})$$
(4)

In (3),  $MADF(\mathbf{p})$  is defined previously as in (1); c is a fixed consistency factor for combining two errors: the block-based  $MADF(\mathbf{p})$  and the pixel-based  $MLEF(\mathbf{x}; \mathbf{p})$ . Experimentally, c is set equal to (<sup>1</sup>/<sub>4</sub>) to reflect the significant contribution of the pixel-based error over the block-based one.  $MLEF(\mathbf{x}; \mathbf{p})$  denoting Mean Local Absolute Error Forward is a mean bidirectional MCI error provided from a forward MV  $F(\mathbf{p})$  at the pixel  $\mathbf{x}$  in the  $\alpha$ -plane

$$MLEF(\boldsymbol{x};\boldsymbol{p}) = \frac{1}{n(\boldsymbol{K})} \cdot \sum_{\boldsymbol{k} \in \boldsymbol{K}} |I_{n}(\boldsymbol{x} + \boldsymbol{k} + \alpha \cdot \boldsymbol{F}(\boldsymbol{p})) - I_{n-1}(\boldsymbol{x} + \boldsymbol{k} - (1 - \alpha) \cdot \boldsymbol{F}(\boldsymbol{p}))|.$$
(5)

**K** is a small local  $5 \times 5$  window around the current pixel x. The window size  $5 \times 5$  yields reliable ME for SDTV resolution.

In (3), if MLEF( $\mathbf{x}$ ;  $\mathbf{p}$ ) is the central mechanism for MVS, the factor  $a_{\rm f}(\mathbf{p})$  is generally equal to 1 and the penalty offset  $b_{\rm f}(\mathbf{p})$  is 0. However, when  $MADF(\mathbf{p})$  is smaller than a threshold value and the component-wise absolute differences between the MV  $F(\mathbf{p})$  and its  $5 \times 5$  average is bigger or equal to another experimentally set threshold, then the factor and the offset values are set to be, respectively, equal to 2 and 1. In practical terms, there is a penalty applied on a given block  $\mathbf{p}$  when its MAD is too small and its MV is relatively isolated.

Similarly, the same principle is applied independently for backward MV. In the  $\alpha$ -plane, selected pixel-based  $B_{\rm S}(\boldsymbol{x})$  can be obtained using (6)–(8) shown at the bottom of the page.

It should be noted that the estimated MV  $F_s(x)$  and  $B_s(x)$ are function of the  $\alpha$  value. Moreover, as stated previously, in non-occlusion regions,  $F_s(x) + B_s(x) = 0$ . In occlusion regions, it can be seen that the ME model is flawed and since MVS is a combining technique of one-directional and bidirectional ME, it is thus difficult to verify if one of  $F_s$  or  $B_s$ , or neither is the true MV. The next section, concerning Halo MV Refinement, aims to address this obstacle. Furthermore, the short abbreviation MWE for Mean Weighted local Error will be used when no forward or backward MV is to be specified.

As illustrated by Fig. 3, in which the horizontal component of forward MV is displayed at pixel resolution, the blocking artifact is strongly reduced after MVS.

For HDTV and higher resolution, the full search technique described above is applied in combination with a hierarchical approach to extend the footprint of the effective search window. MVS technique is then applied at different levels to reduce potential cumulative ME errors and to maintain good image and MV resolution.

$$WEB(\boldsymbol{x};\boldsymbol{p}) = a_b(\boldsymbol{p})[(1-c) \cdot MLEB(\boldsymbol{x};\boldsymbol{p}) + c \cdot MADB(\boldsymbol{p})] + b_b(\boldsymbol{p})$$

$$MWEB(\boldsymbol{x}) = \min_{\boldsymbol{p}(\boldsymbol{x})} WEB(\boldsymbol{x};\boldsymbol{p}) = WEB(\boldsymbol{x};\boldsymbol{p})|_{\boldsymbol{B}(\boldsymbol{p})=\boldsymbol{B}_{\boldsymbol{S}}(\boldsymbol{x})}$$
(6)

$$B_s(\mathbf{x}) = \arg\min WEB(\mathbf{x}; \mathbf{p})$$
(7)

$$MLEB(\boldsymbol{x};\boldsymbol{p}) = \frac{1}{n(\boldsymbol{K})} \sum_{\boldsymbol{k} \in \boldsymbol{K}} |I_n(\boldsymbol{x} + \boldsymbol{k} - \alpha \cdot \boldsymbol{B}(\boldsymbol{p})) - I_{n-1}(\boldsymbol{x} + \boldsymbol{k} + (1 - \alpha) \cdot \boldsymbol{B}(\boldsymbol{p}))|$$
(8)



Fig. 3. Paris sequence (Copyright (c) 1994, 1996, PictureTel corporation)—Moving to the left (darker MV), moving to the right (lighter MV). (a) Original image  $I_{n-1}$ . (b) Original image  $I_n$ . (c) Horizontal forward MV after BME in  $I_{n-1}$ . (d) Horizontal forward MV after MVS in  $I_{n-1/2}$ .

#### B. Halo Consideration MV Refinement

The halo effect is mainly due to the application of erroneous MV at the inner and outer boundaries of moving objects when interpolating the image  $I_{n-\alpha}(\boldsymbol{x})$ . Thus, for proper halo MV refinement (HMVR), a preliminary interpolated image is generated using the previously selected pixel-based forward and backward MV in order to get an approximation of the artifact areas.

1) Preliminary MCI: A possible MCI for preliminary image  $I_{p,\alpha}(\boldsymbol{x})$  can be described as follows:

$$I_{p,\alpha}(\boldsymbol{x}) = (1-\gamma) \cdot I_{n}(\boldsymbol{x}+\alpha \cdot \boldsymbol{F}_{\boldsymbol{s}}(\boldsymbol{x})) + \gamma \cdot I_{n-1}(\boldsymbol{x}+(1-\alpha) \cdot \boldsymbol{B}_{\boldsymbol{s}}(\boldsymbol{x})); \quad (9)$$

Up until now, the weighting  $\gamma$  has been defined as a fixed value (<sup>1</sup>/<sub>2</sub>), as  $\alpha$  or as a function of  $MADF(\boldsymbol{u})$  and  $MADB(\boldsymbol{u})$  [2], [18], [19]. The purpose of the latter is to provide an adaptive mechanism for C/U regions.

 $MADF(\mathbf{u})$  and  $MADB(\mathbf{u})$  are signal dependent and only using them for C/U area detection does not allow for reliable information. In order to provide more robustness in combining  $(I_{n-1}, \mathbf{B}_s)$  and  $(I_n, \mathbf{F}_s)$  for image interpolation, a context-based local statistic is proposed. Consider an  $M \times N$ sliding window around the pixel  $\mathbf{x}$ . The proposed factor  $\gamma(\mathbf{x})$  is the local ratio of the number of pixels in the window, which are in favor of an interpolation using the selected backward MV  $\mathbf{B}_s$ , and the window size (MN). Let SF and SB be pixel-based versions of MADF and MADB, respectively. SF( $\mathbf{x}$ ) and SB( $\mathbf{x}$ ) can be obtained from  $MADF(\mathbf{u})$  and  $MADB(\mathbf{u})$  by a  $W \times W$ up-sampler, followed by suitable separable interpolation filters



Fig. 4. Windows contains Foreground (black pixel) relatively moving to the left, Occluded Background (gray), Non-occluded Background (white). (a) Considered (central) pixel in foreground region. (b) Considered pixel in occlusion area.

to match picture source pixel resolution. Furthermore, let S1 and S2 be two threshold values. The weighting  $\gamma(\boldsymbol{x})$  can be defined more precisely as shown in (10) at the bottom of the page.

In other words, the weighting factor  $\gamma(\boldsymbol{x})$  is not based on an individual MADB result, but on a context-based decision which is more adaptive, and in turn, more reliable.

Note that for the preliminary image  $I_{p,\alpha}(\boldsymbol{x})$ , the interpolations required in (9) can be performed using simple linear filtering.

2) Halo Consideration MV Refinement HMVR: The HMVR concept is based on an  $I \times J$  sized sliding window illustrated by Fig. 4 in which there are three groups of pixels in the vicinity of an occlusion area.

In Fig. 4(a), when the considered pixel is in a foreground region, Group 1 consists heuristically of a local group of pixels with small weighted local error MWE and similar intensity level and similar MV values. Group 2 consists of a local group of pixels with large MWE and different intensity level but similar MV values to that of the central pixel. Group 3 consists of a local group of pixels with small MWE and different intensity levels and different MV values than that of the central pixel. Commonly, a large error is not a reliable indicator of a halo region. However, by combining this information with the local segmentation of vectors and pixel intensities, the identification and grouping of the different regions allow for better halo separation and makes possible robust MV refinement as described below.

Fig. 4(b) illustrates the case where the central pixel is in the occlusion area. There are, again, three groups of pixels of interest. Group 1 consists of a local group of pixels with small MWE and similar MV value but different intensity level from

If 
$$a \leq \frac{1}{2}$$
, then  

$$\gamma(\boldsymbol{x}) = \frac{[\#pixels: (SB(\boldsymbol{x}) < S1) \text{ or } (S1 \leq SB(\boldsymbol{x}) \leq SF(\boldsymbol{x}) + S2)]}{(MN)};$$
If  $a < \frac{1}{2}$ , then  

$$\gamma(\boldsymbol{x}) = 1 - \frac{[\#pixels: (SF(\boldsymbol{x}) < S1) \text{ or } (S1 \leq SF(\boldsymbol{x}) \leq SB(\boldsymbol{x}) + S2)]}{(MN)}$$
(10)

the central pixel of the window. Group 2 consists of a local group of pixels with large MWE and similar intensity levels and similar MV values to that of the central pixel of Fig. 4(b). Group 3 consists of a local group of pixels with small MWE and different MV values but with similar intensity levels to that of the window's central pixel.

Fig. 4, illustrating particular C/U situations, provides a framework to help model a MV correction method. As an example, for the case of Fig. 4(a), MV at the considered pixel can be unchanged or can be lightly changed for smoothness purpose by the mean MV of the pixels in the same group. For the case of Fig. 4(b), MV at the considered pixel has to be changed by the mean MV of the pixels in the window with similar intensities (within a threshold value) but different MV yielding small MWE.

The group of pixels having a set of given properties (such as similar intensities and similar MV to that of the central pixel) can be seen as a shape adaptive window (SAW). This is a locally segmented rectangular sliding window defined by weighting elements 1 or 0. "1" indicates pixels in a window region with similar properties to the considered pixel, "0" corresponds to the negative cases. The component-wise Mean MV provided by such SAW can be interpreted as the result of a generic version of the well-known mean shift procedure or filtering in the literature [28], [29]. Intensity-based SAW filtering has been utilized for noise or coding artifact reduction [30] in the past.

The window size, I by J, should be large enough to obtain a sufficient number of pixels representing each of the groups when the current pixel is located in a suspected halo region. Moreover, I and J should be small enough to avoid irrelevant information which can falsify the MV estimation. In our implementation, the window is asymmetric as J is equal to five lines for hardware-friendly implementation and I is equal to 11 columns so that it is bigger than the window W's length, W = 8.

Aside from the missing information on MWE, Fig. 4 also provides some indication for MV refinement detection even for the case of Fig. 4(b) in which the considered pixel is situated in the occluded group with similar intensity and similar (but false) MV. The indication can be  $N_R$ , the number of pixels that are similar in intensity and MV value to the considered central pixel. The idea is based on the following observation: if the window size is large enough, the number of occluded pixels is relatively small.

Let  $N_D$  be the number of pixels of similar intensity but different MV values to that of the central pixel. Let  $N_{\rm RD}$  be the number of pixels with similar intensities as the central pixel in the window. As a result,  $N_{\rm RD} = N_R + N_D$ .  $N_{\rm RD}$  is smaller than the window size.

Fig. 5 illustrates the Decision Map (DM) for MV correction. Depending on the current pixel position,  $N_{\rm RD}$  is a varying number whereas  $I \times J$  is a fixed window size value. In order to get a stable and coherent decision boundary, it is important to normalize the DM's horizontal and vertical axis, respectively, with the maximum numbers IJ and  $N_{\rm RD}(\boldsymbol{x})$ . As such, for a given  $N_R(\boldsymbol{x})$ , the normalized ratios for the current decision are determined by

$$a_R(\boldsymbol{x}) = \frac{N_R(\boldsymbol{x})}{(IJ)}$$
$$b_R(\boldsymbol{x}) = \frac{N_R(\boldsymbol{x})}{N_{\text{RD}}(\boldsymbol{x})}.$$
(1)



Fig. 5. Decision map (a, b):  $Z_1$  Select different MV,  $Z_2$  Keep the current MV,  $Z_3$  Select similar MV.  $a_R = N_R/(IJ)$ ,  $b_R = N_R/N_{RD}$ .

If the resulting point  $(a_R, b_R)$  falls in the zone  $Z_1$ , as illustrated, the current MV will be substituted by the mean MV of pixels with similar intensities but different MV. In the zone  $Z_3$ , in the right-hand high corner of DM, the current MV can be changed by the mean MV of pixels with similar intensities and similar MV. Otherwise, in  $Z_2$ , the current MV will be preserved. Therefore, the proposed MV correction process does not require explicit detection of C/U regions and can apply for all pixels in the to-be-interpolated image without any distinction.

Thus, as illustrated by Fig. 4(b), the MV in Group 2 will be substituted by the mean value of motion vectors of Group 3. In Fig. 4(a), the MV in the Group 1 will not be corrected.

A pseudo code is given to summarize the HMVR' mechanism as follows:

Let  $q \in$  Sliding Window of dimensions I, J centered at  $\boldsymbol{x}$ ;

Let  $V_{\boldsymbol{s}}(\boldsymbol{x}) MV$  input;  $V_{\boldsymbol{s}}(\boldsymbol{x}) = F_{\boldsymbol{s}}(\boldsymbol{x})$  or  $B_{\boldsymbol{s}}(\boldsymbol{x})$ ;

Let  $V_1(x)HMVR$  output;

Let  $I_{p,\alpha}(\boldsymbol{x})$  Preliminary MCI;

Let  $LI_{p,\alpha}(\boldsymbol{x})$  Low-pass filtered version of  $I_{p,\alpha}(\boldsymbol{x})$ 

Shape Adaptive Window Local Segmentation by suitable thresholds;

$$\omega_R(\boldsymbol{q}; \boldsymbol{x}) = 1 \text{ if } \boldsymbol{V}_{\boldsymbol{s}}(\boldsymbol{q}) \cong \boldsymbol{V}_{\boldsymbol{s}}(\boldsymbol{x}) \text{ and } LI_{p,\alpha}(\boldsymbol{q}) \cong LI_{p,\alpha}(\boldsymbol{x})$$
  
 $\omega_R(\boldsymbol{q}; \boldsymbol{x}) = 0 \text{ if else.}$ 

 $N_R(\boldsymbol{x}) = (\text{Number of } \omega_R(\boldsymbol{q}; \boldsymbol{x}) = 1)$ 

 $\omega_D(\boldsymbol{q};\boldsymbol{x}) = 1 \text{ if } \boldsymbol{V}_{\boldsymbol{s}}(\boldsymbol{q}) \neq \boldsymbol{V}_{\boldsymbol{s}}(\boldsymbol{x}) \text{ and } LI_{p,\alpha}(\boldsymbol{q}) \cong LI_{p,\alpha}(\boldsymbol{x})$  $\omega_D(\boldsymbol{q};\boldsymbol{x}) = 0 \text{ if else.}$ 

 $N_D(\boldsymbol{x}) = (\text{Number of } \omega_D(\boldsymbol{q}; \boldsymbol{x}) = 1)$ 

Number of pixels of similar intensities;  $N_{\text{RD}}(\boldsymbol{x}) = N_R(\boldsymbol{x}) + N_D(\boldsymbol{x})$ 

Normalized Ratio for decision and correction;

$$a_R(\boldsymbol{x}) = \frac{N_R(\boldsymbol{x})}{(IJ)};$$
$$b_R(\boldsymbol{x}) = \frac{N_R(\boldsymbol{x})}{N_{\rm RD}(\boldsymbol{x})}$$

Decision and Correction;

If  $(a_R, b_R) \in \mathbf{Z1}$ 

$$\boldsymbol{V_1}(\boldsymbol{x}) = SAW Mean(\boldsymbol{V_s}(\boldsymbol{q})) = \frac{\Sigma_{\boldsymbol{q}}(\boldsymbol{V_s}(\boldsymbol{q}) \cdot \omega_D(\boldsymbol{q}; \boldsymbol{x}))}{N_D(\boldsymbol{x})}$$

If 
$$(a_R, b_R) \in \mathbb{Z}3$$
  
 $V_1(\mathbf{x}) = SAW Mean (V_s(q)) = \frac{\sum_{\mathbf{q}} (V_s(\mathbf{q}) \cdot \omega_R(\mathbf{q}; \mathbf{x}))}{N_R(\mathbf{x})}$   
11) If else,  $V_1(\mathbf{x}) = V_s(\mathbf{x});$  (12)



Fig. 6. Football sequence – From left to right  $\alpha = 1, 0.8, 0.6, 0.4, 0.2, 0.$  (a) Interpolation without both MVS and HMVR (b) Interpolation with MVS and HMVR.

The proposed HMVR is applied separately to the forward and backward MV,  $F_s(x)$  and  $B_s(x)$ . Let the resulting MV be  $F_1(x)$  and  $B_1(x)$ .

Since HMVR is composed of various pixel-based hard decisions, a MV Blending and Isolated MV Filtering are proposed for smoothing decision transitions. These latter blocks are necessary to minimize the remaining artifacts left when halo is properly reduced.

MV Blending is a soft mixing between the refined MV and its corresponding selected MV input from MVS. More accurately, the forward MV  $F_1(x)$  will be combined with the selected MV  $F_s(x)$  using a pixel-based weighting factor fe(x). Let  $F_2(x)$  be the blending result output given as follows:

$$F_2(\boldsymbol{x}) = F_{\boldsymbol{s}}(\boldsymbol{x}) + [F_1(\boldsymbol{x}) - F_{\boldsymbol{s}}(\boldsymbol{x})] \cdot fe(\boldsymbol{x}). \quad (13)$$

In (13), the weighting factor  $fe(\mathbf{x})$  can be given by the following equations in which  $fc(\mathbf{x})$  is the comparator output for MWEF( $\mathbf{x}$ ) and  $lp(\mathbf{x})$  is the impulse response of the low-pass filter:

$$fe(\boldsymbol{x}) = fc(\boldsymbol{x}) * lp(\boldsymbol{x})$$

$$fc(\boldsymbol{x}) = \begin{cases} 1, & \text{if } MWEF(\boldsymbol{x}) \ge Threshold = 2\\ 0, & \text{if else} \end{cases}$$

$$lp(\boldsymbol{x}) = \frac{\begin{bmatrix} 1 & 2 & 1\\ 2 & 4 & 2\\ 1 & 2 & 1 \end{bmatrix}}{16}.$$
(14)

In a similar manner,  $B_2(x)$ , the blended version of  $B_1(x)$ , is given by

$$\boldsymbol{B}_2(\boldsymbol{x}) = \boldsymbol{B}_{\boldsymbol{s}}(\boldsymbol{x}) + [\boldsymbol{B}_1(\boldsymbol{x}) - \boldsymbol{B}_{\boldsymbol{s}}(\boldsymbol{x})] \cdot b\boldsymbol{e}(\boldsymbol{x})$$
(15)

where  $be(\boldsymbol{x})$  is a pixel-based weighting factor provided by backward estimation error of  $MWEB(\boldsymbol{x})$ 

$$be(\boldsymbol{x}) = bc(\boldsymbol{x}) * lp(\boldsymbol{x})$$
  

$$bc(\boldsymbol{x}) = \begin{cases} 1, & \text{if } MWEB(\boldsymbol{x}) \ge Threshold = 2\\ 0, & \text{if else.} \end{cases}$$
(16)

In non-occlusion regions, the MWE resulting from pixel-based bidirectional and block-based one-directional

ME is relatively small. A low value (< 2) threshold given as in (14) and (16) can justify the soft mixing decision in (13) and (15) by considering the following:

By keeping the threshold value low, the selection of the corrected MV, is overly favored. However, when used in combination with the HMVR, which is already constrained by a number of conditions and generates these corrected MV, the over-detection of MV Blending block is masked by the encapsulation of HMVR's regional properties and thus, becomes a non-issue. Of course, more elaborate decisions, for example by combining the relation F + B = 0 in non-occlusion regions, could be possible. However, the problem of isolated MV remains. Often, a case identified as Isolated MV and not properly addressed will create isolated and rather distracting *spikes* of pixel intensities.

The present Isolated MV Filtering is an adaptive median filter: If the blended MV  $F_2(\mathbf{x})$  is isolated relatively to the  $3 \times 3$  neighboring MV  $F_2(\mathbf{q})$ , then the filter output  $F_o(\mathbf{x})$  is given by the 9-points median forward MV  $F_2(\mathbf{q})$ . Precisely, the component-wise MV filtering can be described as follows.

Let  $F_{2c}(\mathbf{q})$  and  $F_{2r}(\mathbf{q})$  be the horizontal and vertical components of  $F_2(\mathbf{q})$  in the window. The horizontal and vertical components of  $F_0(\mathbf{x})$  filtered output MV are determined as

$$N_{c}(\boldsymbol{x}) = Number \boldsymbol{F}(\boldsymbol{q}) : |F_{2c}(\boldsymbol{q}) - F_{2c}(\boldsymbol{x})| < Th = 3$$

$$F_{oc}(\boldsymbol{x}) = \begin{cases} Median(F_{2c}(\boldsymbol{q})), & \text{if } N_{c}(\boldsymbol{x}) \leq NTh = 3 \\ F_{2c}(\boldsymbol{x}), & \text{else} \end{cases}$$

$$N_{r}(\boldsymbol{x}) = Number \boldsymbol{F}(\boldsymbol{q}) : |F_{2r}(\boldsymbol{q}) - F_{2r}(\boldsymbol{x})| < Th = 3$$

$$F_{or}(\boldsymbol{x}) = \begin{cases} Median(F_{2r}(\boldsymbol{q}) & \text{if } N_{r}(\boldsymbol{x}) \leq NTh = 3 \\ F_{2r}(\boldsymbol{x}), & \text{else} \end{cases}$$
(17)

Similar filtering is also applied for providing backward MV  $B_{o}(x)$ .

The resulting forward and backward  $F_{o}(x)$  and  $B_{o}(x)$  are now utilized for MCI.

# C. MCI

If the first proposed MCI is only approximated for analysis, the second MCI shall be more elaborate to further reduce artifacts. A possibility is to imply the  $\alpha$  position. If the interpolated image is near from the existing image  $I_n$ , it will be reasonable to use only  $I_n$ . Inversely, at the other end, it will be  $I_{n-1}$ . This



Fig. 7. Comparison of PSNR performance (a) *Bus*, (b) *Foreman*, (c) *Cheerleaders*, (d) *Calendar Mobile*.

TABLE I PSNR Performance Comparisons Among Four Frame Interpolation Methods for Six Video Sequences

|               | Proposed<br>Method | Without<br>HMVR | [31]  | BDME  |
|---------------|--------------------|-----------------|-------|-------|
| Bus           | 32.00              | 31.36           | 31.57 | 27.44 |
| Foreman       | 38.51              | 38.24           | 37.75 | 35.00 |
| Flower Garden | 33.29              | 33.20           | 32.24 | 30.81 |
| Mobile        | 32.93              | 32.75           | 31.67 | 26.09 |
| Ferris wheel  | 41.23              | 40.71           | 37.45 | 40.05 |
| Cheerleaders  | 29.82              | 29.06           | 29.37 | 27.71 |



Fig. 8. Cropped images—*Foreman* sequence—frame 57. (a) Original, (b) [31], SSIM = 0.93, (c) without both MVS and HMVR, SSIM = 0.91, (d) Proposed method, SSIM = 0.98.

consideration will be useful, as an example, for a 5-times conversion from 24 to 120 Hz. The following interpolation is proposed for MC interpolated image  $I_{n-\alpha}(\boldsymbol{x})$ 

If 
$$1 > \alpha \ge \alpha_{\rm H}$$
,  
 $I_{\rm n-\alpha}(\boldsymbol{x}) = (1 - \gamma) \cdot I_{\rm n-1}(\boldsymbol{x} - (1 - \alpha)) \cdot \boldsymbol{F}_{\boldsymbol{0}}(\boldsymbol{x}))$   
 $+ \gamma \cdot I_{\rm n-1}(\boldsymbol{x} + (1 - \alpha)) \cdot \boldsymbol{B}_{\boldsymbol{0}}(\boldsymbol{x}))$  (18)  
If  $\alpha_{\rm L} \ge \alpha > 0$ ,

$$I_{n-\alpha}(\boldsymbol{x}) = (1-\gamma) \cdot I_n(\boldsymbol{x} + \alpha \cdot \boldsymbol{F}_{\boldsymbol{O}}(\boldsymbol{x})) + \gamma \cdot I_n(\boldsymbol{x} - \alpha \cdot \boldsymbol{B}_{\boldsymbol{O}}(\boldsymbol{x}))$$
(19)

If 
$$\alpha_{\rm H} > \alpha > \alpha_{\rm L}$$
,  
 $I_{\rm n-\alpha}(\boldsymbol{x}) = (1 - \gamma) \cdot I_{\rm n}(\boldsymbol{x} + \alpha \cdot \boldsymbol{F}_{\boldsymbol{O}}(\boldsymbol{x}))$   
 $+ \gamma \cdot I_{\rm n-1}(\boldsymbol{x} + (1 - \alpha) \cdot \boldsymbol{B}_{\boldsymbol{O}}(\boldsymbol{x}))$ . (20)

In (18)–(20), the local statistic context-based weighting factor  $\gamma$ , function of both  $\alpha$  and  $\boldsymbol{x}$ , is defined as in (10). The  $\boldsymbol{F}_{o}(\boldsymbol{x})$  and  $\boldsymbol{B}_{o}(\boldsymbol{x})$  are also function of  $\alpha$  as described in the HMVR subsection. For  $\alpha = 1/2$ , (9) and (20) are identical. Finally,  $\alpha_{\rm H}$  and  $\alpha_{\rm L}$  are fixed values and  $\alpha_{\rm H} + \alpha_{\rm L} = 1$ .

The proposed MCI thus provides sharp interpolated images and yields a smoothed temporal transition between an existing image and its neighboring interpolated images.

Fig. 6 illustrates at the same time the proposed MVS, HMVR and MCI techniques. It represents a 5-times interpolation between two existing images, frame 93 and 94, i.e.,  $\alpha = 1, 0.8, 0.6, 0.4, 0.2$ , and 0. The first and second rows represent the results without and with MVS and HMVR, respectively. Results from the latter are noticeably sharper.

## **III. EXPERIMENTAL RESULTS**

In this section, various video sequences have been tested to evaluate the performance of the proposed method. To compare





Fig. 9. Bus sequence. (a) Original frame 33. (b) [31]. (c) Without both MVS and HMVR. (d) Bi-directional (BDME). (e) Proposed method.

the performance, every frame from the test sequences is skipped and re-interpolated with two original adjacent frames by the traditional bidirectional method (BDME), the proposed model without halo correction, the whole proposed model as well as the pixel-based FRC model as in [31]. The interpolated frames are then compared with the corresponding original skipped frames.

The traditional bidirectional (BDME) method is implemented with a  $16 \times 16$  block size, which gives better PSNR performance than  $8 \times 8$  block size in our implementation. The pixelbased FRC interpolation related to [31] is performed with "High Quality" option.

# A. Objective Evaluation

The objective evaluation is based on PSNR defined as

$$PSNR = 10\log_{10} \left( \frac{255^2}{\frac{1}{\text{ColorImageSize}} \sum_{\boldsymbol{x}} \left( I_n(\boldsymbol{x}) - \hat{I}_n(\boldsymbol{x}) \right)^2} \right)$$
(21)

in which  $I_n(\mathbf{x})$  and  $\hat{I}_n(\mathbf{x})$  are, respectively, the original and the interpolated color images.

Fig. 7 illustrates the frame-by-frame PSNR evolution of the four methods respectively for *Bus, Foreman, Cheerleaders*, and *Calendar Mobile* sequences. It can be seen that the proposed method yields a superior performance consistency throughout. Table I represents a PSNR comparison for six video sequences. The proposed method outperforms the other considered existing methods. Moreover, the proposed algorithm is based on feed-forward technique suitable for pipelined implementation and aimed for real-time processing using contemporary IC technology.

#### B. Subjective Evaluation

Since PSNR represents an average or a global fidelity measure between the interpolated image and the original one for the whole image, it cannot accurately represent the image quality perceived by the human visual system. Subjective image quality is also important to evaluate in any application that targets a real implementation.

Figs. 8 and 9 show the original images *Foreman* and *Bus* together with the interpolated results of the considered methods. Fig. 8 represents cropped images in a window and their associated SSIM values [24]. For the image *Bus* in Fig. 9 halo artifacts and/or deformed structures can be observed in the resulting images from existing methods. More interpolated results can be viewed at http://www.gel.usherbrooke.ca/tran/

The interpolated frame yielded by the proposed model exhibits the best subjective visual quality.

#### **IV. CONCLUSION**

In this paper, we propose a new FRC method based on MV Selection, Halo consideration, and MV Refinement. Combined with the classical BMA, MV Selection is an effective way to get dense MV field in an interpolated plan without holes or overlapped areas. For Halo reduction, a three-group model in a sliding window is introduced. Shape Adaptive Window defined at the same time by MV and preliminary interpolated intensity yields a possibility for false MV correction without explicit occlusion detection. MCI for many times interpolation is extended using interpolated plane position information and local statistic context-based weighting factor,  $(\gamma)$ .

An immediate extension of the work can be foreseen by combining it with a hierarchical approach for HD or higher resolution.

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