

Motion Estimation on Interlaced Video

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ABSTRACT

Motion compensated de-interlacing and motion estimation based on Yen's generalisation¹ of the sampling theorem (GST) have been proposed by Delogne² and Vandendorpe.³ Motion estimation methods using three-fields have been designed on a block-by-block basis, minimising the difference between two GST predictions. We will show that this criterion degenerates into a two-fields criterion, leading to erroneous motion vectors, when the vertical displacement per field period is an even number of pixels. We provide a solution for this problem, by adding a term to the matching criterion.

Keywords: Motion estimation, motion compensation, de-interlacing.

1. INTRODUCTION

With recent display technologies like LCD and PDP, conversion from interlaced to progressive video formats is necessary. The best solution to obtain progressive video from an interlaced input is to apply a motion compensated de-interlacing algorithm.⁴ One can use an interpolator filter to generate the missing lines. For the motion compensated de-interlacing, in addition to the interpolation filter, a motion estimation criterion, which provides correct motion vectors has to be adopted.

In this paper, we address the problem of correct motion estimation on interlaced material. Based on the Generalised Sampling Theorem (GST), a motion estimation criterion was proposed by Vandendorpe *et al.*,³ using three video input fields. This motion estimator minimises the difference between a GST prediction, using samples from the previous and pre-previous fields, and an existing pixel in the current field. This minimisation is performed on a block-by-block basis. Another possibility that we shall introduce in this paper is to design a motion estimator that minimises the difference between two GST predictions, each of these predictions being calculated using one set of samples from the current field and a second set of samples from the previous or the next field. Both criteria are based on the assumption that the motion is uniform over two field periods. The advantage of our proposal is that the GST predictions use symmetrically located pixels with respect to the current field.

When the motion vector candidates correspond to an even number of pixels displacement in the vertical direction between two successive fields, the GST filter output is a single shifted pixel and is no longer an interpolation. As a consequence, all three-field GST based motion estimation criteria degenerate into two-field criteria. In Section 2 we will show how this degeneration occurs and that it can lead to erroneous motion vectors.

The solutions proposed in this paper consist in adding a term in the motion estimation criterion, which prevents that the three-field criterion degenerates.

Since our motion estimation criterion is based on the GST-interpolation filter, we will first briefly summarise the generalised sampling theorem. In Section 2, we will describe the motion estimation criteria based on the GST filter and we will illustrate the problem that occurs for specific displacements. Some possible solutions using four fields are also presented. The extension of this criterion, which provides a solution to improve the GST motion estimation, will be presented in Section 3.2. We conclude with an evaluation.

1.1. The GST-interpolation filter

According to the sampling theorem, a bandwidth-limited signal with a maximum frequency of $0.5f_s$ can exactly be reconstructed after sampling at a frequency higher than f_s (Nyquist criterion). In 1956, Yen¹ showed a

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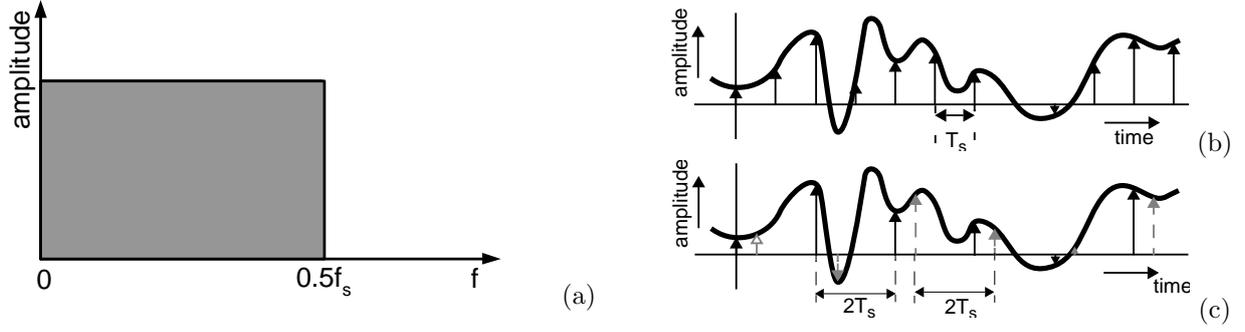


Figure 1. Generalisation of the sampling theorem; a) the signal is bandwidth limited to $0.5f_s$, b) sampling according to the standard sampling theory, c) sampling according to Yen's generalisation of the sampling theory ($T_s = \frac{1}{f_s}$).

generalization, proving that a signal with a bandwidth of $0.5f_s$ can be reconstructed from N independent sets of samples, all obtained by sampling the signal at f_s/N . An illustration of the standard sampling theorem and of Yen's generalization for $N = 2$ is shown in Figure 1.

Yen's generalisation of the sampling theorem has been proposed as the solution for de-interlacing by Delogne² and Vandendorpe.³ A field of interlaced video can be regarded as an image, which is sampled at the frequency $0.5f_s$.

As shown in Figure 2 for this case, the first of the two required independent sets of samples is created by shifting the samples from the previous field over the motion vector towards the current temporal instance. The second set of samples contains all pixels of the current field. The two sets are assumed to be independent, which is true unless a so-called "critical velocity" occurs, i.e. a velocity leading to an odd integer pixel displacement per field period. In case the assumption is valid, Yen's generalization of the sampling theorem can be applied to interpolate a pixel in the current field. The output sample results, according to the theory, as a weighted sum of samples from the two sets of samples. We shall refer to this weighted sum as the "GST interpolation" filter.

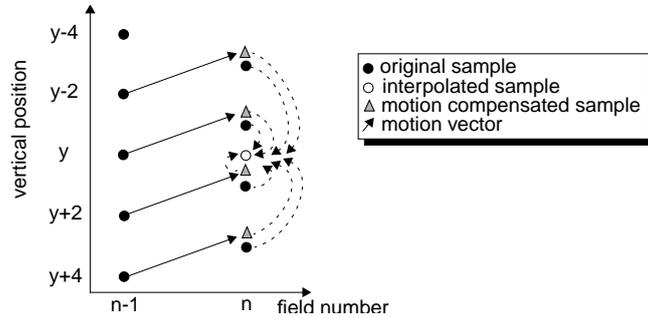


Figure 2. The GST interpolation filter, using samples from the current field and samples from the previous field shifted along the displacement vectors.

Using $F(\vec{x}, n)$ for the luminance value of the pixel at position $\vec{x} \equiv \begin{pmatrix} x \\ y \end{pmatrix}$ in image number n , and F_i for the interpolated pixels at the missing line, we can define the output of the GST de-interlacing method as:

$$F_i^{n,n-1}(\vec{x}, n) = \sum_k F(\vec{x} - (2k+1)\vec{u}_y, n)h_1(k, \delta_y) + \sum_m F(\vec{x} - \vec{d}(\vec{x}, n) - 2m\vec{u}_y, n-1)h_2(m, \delta_y),$$

$$k, m = \{\dots -1, 0, 1, 2, 3, \dots\} \quad (1)$$

with h_1 and h_2 defining the GST filter, $\vec{u}_y \equiv \begin{pmatrix} 0 \\ 1 \end{pmatrix}$, and the modified motion vector $\vec{d}(\vec{x}, n) = (d_x(\vec{x}, n), d_y(\vec{x}, n))^T$ is defined as:

$$\vec{d}(\vec{x}, n) = \begin{pmatrix} d_x(\vec{x}, n) \\ 2 \left[\frac{d_y(\vec{x}, n)}{2} \right] \end{pmatrix} \quad (2)$$

Here d_x, d_y are the displacements (motion vectors) in the x and y directions, respectively. The operator $[\cdot]$ is rounding to the nearest integer value, and δ_y the vertical motion *fraction* is defined by:

$$\delta_y(\vec{x}, n) = \left| d_y(\vec{x}, n) - 2 \left[\frac{d_y(\vec{x}, n)}{2} \right] \right| \quad (3)$$

Similarly, one can define the horizontal motion *fraction*,

$$\delta_x(\vec{x}, n) = \left| d_x(\vec{x}, n) - 2 \left[\frac{d_x(\vec{x}, n)}{2} \right] \right| \quad (4)$$

In line with the literature,⁴⁻⁸ in Equation (1) we assumed separate horizontal and vertical interpolators and focus on the interpolation in the y -direction. Nevertheless for video applications a non-separable GST filter, composed of h_1 and h_2 , depending on both the vertical motion *fraction* $\delta_y(\vec{x}, n)$ and on the horizontal motion *fraction* $\delta_x(\vec{x}, n)$ is more adequate.⁹ Note, that in the above equations, motion is taken into account through the linear GST filters h_1 and h_2 .

Assume that the current field contains the odd scanning lines only. Then, the corresponding $F^e(\vec{x}, n)$ is defined by

$$F^e(\vec{x}, n) = \sum_k F(\vec{x} - (2k+1)\vec{u}_y, n)h_1(k, \delta_y) + \sum_m F(\vec{x} - \vec{d}(\vec{x}, n) - 2m\vec{u}_y, n-1)h_2(m, \delta_y), \quad k, m = \{\dots -1, 0, 1, 2, 3, \dots\} \quad (5)$$

In the separable case, Equation (5) then simplifies to:

$$F^e(y, n) = \sum_k F(y - (2k+1), n)h_1(k, \delta_y) + \sum_m F(y - d_y - 2m, n-1)h_2(m, \delta_y). \quad (6)$$

If a progressive previous image F^p would be available, F^e could be determined as a linear combination of samples from the previous image:

$$F^e(y, n) = \sum_q F^p(y - q, n-1)h(q) \quad (7)$$

Since it is convenient to derive the filter coefficients in the z -domain, Equation (7) is transformed into:

$$F^e(z, n) = (F^p(z, n-1)H(z))_e = F^o(z, n-1)H^o(z) + F^e(z, n-1)H^e(z) \quad (8)$$

where $(X)_e$ is the even field of X *. Similarly:

$$F^o(z, n) = (F^p(z, n-1)H(z))_o = F^o(z, n-1)H^e(z) + F^e(z, n-1)H^o(z) \quad (9)$$

which can be rewritten as:

$$F^o(z, n-1) = \frac{F^o(z, n) - F^e(z, n-1)H^o(z)}{H^e(z)} \quad (10)$$

*Note that the coefficients $H^o(z)$ and $H^e(z)$ are the weighting factors corresponding to the odd and the even contributions to the even lines $F^e(z, n)$ in Eq. (8). Nevertheless, one should not interpret them as the *odd* or *even* coefficients, as this interpretation would not hold for the odd lines $F^o(z, n)$ in Eq. (10).

Substituting Equation (10) into (8) results in:

$$F^e(z, n) = H_1(z)F^o(z, n) + H_2(z)F^e(z, n - 1) \quad (11)$$

with

$$\begin{aligned} H_1(z) &= \frac{H^o(z)}{H^e(z)} \\ H_2(z) &= H^e(z) - \frac{(H^o(z))^2}{H^e(z)} \end{aligned} \quad (12)$$

The GST filter coefficients are solely determined by the interpolator $H(z)$. Vandendorpe *et al.*³ apply the sinc-waveform interpolator for deriving the GST filter coefficients:

$$\begin{aligned} h_1(k) &= (-1)^k \frac{\text{sinc}(\pi(k - \frac{1}{2})) \frac{\sin(\pi\delta_y)}{\cos(\pi\delta_y)}}{\cos(\pi\delta_y)} \\ h_2(k) &= (-1)^k \frac{\text{sinc}(\pi(k + \delta_y))}{\cos(\pi\delta_y)} \end{aligned} \quad (13)$$

2. MOTION ESTIMATION ON INTERLACED VIDEO APPLYING THE GENERALISED SAMPLING THEOREM

Vandendorpe *et al.*³ proposed a solution for motion estimation on interlaced video, using the generalised sampling theorem. This solution, which is illustrated in Figure 3a, is based on the assumption that the motion between two successive fields is uniform. Further, the motion estimation procedure will provide the value for the motion vector which minimises the difference between the known luminance samples of the current field n and the estimated luminance calculated using the GST interpolation filter from the samples from fields $n - 2$ and $n - 1$.

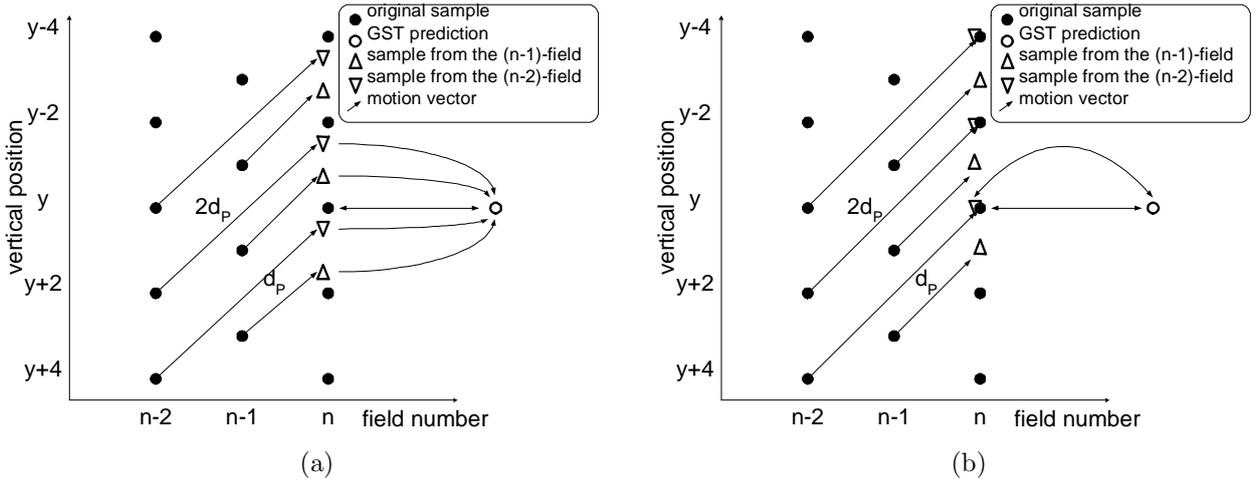


Figure 3. Motion estimation method proposed by Vandendorpe *et al.*³ for an arbitrary displacement per picture (a) and when the candidate vector $\vec{d}_{pre-P} = 2\vec{d}_P$ corresponds to an even number of pixels displacement per picture in the vertical direction (b).

The method introduced by Vandendorpe *et al.* uses samples from the pre-previous field $n - 2$. The correlation between this field and the current field is lower than between two successive fields, because of the larger temporal distance between the samples.

Therefore, we proposed a motion estimation method that uses samples situated at an equal distance from the current field, i.e. samples from the previous and the next field.⁹ Our motion estimation criterion utilizes the freedom to combine pixels from the previous, or from the next, field with the current pixels in the GST-interpolator, when interpolating a pixel in the current field.

Thus, Equation (1) can be applied to calculate the missing pixels at position (\vec{x}, n) according to:

$$F_i^{n,n+1}(\vec{x}, n) = \sum_k F(\vec{x} - (2k+1)\vec{u}_y, n)h_1(k, \delta_y) + \sum_m F(\vec{x} - \vec{d}(\vec{x}, n) - 2m\vec{u}_y, n+1)h_2(m, \delta_y),$$

$$k, m = \{\dots -1, 0, 1, 2, 3, \dots\} \quad (14)$$

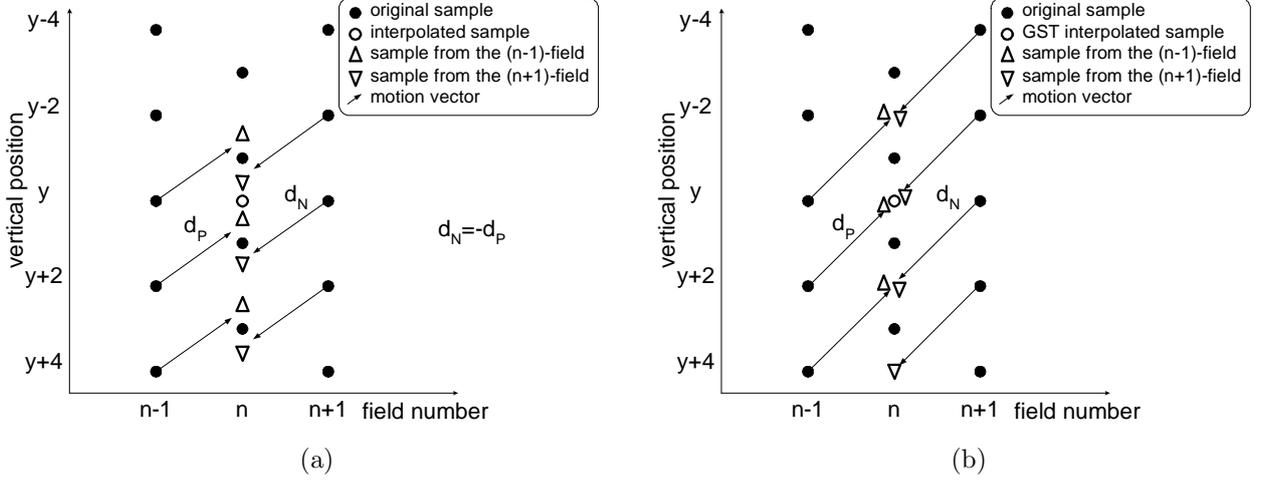


Figure 4. Motion estimation criterion (15) applied on a candidate vector $\vec{d}_P = -\vec{d}_N$ for an arbitrary vertical displacement (a), and when the candidate vector corresponds to an even number of pixels displacement per picture in the vertical direction (b).

Assuming that the motion vector is linear over two field periods, we can calculate the motion vector using the optimisation criterion

$$\vec{d}_P = \arg \min_{\vec{d}_P} |F_{\vec{d}_P}^{n,n-1}(\vec{x}, n) - F_{\vec{d}_N}^{n,n+1}(\vec{x}, n)|_{\vec{d}_N = -\vec{d}_P} \quad (15)$$

for all \vec{x} belonging to a 8×8 block of pixels and \vec{d}_P being the motion vector with respect to the previous field, while \vec{d}_N the motion vector with respect to the next field. We illustrate this criterion in Figure 4a.

Equation (13) suggests that for motion vectors corresponding to an even number of pixels displacement between two fields, i.e. for $\delta_y = 0$, Equations (1) and (14) reduce to

$$F_{\vec{d}_P}^{n,n-1}(\vec{x}, n) = F(\vec{x} + \vec{d}_P, n-1), \quad (16)$$

and

$$F_{\vec{d}_N}^{n,n+1}(\vec{x}, n) = F(\vec{x} + \vec{d}_N, n+1). \quad (17)$$

Therefore, the minimization criterion (15) takes into account only shifted pixels from the previous, $(n-1)$, and the shifted pixels from the next, $(n+1)$ -field, resulting in a two field motion estimator. As a consequence, in the minimisation criterion we compare only the *motion compensated* pixels from the neighbouring fields, without involving pixels from the current field n at all, as we can see in Figure 4b. Later in this section, we shall show that the absolute difference given in Equation (15) can result in a local minimum for thin moving objects, which does not correspond to the real motion vector.

This situation also occurs in the original, three-fields solution of Vandendorpe *et al.*,³ in which the fields $n-2$ and $n-1$ are shifted towards the field n . Indeed, also when the GST prediction $F_{\vec{d}, 2\vec{d}}^{n-1, n-2}(x, y \pm 1, n)$ from

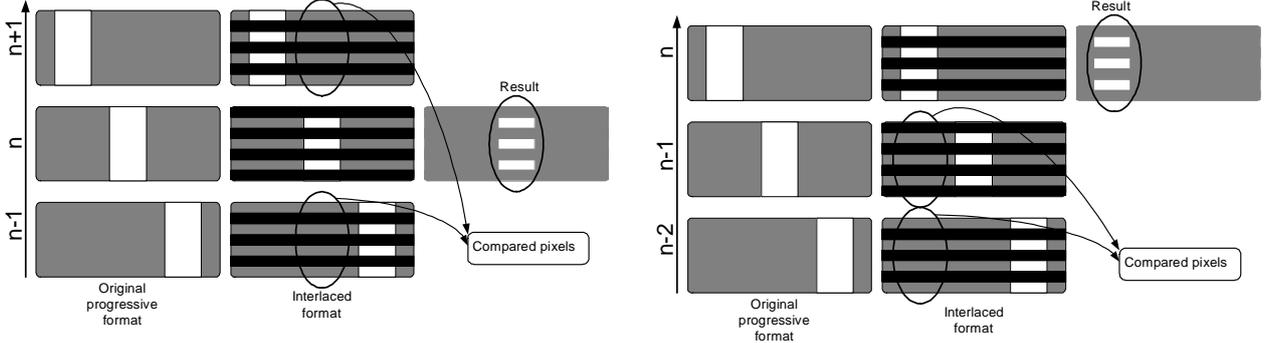


Figure 5. Erroneous motion estimation based on (a) the criterion (15) and (b) the solution proposed by Vandendorpe *et al.*³

the previous ($n - 1$ -field) and the pre-previous ($n - 2$ -field) shifted along the displacements vectors \vec{d} and $2\vec{d}$, respectively, are used in the criterion, the three-fields motion estimation degenerates into a two-fields one for even motion vectors, as depicted in Figure 3b.

In this case, the prediction from the fields $n - 1$ and $n - 2$ corresponds to a shifted pixel from the pre-previous field,

$$F_{\vec{d}, 2\vec{d}}^{n-1, n-2}(x, y \pm 1, n) = F(\vec{x} + 2\vec{d}, n - 2), \quad (18)$$

and consequently, the motion estimation will minimise the criterion

$$\vec{d} = \arg \min_{\vec{d}} |F_{\vec{d}, 2\vec{d}}^{n-1, n-2}(x, y \pm 1, n) - F(x, y \pm 1, n)| = \arg \min_{\vec{d}} |F(\vec{x} + 2\vec{d}, n - 2) - F(x, y \pm 1, n)|. \quad (19)$$

Basically, in Equation (18) the GST output $F_{\vec{d}, 2\vec{d}}^{n-1, n-2}(x, y \pm 1, n)$, using samples from the previous and the pre-previous fields, only the samples from the pre-previous field have a contribution, and therefore the three-fields criterion degenerates into a two-fields one.

The erroneous motion vectors result in de-interlacing artifacts, which particularly occur in the case of small, relatively fast moving objects. The effect is illustrated in Figure 5a, for the GST motion estimator using the previous and the next field, and in Figure 5b, for the GST motion estimator according to Vandendorpe *et al.*³

As an example, we display the field of the motion vectors, for a snapshot of the sequence *Bicycle* (see Figure 12), containing small, relatively fast moving objects (bicycle spokes). Figure 6a represents the estimated motion vectors using the criterion (15), while in Figure 6b we display the corresponding results using Vandendorpe's three-fields method.

In both cases, the black background areas behind the spoke, visible in both neighbouring fields match perfectly, which leads to incorrect motion vectors for the spoke itself. The GST de-interlacing results obtained with these vectors are displayed in Figures 6c and 6d for each method. Apparently, the vector field causes discontinuities in the spokes of the bicycle wheel.

As an alternative to Vandendorpe's solution, Delogne *et al.*² proposed a method using four successive fields instead of three, as illustrated in Figure 7a, that is not subject to degeneracy in case of even vertical displacements:

$$\vec{d} = \arg \min_{\vec{d}} (|F_{\vec{d}, 2\vec{d}}^{n-1, n-2}(x, y \pm 1, n) - F(x, y \pm 1, n)| + |F_{\vec{d}, 2\vec{d}}^{n-2, n-3}(\vec{x} + \vec{d}, n - 1) - F(\vec{x} + \vec{d}, n - 1)|). \quad (20)$$

Although the samples from the field $n - 1$ are now taken into account, this criterion has the drawback that it is based on the assumption of linear motion over a three field periods. [†] Nevertheless, this four-fields method

[†]The displacement between two of the four fields used in Delogne's criterion (20) can be expressed as a multiple of the displacement vector \vec{d} only if the motion is assumed to be uniform over a three field periods.

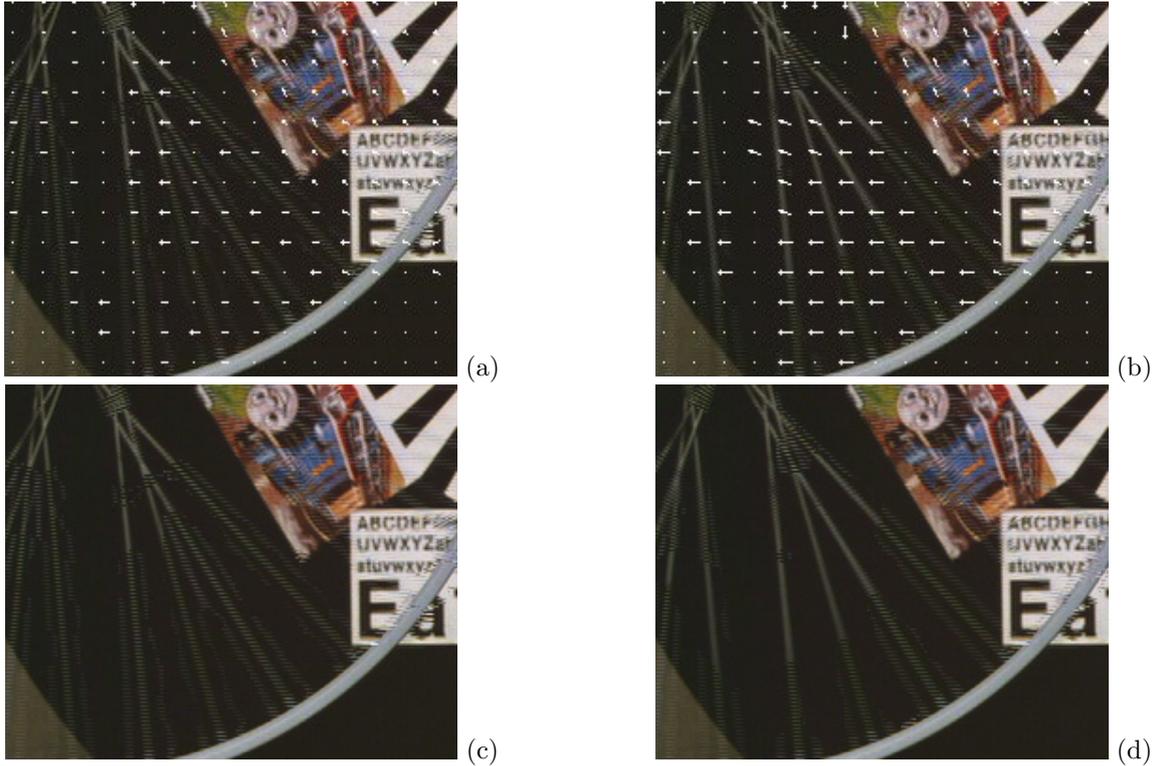


Figure 6. Motion vectors, calculated using the criterion (15) (a) and Vandendorpe's criterion (b), and the corresponding resulting GST interpolation (c) and (d).

leads to an improved consistency of the vector field and to reduced de-interlacing artifacts along the bicycle spokes. The results are displayed in Figure 8.

3. IMPROVED CRITERIA

In this subsection, we present two alternatives to Delogne's four-field method.

3.1. Four-fields recursive criterion

Our first proposal is using a four field motion minimisation criterion and exploits the fact that the previous $n - 1$ -field has been de-interlaced. Consequently, we can perform motion compensation to predict *existing samples* in the current field. Adding this prediction error to the match criterion forces the estimator to use the pixels belonging to the spoke of our problem sequence, as we illustrate in Figure 9a. The output $G_{\vec{d}_P}^{n,n-1}(\vec{x}, n)$ of the bilinear interpolator is given by

$$\begin{aligned}
 G_{\vec{d}_P}^{n,n-1}(\vec{x}, n) = & (1 - \delta_y)(1 - \delta_x)F(\vec{x} + \vec{d}_P, n - 1) + (1 - \delta_y)\delta_x F\left(\vec{x} + \vec{d}_P + \begin{pmatrix} \text{sign}(d_P^x) \\ 0 \end{pmatrix}, n - 1\right) \\
 & + \delta_y(1 - \delta_x)F\left(\vec{x} + \vec{d}_P + \begin{pmatrix} 0 \\ \text{sign}(d_P^y) \end{pmatrix}, n - 1\right) + \delta_y\delta_x F\left(\vec{x} + \vec{d}_P + \begin{pmatrix} \text{sign}(d_P^x) \\ \text{sign}(d_P^y) \end{pmatrix}, n - 1\right).
 \end{aligned} \tag{21}$$

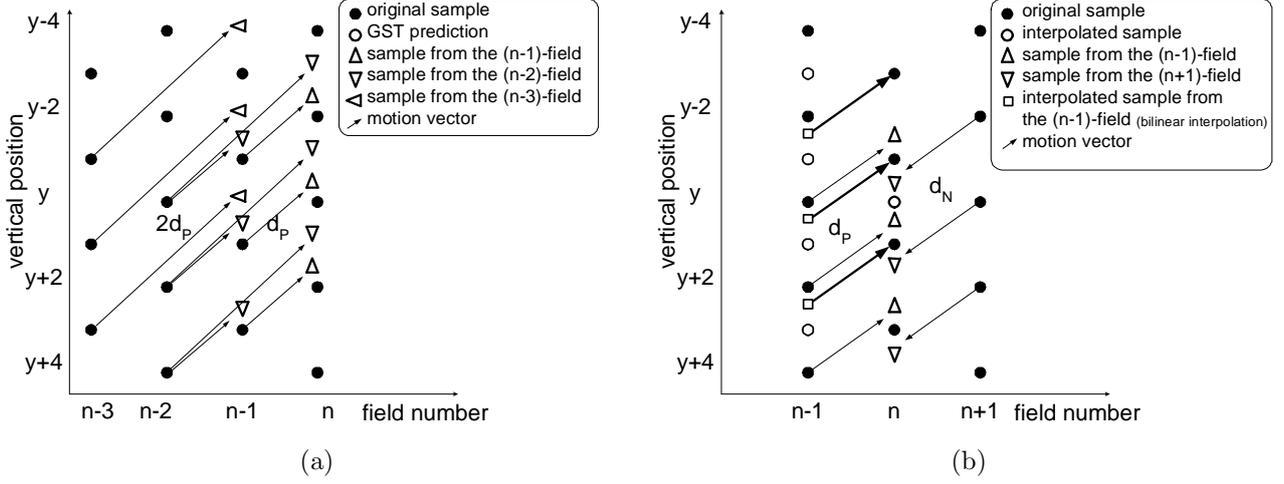


Figure 7. Four-fields motion estimation criterion² (a) and the modified motion estimation criterion (22), using four fields (one previous frame and one current and next fields) (b).

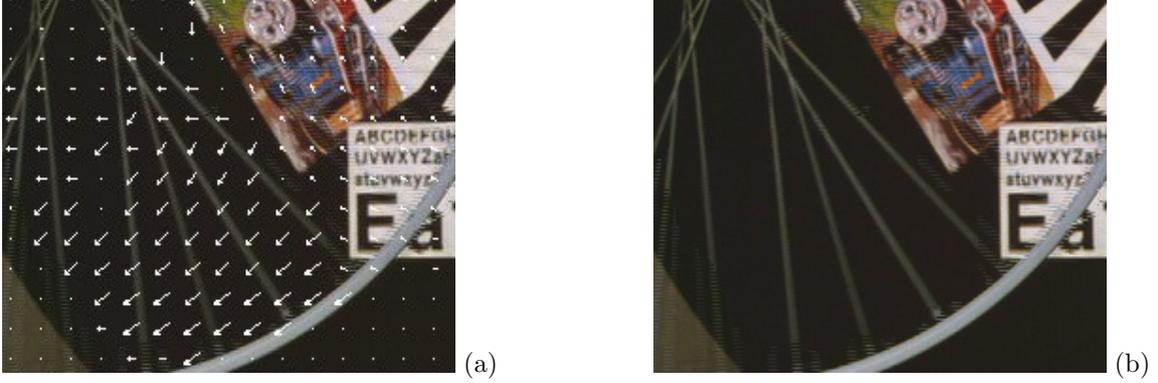


Figure 8. Motion vectors, calculated using the four-fields Delogne's motion estimation criterion (a) and the corresponding resulting GST interpolation (b).

We illustrate this improved motion estimation criterion in Figure 7b. In this proposal, we replace the initial motion estimation criterion (15) with

$$\vec{d}_P = \arg \min_{\vec{d}_P} (|F_{\vec{d}_N}^{n,n+1}(\vec{x}, n) - F_{\vec{d}_P}^{n,n-1}(\vec{x}, n)|_{\vec{d}_N = -\vec{d}_P} + |G_{\vec{d}_P}^{n,n-1} \left(\begin{pmatrix} x \\ y+1 \end{pmatrix}, n \right) - F \left(\begin{pmatrix} x \\ y+1 \end{pmatrix}, n \right)|). \quad (22)$$

The vector field is now following the true motion of the spokes of the bicycle wheel, since now also for even vector displacements the samples existing in the current field occur in the modified criterion (22). This is achieved without requiring uniform motion over more than two field periods. The result of the motion estimation and of the GST de-interlacing is shown in Figure 10.

Even though the results obtained with criterion (22) are satisfactory, and the assumption of linear motion over a two field periods remains valid, the use of an additional field memory is a drawback. In the next section, therefore, we introduce a solution to the even-vectors problem, which is more attractive from a practical point of view, as it only requires two field memories.

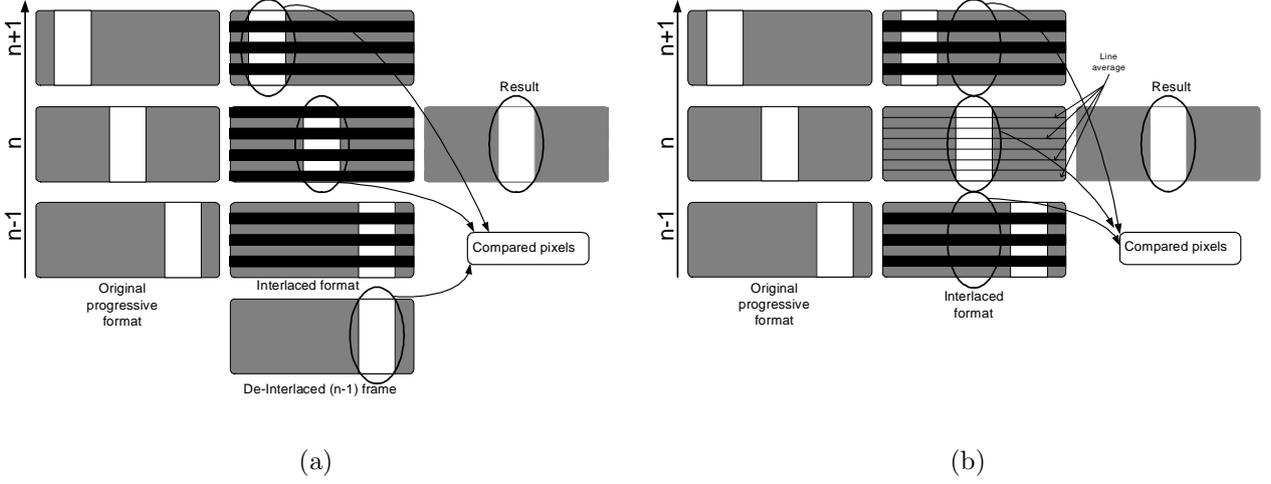


Figure 9. Motion estimation based on the modified criterion (22). (a) and improved motion estimation criterion with an additional term, which compares the GST predictions with the line average in the middle (current) field (b).

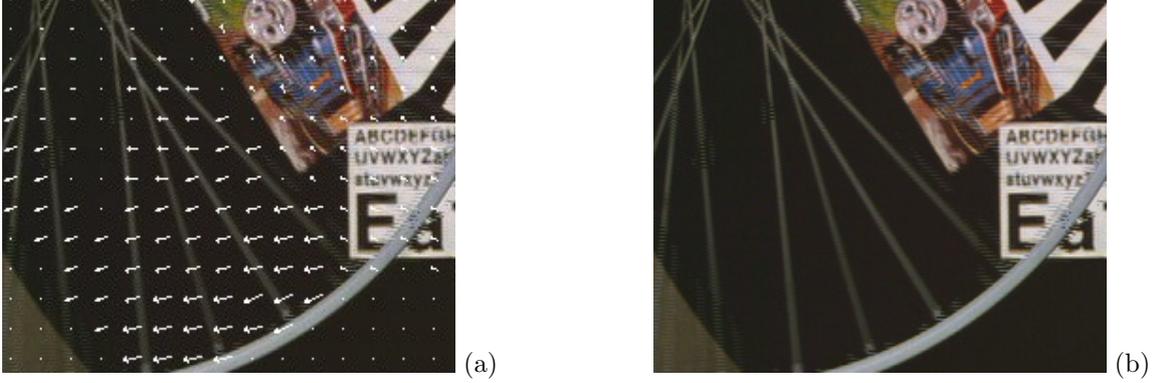


Figure 10. Motion vectors, calculated using the four-fields motion estimation criterion (22) (a) and the corresponding resulting GST interpolation (b).

3.2. Low-cost alternative

In order to prevent the effect described in the previous section at even vertical displacements, we impose an additional constraint on the GST-interpolated pixels, which involves the pixels from the current (middle, or extreme) field as well. To this end, we not only compare motion compensated pixels in order to obtain the correct motion vector, but each GST prediction from the next and previous fields will additionally be compared with the result of a line average in the current field.

Consequently, we replace the initial motion estimation criterion (15) with

$$\begin{aligned} \vec{d}_P = \arg \min_{\vec{d}_P} (&|F_{\vec{d}_N}^{n,n+1}(\vec{x}, n) - F_{\vec{d}_P}^{n,n-1}(\vec{x}, n)| + |F_{\vec{d}_N}^{n,n+1}(\vec{x}, n) - LA(\vec{x}, n)| \\ &+ |F_{\vec{d}_P}^{n,n-1}(\vec{x}, n) - LA(\vec{x}, n)|) |_{\vec{d}_N = -\vec{d}_P}, \end{aligned} \quad (23)$$

where $LA(\vec{x}, n)$ is the intra-field interpolated pixel at the position \vec{x} in the current field, using a simple line average (LA), as shown in Figure 9b.

Table 1. Mean Square Error evaluation of the GST de-interlacer for various motion estimators.

Sequence	Three fields (Vanderdorpe)	Three fields (Symmetrical)	Four Fields (Delogne)	Four Fields (Proposed complex)	Three Fields (Proposed simple)
Bicycle	64.46/38.96	61.86/41.03	46.07/32.07	46.95/32.84	41.39/30.72
Girl-Squares	67.53/11.97	50.05/18.44	39.98/13.77	33.93/12.47	30.26/11.77
Siena	2.96/ 6.96	2.71/6.89	2.70/6.36	2.76/6.91	2.89/7.37
Kiel	76.48/82.66	67.07/76.66	64.24/74.90	64.51/75.44	72.40/83.91

The additional terms in the criterion (23), which include the line averaging in the current field, is meant to increase the robustness against errors of the motion vectors, as it prevents matching black to black from both sides of the spoke in the previously given example. The line average term ensures that now black is also matched to the spoke for the incorrect motion vector. As a consequence, even though the interpolation filter is the same

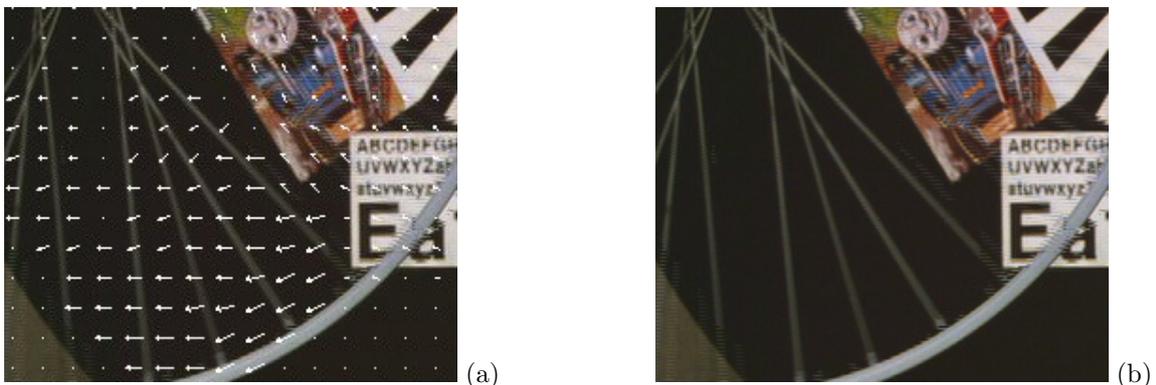


Figure 11. Motion estimation based on the criterion (23) (a) and the corresponding result of the GST de-interlacing (b).

as in the previous section, the discontinuities in the spoke are eliminated because of the use of the correct motion vectors. This is further illustrated by comparing the result in Figure 5 with the corrected one in Figure 9b and, equivalently, the de-interlacing result in Figure 6c and d with the proposed three-field method result in Figure 11b.

4. RESULTS AND CONCLUSION

In this section, we present an evaluation of the quality of the motion estimators discussed in the previous sections. To that end, we calculate the Mean Square Error (MSE) of a set of motion compensated GST de-interlaced sequences with respect to the original progressive sequences. The content of these video sequences, of which a snapshot is given in Figure 12, includes sequences with local and irregular motion (*Bicycle*, *Girl-Squares*) and sequences with globally moving fine vertical detail (*Siena* and *Kiel*).

For each sequence and each motion estimation method, the pair MSE_1/MSE_2 in Table 1 indicates the MSE evaluation corresponding to two de-interlacing methods. The first number MSE_1 represents the MSE by simply applying the GST interpolation filter for de-interlacing, while the second number MSE_2 represents a robust GST de-interlacer, which we have introduced in a previous publication.⁹ The robust solution consists in defining two error factors for the GST de-interlacer ϵ_{GST} and for a intra-field (line average *LA*) de-interlacer

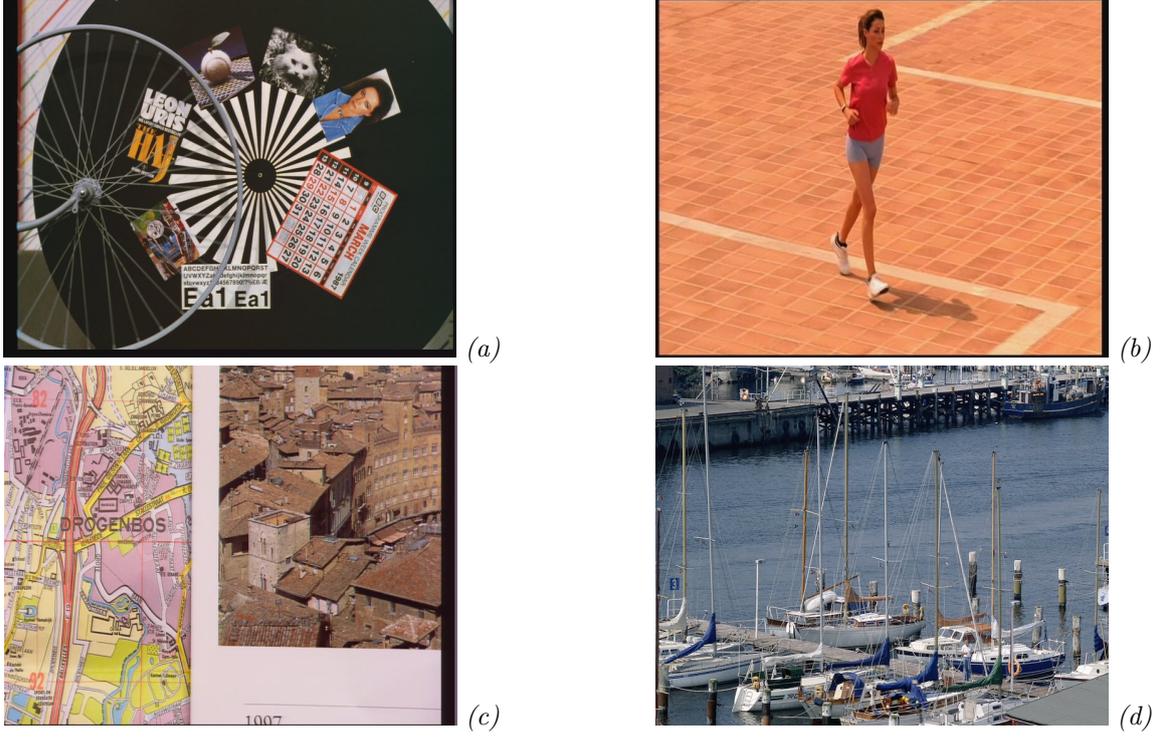


Figure 12. Snapshots from video test sequences with local and irregular motion *Bicycle* (a) and *Girl-Squares* (b) and with fine vertical detail in regular motion *Siena* (c) and *Kiel* (d).

ε_{LA} respectively, and combining the *GST* output with the *LA* output, according to:

$$F(\vec{x}, n) = \frac{1}{2(\varepsilon_{LA}^{-1} + \varepsilon_{GST}^{-1})} (\varepsilon_{GST}^{-1} (F_{\vec{d}_P}^{n,n-1}(\vec{x}, n) + F_{\vec{d}_N}^{n,n+1}(\vec{x}, n)) + \varepsilon_{LA}^{-1} (F(x, y + 1, n) + F(x, y - 1, n))) \quad (24)$$

where

$$\varepsilon_{LA}(\vec{x}, n) = |F(x, y + 1, n) - F(x, y - 1, n)| \quad (25)$$

and

$$\varepsilon_{GST}(\vec{x}, n) = \left| F_{\vec{d}_P}^{n,n-1}(\vec{x}, n) - F_{\vec{d}_N}^{n,n+1}(\vec{x}, n) \right|. \quad (26)$$

Equation (24) can then be used, e.g. to fade between the average of the two outputs, in case they are considered reliable, and a fall-back option, e.g. line averaging (*LA*).

Based on these results, we can conclude that the original three-fields methods of Vanderdorpe, as well as the symmetrical three-fields option lead to unreliable motion vectors and consequently to undesirable artifacts in the *GST* de-interlacer when the sequences are characterised by local and irregular motion. Some improvement is obtained by using the robust de-interlacing solution (24).

A large improvement is obtained by using, either the four fields solutions (Delogne's solution and our complex proposed solution), or the proposed robust three fields solution. A slightly lower quality of Delogne's solution with respect to the recursive and to the improved three-fields solutions noticed on the sequence *Girl-Squares* is possibly due to the fact that Delogne assumes uniform motion over a larger temporal period.

The various methods lead to comparable results when applied on sequences with regular motion, such as *Siena* and *Kiel*. The low-cost solution leads to lower quality results on the *Kiel* sequence. This is due to the fact

that for video sequences characterised by a very fine detail in the vertical direction, the additional terms in the criterion (23) have a very large contribution.

While the proposed four fields solution gives satisfactory results, we believe that the simpler three fields solution is more attractive for practical applications, as it only requires two field memories.

5. RELEVANCE

De-interlacing is the primary resolution determinant of high-end video displays to which important emerging non-linear scaling techniques,¹⁰ can only add finer details. With the introduction of new display technologies like LCD and PDP the limitation in the image resolution is no longer in the display, but rather in the source, or in the transmission format. At the same time, most of these displays require a progressively scanned video input. Therefore, high quality de-interlacing is an important pre-requisite for superior image quality on these emerging displays.

GST-based de-interlacing is the *theoretically optimal* way to generate progressive images from interlaced video. Its main weakness, so far, was the vulnerability for vector inaccuracies. In the current paper, we propose a high-end, four-field motion estimation algorithm and a low-cost, three-field algorithm, to be applied on interlaced material. The first one is based on a recursive approach, while in the low-cost solution we combine the motion estimation criterion, minimising the difference between two GST predictions, with an intrafield minimising criterion, resulting in a more robust motion estimator.

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