A Hybrid Image Coder: Adaptive Intra-Interframe Prediction Using Motion Compensation

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Abstract

A hybrid image predictive coding method is presented. The intraframe predictor is an adaptive FIR filter using the well-known LMS algorithm to track continuously spatial local characteristics of the intensity. The interframe predictor is motion-adaptive using a pel-recursive method estimatingthe displacement vector. A weight coefficient is adapted continuously in order to favour the prediction mode which performs better between intraframe or only motion compensation mode. A crucial problem in predictive coding, particularly with adaptive techniques, is that of sensitivity to transmission errors. A method ensuring the autoadjustment of the decoder in the presence of isolated transmission errors is proposed for the intraframe mode. Neither overhead information nor error-correcting code are needed.

I. Introduction

Among different image coding methodologies, predictive coding can be simply implemented and produces good results at higher rates. In this paper we are interested in adaptive methods of predictive coding. Knowing that there exist simultaneously spatial and temporal redundancies, we consider a hybrid structure of intra- and inter-frame coding. The spatial part of the predictor is a linear filter, but the statistical characteristics of the luminance vary spatially. An approach which permits tracking of the variations is an adaptive filter. A method of adapting the 2D filter consists of switching between different filters, the switching based on a classification rule.

This technique requires the transmission of overhead information, i.e. the class of each pel. Another adaptive method is to identify the optimum linear filter for a block of the frame using least squares [5]. The coefficients of the filter must also be transmitted in this case. To avoid the transmission of additional information we use here a continuously adapted filter, the adaptation being based on previously reconstructed pels. The adaptive algorithm used is that of least mean squares (LMS) of Widrow.

The temporal part of the predictor is adapted using an estimator of the displacement vector. A pel-recursive estimator is used, like that of D.R. Walker and K.R.Rao [8] and of C. Cafforio and F. Rocca [1]. We discuss the displacement estimator in more detail in Section II.

Thus we have an adaptive filter for spatial prediction and a motion adaptive inter-frame prediction. We can assume that in some regions one type of prediction performs better than the other, in the sense that the prediction error is minimized. We must then adapt between these two parts of the predictor. One method is to use an automatic switching based on a classification rule, in which case the result of the classification must be transmitted. We propose here to adapt continuously a weight coefficient for the inter-frame predictor. The predictor can then be written as

$$\hat{I}(i,j;k) = \sum_{(m,n)\in S} a(m,n)\bar{I}(i-m,j-n;k) + b\bar{I}(i-\hat{u},j-\hat{v};k-1) \tag{1}$$

where I is the luminance or the intensity, $\bar{I}$ is the reconstructed intensity, (i,j) are the spatial coordinates, k is the temporal coordinate, S is a quarter-plane or a nonsymmetric half-plane domain, $\hat{u}$ and $\hat{v}$are the components of the estimated displacement vector. The coefficients of the spatial filter $\{a(m,n)\}$ and the weight coefficient b are continuously adapted using the LMS algorithm.

The prediction error is not stationary and its probability distribution is unknown. A reduction of the distortion is obtained, if the quantizer is not fixed, but adapted to the statistics of the prediction error. A generalization of known techniques in 1D predictive coding is given in this paper for a scalar three-level quantizer.

It is known that predictive coding is sensitive to transmission errors, even with constant length codes. The sensitivity to transmission errors is greater if the predictor is adaptive and the adaptation is based on the prediction error. A topic also studied in this paper is the adjustment of the decoder in the presences of transmission errors. We consider only errors damaging separate pels and we demonstrate that the auto-adjustment of the decoder can be obtained using some regularization constraints.

The organization of the paper is as follows. In Section II the algorithm of motion estimation is briefly presented. In Section III the algorithm of adaptive updating the coefficients is given. In Section IV the adaptive quantizer used in this paper is presented. Section V presents constraints and modifications used to obtain the auto-adjustment of the decoder in the case of transmission errors. Section VI gives some results of the algorithms given in this paper.

II. Motion Compensation

The algorithm used here to estimate the displacement vector is similar to that of D.R. Walker and K.R. Rao [8] and C. Cafforio and F. Rocca [1]. It is a pel-recursive intensity-based algorithm which is presented below.

At a point (i,j) (i being the horizontal coordinate and j the vertical one) an *a priori* estimation of the displacement vector is obtained from the previous point $(i-1,j)$

$$\begin{cases} u^0(i,j) = \hat{u}(i-1,j) \\ v^0(i,j) = \hat{v}(i-1,j) \end{cases} \tag{2}$$

As the estimation method is based on intensity using local measurements, the algorithm may estimate false displacements. Discontinuities on the real velocity vector field also exist, because in natural scenes independent 3D rigid movements, or edges between different surfaces which are subject to the same 3D rigid motion may exist. An efficient estimate of the velocity vector necessitates the joint detection of all these discontinuities. This detection must be based on the correctness of the *a priori* estimation of the displacement vector and consequently on the prediction error of the intensity.

The prediction error based on the displacement vector and consequently on the prediction error of the intensity. The prediction error based on the displacement estimation is the displaced frame difference (DFD) given in the following

$$e^0(i,j) = I(i,j;k) - I(i-u^0, j-v^0; k-1)$$

Discontinuities are detected, if the DFD is significantly larger than the frame difference

$$|e^0(i,j)| - |I(i,j;k) - I(i,j;k-1)| > \quad \textit{threshold} \tag{3}$$

If a discontinuity is detected a reset codes is transmitted, and the *a priori* estimation is initialized.

Independently of the detection of a discontinuity the displacement vector must be updated. The criterion which is optimized is the square of the *a posteriori* displaced frame difference

$$e(i,j) = I(i,j;k) - I(i-u, j-v; k-1)$$

under some regularization constraints. Finally the following quadratic form must be minimized

$$Q(u,v) = e^2(i,j) + \lambda[(u-u^0)^2 + (v-v^0)^2]$$

In reality this criterion is not directly quadratic on the unknown parameters u and v. A first order development is admitted in order to obtain the linearization of $e(i,j)$

$$e(i,j) = e^0(i,j) + I_x(u-u^0) + I_y(v-v^0)$$

where

$$I_x = I_x(i-u^0, j-v^0; k-1)$$

and

$$I_y = I_y(i-u^0, j-v^0; k-1)$$

Using this approximation we obtain the following solution

$$\begin{bmatrix} \hat{u}(i,j) \\ \hat{v}(i,j) \end{bmatrix} = \begin{bmatrix} u^0 \\ v^0 \end{bmatrix} - \frac{e^0(i,j)}{\lambda + I_x^2 + I_y^2} \begin{bmatrix} I_x \\ I_y \end{bmatrix} \tag{4}$$

In practice the reconstructed image intensity is used to determine the horizontal and the vertical gradients I_x and I_y, in order to have exactly the same estimator at the decoder. For the same reason the DFD is calculated using the reconstructed intensity.

III. Intra-Interframe Adaptation

The coefficients $\{a(m,n)\}$ and b of the predictor are adapted continuously, pel by pel, to the local characteristics of the intensity, using the LMS algorithm. The LMS adaptive filter has been used in one-dimensional predictive coding, and in a wide range in one-dimensional signal processing applications. The LMS algorithm has also been used by P. Pirsch [7] to adapt the weight coefficients for a predictor using a weighted sum of previous frame and intraframe predictions. A thorough study of adaptive FIR filers is given by O. Macchi and M. Bellanger [4]. An extension of the LMS algorithm for two-dimensional signals is discussed by M. Hadhoud and D. Thomas [3].

The stochastic gradient algorithm minimizes the mean square prediction error ($\mathcal{E}$ being the notation for the average)

$$\mathcal{E}\{[I(i,j;k) - \hat{I}(i,j;k)]^2\}$$

The coefficients (here three intraframe coefficients) are updated by the following expression

$$\begin{bmatrix} a(0,1) \\ a(0,1) \\ a(1,1) \\ b \end{bmatrix}_{(i,j)} = \begin{bmatrix} a(0,1) \\ a(1,0) \\ a(1,1) \\ b \end{bmatrix}_{(i-1,j)} + \mu\bar{\varepsilon}(i,j) \begin{bmatrix} \bar{I}(i,j-1;k) \\ \bar{I}(i-1,j;k) \\ \bar{I}(i-1,j-1;k) \\ \bar{I}(i-\hat{u},j-\hat{v};k-1) \end{bmatrix} \tag{5}$$

where $\bar{\varepsilon}$ is the quantized prediction error and μ is known as the adaptation step size. It has been proved that the inequality

$$0 < \mu < \frac{2}{LP}$$

(L: number of coefficients, P: power of the intensity signal) is necessary to ensure the convergence [4]. In fact, the adaptation step size must be big enough to forget quickly the initial conditions and to have good tracking properties and it must be small enough to obtain a low steady state error.

IV. Adaptive Quantization

A scalar three-level adaptive quantizer is used to quantize the prediction error. A normalization factor s is used in order to take into account the dispersion of the prediction error. The normalization factor is adapted by a backwards technique, like that studied by D. Goodman and A. Gersho [2]. The correction of the quanitzer parameter uses the quantized value of the prediction error ε. The normalization factor is updated by the following algorithm

$$s(i,j) = \frac{\sigma(i,j-1)\sigma(i-l,j)}{\sigma(i-l,j-1)}$$

$$\varepsilon_1(i,j) = Q\left(\frac{\varepsilon(i,j)}{s(i,j)}\right)$$

$$\hat{\varepsilon}(i,j) = \varepsilon_1(i,j)s(i,j)$$

$$\sigma(i,j) = M(\varepsilon_1(i,j))s(i,j)$$

$M(\varepsilon_1(i,j))$ is a positive valued function which for the three- level quantizer satisfies

$$M(q) = M(-q) > 1; \;\; M(0) < 1$$

V. Decoding in the Presence of Transmission Errors

The main problem with predictive coding, and particularly with adaptive methods, was found to be its instability in the presence of transmission errors. It is important to ensure the robustness of the decoder without rate augmentation. The criterion of adaptation of the predictor must then be modified. We study this problem in the case of intraframe coding without motion compensation ($b = 0$).

The quadratic form minimized by the LMS algorithm is modified by the introduction of a regularization term. We use the following criterion

$$J_s = \mathcal{E}\{\varepsilon^2\} + \alpha\mathcal{E}\{[\hat{I}(i,j) - \hat{I}_f(i,j)]^2\}$$

where $\hat{I}_f(i,j)$ is the output of a fixed stable predictor. A modification of the update equation results

$$\begin{bmatrix} a(0,1) \\ a(1,0) \\ a(1,1) \end{bmatrix}_{i,j} = \begin{bmatrix} a(0,1) \\ a(1,0) \\ a(1,1) \end{bmatrix}_{i-l,j} + \mu[\varepsilon(i,j) - \alpha(\hat{I}(i,j) - \hat{I}_f(i,j))] \begin{bmatrix} \bar{I}(i,j-1;k) \\ \bar{I}(i-1,j;k) \\ \bar{I}(i-1,j-1;k) \end{bmatrix} \quad (6)$$

This algorithm ensures the robustness of the decoder, if the errors damage separate pels. This is the case if the codes have the same length. The case of variable length codes is more difficult and complicated; it is not considered here.

VI. Simulations and Results

The coder described in this paper has been simulated for the "CAR" sequence of images provided by CCETT (COST 211 bis European normalization). In this sequence the car is in movement and the camera pans the scene. A strong additional noise disturbs the intensity and different types of spatial details are present in the scene. To appreciate the importance of the motion, the empirical standard deviation of the difference between the first two frames of the sequence is 30.1.

The quality criterion is given by the mean square distortion

$$D = \frac{1}{MN}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}[I(i,j) - \bar{I}(i,j)]^2$$

or equivalently by $\sqrt{D}$. The power of the prediction error is given in order to appreciate the performance of the predictor. Finally, the entropy of the quantized prediction error is given, this quantity being closely linked to the compression rate.

Without quantization the square root of the prediction error was 14.3 for the adaptive intraframe predictor ($b = 0$), 14.1 for the motion-compensated prediction and 12.2 for the hybrid adaptive predictor presented in this paper. Using the adaptive quantizer of Section IV we obtain the following table of numerical results for the second frame of the sequence (Tab. 1).

If the rate of transmission erros is about 10^{-3}, the stabilization method of Section V gives 8.6 as square root of the distortion at the coder and 9.2 at the decoder for frame "CAR_00". This distortion is practically visually imperceptible. These results illustrate the little sensitivity of the proposed adaptive method to transmission errors.

	Hybrid Prediction	Motion Compensation	Adaptive Intraframe
$\sqrt{P_\epsilon}$	15.5	17.2	16.8
$\sqrt{D}$	8.0	9.2	9.0
H	1.3	1.4	1.4

Table 2: Table of numerical results for "CAR_01" frame.

Conclusion

An adaptive intra/interframe predictive coding method is presented. The simulation of the proposed method for a very crtical image sequence has illustrated a certain improvement in comparison with no adaptive methods or only motion compensation techniques. Only a little complexity increase from motion compensation pel-recursive methods is needed. The crucial problem of transmission errors is considered in the case of adaptive intraframe prediction. Only some algorithmic complexity is added in order to make the decoder in practice not sensitive to channel errors. The transmission rate is not increased. The more general case of intra/interframe coding in presence of transmission errors is under investigtion. Knowing that pel predictive methods produce good results at higher rates, which are improved using adaptive techniques, we think that replacing the pel prediction by block prediction mode one could also obtain good results at lower bit-rates.

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