Fast Sub-pixel Motion Estimation Techniques Having Lower Computational Complexity

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Abstract — *This paper proposes fast sub-pixel motion estimation techniques having lower computational complexity. The proposed methods are based on mathematical models of the motion-compensated prediction errors in compressing moving pictures. Unlike conventional hierarchical motion estimation techniques, the proposed methods avoid sub-pixel interpolation and subsequent secondary search after the integer-precision motion estimation, resulting in reduced computational time. In order to decide the coefficients of the models, the motion-compensated prediction errors of the neighboring pixels around the integer-pixel motion vector are utilized. The prediction errors, here, were already obtained during the pixel accuracy motion search. Once the coefficients are determined, the models estimate motion compensated prediction errors at sub-pixel locations surrounding the integer-pixel motion vector, yielding the sub-pixel motion vector. The performance of the proposed methods, despite substantially lower computational complexity, is close to that of the conventional interpolation-and-search method.*

Index Terms — Half-pixel accuracy, Sub-pixel accuracy, Motion Estimation, Motion Compensation.

I. INTRODUCTION

To achieve efficient compression for video sequences, ME(Motion Estimation) and MC(Motion Compensation) are required to reduce temporal redundancy. ME is carried out using one of many well-known techniques such as BMA (Block Matching Algorithm), spatio-temporal constraint method [1], etc. ME and MC yield MVs(motion vectors) and prediction errors between the reference picture and the current picture to be coded.

Since the integer-pixel accuracy ME has less accuracy than the sub-pixel accuracy case, ME is often performed at sub-pixel accuracy level for higher compression efficiency. In practice, precision of MVs is a priori specified. Half-pixel accuracy is, for instance, a typical choice as a tradeoff between reduced prediction errors and increased overheads for representing MVs.

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Contributed Paper
Original manuscript received July 18, 2003
Revised manuscript received June 23, 2004

In conventional hierarchical ME, ME is first performed at integer pixel level and then half pixel level search is applied at eight half-pixel positions around the MV obtained at the first step [2]. This secondary search requires half-pixel interpolation in advance, which is also substantially time-consuming. In recent international standards such as MPEG-4, the half-pixel ME is far extended to 1/4-pixel or 1/8-pixel accuracy [3]. There have been various architectural attempts to implement real-time video encoders. Regardless of full hardware VLSI design [4] or RISC-based design with dedicated hardware modules [5], they tend to have limitation in performance due to high complexity of ME. Therefore, a number of efforts have been made to reduce time for ME since ME takes up a major portion of encoder complexity. The 2-D logarithmic search [6] or three-step search [7] consumes less computational time than the full search method but they may fall into local minimum positions.

Half pixels (a.k.a. in-between pixels) are obtained by interpolating integer pixels, which increases computational complexity. There are half-pixel accuracy searching methods [8~13] to decrease complexity caused by interpolation. But these methods commonly yield large errors due to excessively simplified MC-error models.

In this paper we propose fast sub-pixel ME techniques having lower computational complexity. The proposed methods are based on mathematical models of the mean-square MC prediction errors in compressing moving pictures. Unlike conventional hierarchical ME techniques, the proposed methods avoid sub-pixel interpolation and subsequent secondary search after the integer-precision ME, resulting in reduced computational time. In order to decide the coefficients of the models, the MC prediction errors of the neighboring pixels around the integer-pixel MV are utilized. The prediction errors, here, were already obtained during the pixel accuracy motion search. Once the coefficients are determined, the models estimate MC prediction errors at sub-pixel locations surrounding the integer-pixel MV, yielding the sub-pixel MV. The proposed mathematical models are referred to as Model 1, Model 2, Model 3, modified Model 2, and modified Model 3, respectively. Experimental results show that performance depends on the order of the models. The performance of the proposed methods, regardless of lower computational complexity, is close to that of the conventional interpolation-and-search method.

II. PROPOSED METHODS AND MODELS

We propose five mathematical models of mean-square MC prediction errors (For simplicity, we omit "mean-square" throughout this paper without loss of clarity). Using those models and integer-pixel level ME, we find sub-pixel accuracy MV by evaluating the values of the model function at sub-pixel positions neighboring the integer MV. This proposed method requires neither sub-pixel interpolation nor secondary search thereafter. Therefore the proposed methods tremendously reduce computational complexity in sub-pixel ME.

A. Model 1 – Nonsingular case, Inverse matrix solution

In Fig.1, ○ denotes integer pixels and × denotes half pixels between integer pixels. Let the origin (0,0) denote the position of the integer-pixel accuracy MV selected via full search. Therefore, half-pixel accuracy MV is one of eight half pixel positions around (0, 0) or the origin (0, 0) itself, depending on MC prediction errors at those 9 positions. Here, we model the MC prediction error plane as

$$\begin{aligned} f(x,y) &= c_1x^2y^2 + c_2x^2y + c_3xy^2 + c_4xy \\ &+ c_5x^2 + c_6x + c_7y^2 + c_8y + c_9 \end{aligned} \quad (1)$$

The coefficients here can be determined using the MC prediction errors at 3x3 integer-pixel positions around (0,0). Note that the integer-pixel MV denoted by (0,0) has been found via full search. Thus it can be assumed that the mean-square MC prediction errors at (0,0) and eight neighboring integer-pixel positions are already known. These 9 error values determine 9 coefficients in (1). Substituting the 9 MC prediction errors sequentially from the upper left position (namely, (-1,-1)) to the lower right position (namely, (1,1)), we have

$$\begin{bmatrix} f(1) \\ f(2) \\ f(3) \\ f(4) \\ f(5) \\ f(6) \\ f(7) \\ f(8) \\ f(9) \end{bmatrix} = \begin{bmatrix} 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 \\ 0 & 0 & 1 & 0 & 0 & -1 & 1 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & -1 & -1 & -1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \\ c_9 \end{bmatrix} \quad (2)$$

where $f(n)$ denotes the MC prediction errors. It can be easily seen that the inverse matrix of (2) exists and is given by (3).

$$\begin{bmatrix} 1/4 & -1/2 & 1/4 & -1/2 & 1 & -1/2 & 1/4 & -1/2 & -1/4 \\ -1/4 & 1/2 & -1/4 & 0 & 0 & 0 & 1/4 & -1/2 & 1/4 \\ 0 & 0 & 0 & 1/2 & -1 & 1/2 & 0 & 0 & 0 \\ -1/4 & 0 & 1/4 & 1/2 & 0 & -1/2 & -1/4 & 0 & 1/4 \\ 1/4 & 0 & -1/4 & 0 & 0 & 0 & -1/4 & 0 & 1/4 \\ 0 & 0 & 0 & -1/2 & 0 & 1/2 & 0 & 0 & 0 \\ 0 & 1/2 & 0 & 0 & -1 & 0 & 0 & 1/2 & 0 \\ 0 & -1/2 & 0 & 0 & 0 & 0 & 0 & 1/2 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} f(1) \\ f(2) \\ f(3) \\ f(4) \\ f(5) \\ f(6) \\ f(7) \\ f(8) \\ f(9) \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \\ c_9 \end{bmatrix} \quad (3)$$

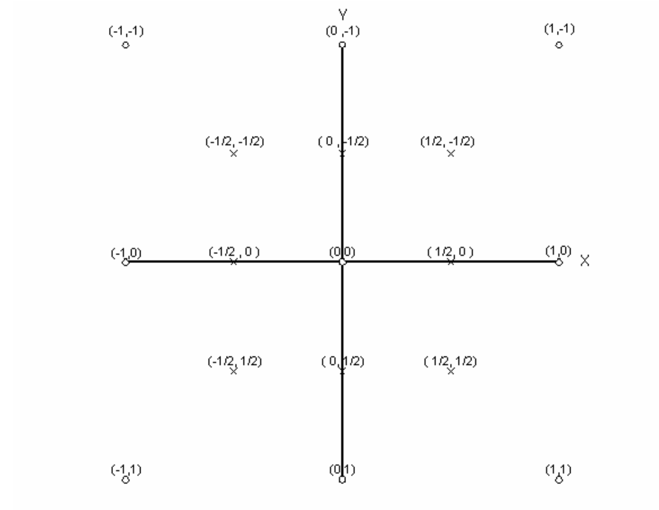

Fig. 1. Pixels and half- pixels

Obviously this inverse matrix is fixed and common for every macroblock's sub-pixel ME, in other words, no repeated calculation is required. Furthermore, the 9x9 matrix in (3) has sparse and regular features, giving a favorable contribution to lower complexity. No multiplication is needed. The MC-prediction errors at the neighboring sub-pixel positions can be obtained by substituting the values of –0.5, 0, and 0.5 (in case of half-pixel accuracy) for x and y in (1). The position that gives the minimum MC prediction errors shall be the sub-pixel accuracy MV. To further reduce computational time, each polynomial term of Eq. (1) can be pre-calculated as follows.

$$f(x,y) = c_1x^2y^2 + c_2x^2y + c_3x^2 + c_4xy^2 + c_5xy + c_6x + c_7y^2 + c_8y + c_9$$

$$\begin{bmatrix} f(-0.5,-0.5) \\ f(\ \ 0,-0.5) \\ f(\ 0.5,-0.5) \\ f(-0.5,\ \ 0) \\ f(\ \ 0,\ \ 0) \\ f(\ 0.5,\ \ 0) \\ f(-0.5,\ 0.5) \\ f(\ \ 0,\ 0.5) \\ f(\ 0.5,\ 0.5) \end{bmatrix} = \begin{bmatrix} 0.0625 & -0.125 & 0.25 & -0.125 & 0.25 & -0.5 & 0.25 & -0.5 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.25 & -0.5 & 1 \\ 0.0625 & -0.125 & 0.25 & 0.125 & -0.25 & 0.5 & 0.25 & -0.5 & 1 \\ 0 & 0 & 0.25 & 0 & 0 & -0.5 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0.25 & 0 & 0 & 0.5 & 0 & 0 & 1 \\ 0.0625 & 0.125 & 0.25 & -0.125 & -0.25 & -0.5 & 0.25 & 0.5 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.25 & 0.5 & 1 \\ 0.0625 & 0.125 & 0.25 & 0.125 & 0.25 & 0.5 & 0.25 & 0.5 & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \\ c_9 \end{bmatrix} \quad (4)$$

The matrix in Eq. (4) is also fixed and is a sparse matrix as well, facilitating estimation of MC prediction errors at 8 neighboring half-pixel positions. Fig. 2 shows a typical MC prediction error surface. Fig. 3 represents MC prediction error values at 9 candidate positions around the origin (0, 0). Note that the MC prediction error surface in the proposed model is parabola in both horizontal and vertical directions. Fig. 4. shows the graphs of the error surface with fixed x and fixed y, respectively. Here, the origin (0, 0) represents the integer-pixel MV found via full search. The integer-precision MV is then refined into half-pixel precision MV by choosing the position among 9 candidates that gives the minimum estimate of the MC prediction errors.

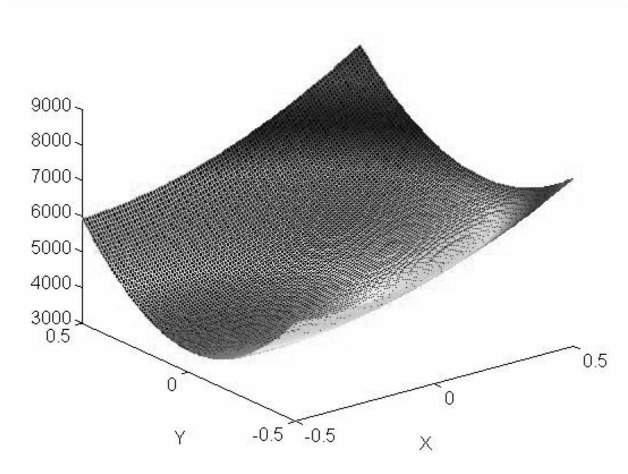

Fig. 2. MC prediction error surface

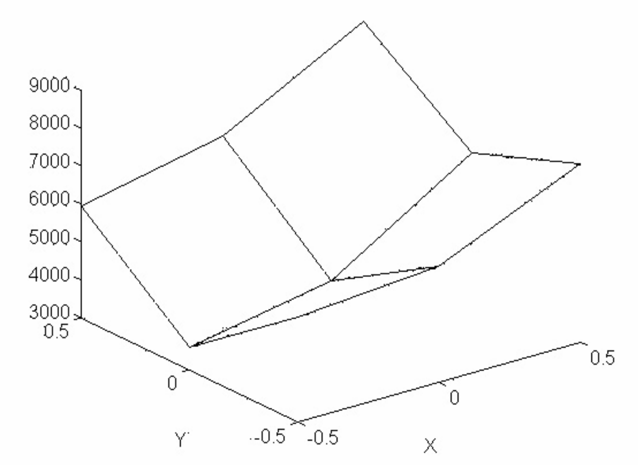

Fig. 3. MC prediction errors at 9 half-pixel positions

B. *Model 2 – Singular Case, Least square solution*

From Model 1, a simplified model can be obtained by eliminating rather complicated higher-order terms such as x^2y^2, x^2y, and xy^2.

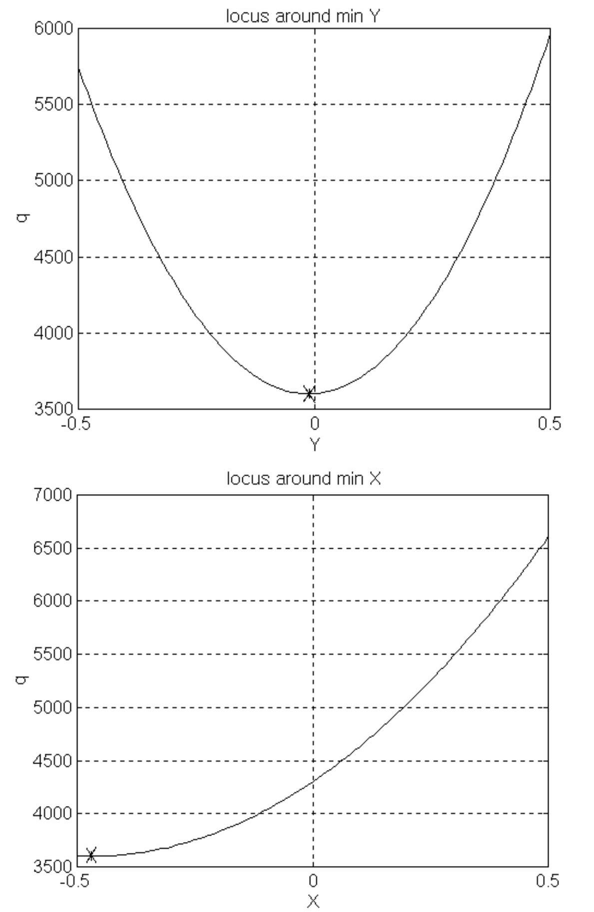

Fig. 4. Cross-section of MC prediction error surface with fixed x and fixed y

$$f(x,y) = c_1x^2 + c_2xy + c_3y^2 + c_4x + c_5y + c_6 \qquad (5)$$

The contour lines of MC prediction errors in this model are shown in Fig. 5. Here, there are 6 unknown coefficients and 9 known values (i.e. 9 MC prediction errors at 9 integer positions around (0, 0)). Substituting the 9 MC prediction errors sequentially from the upper left position (-1,-1) to the lower right position (1,1) into (5), we have

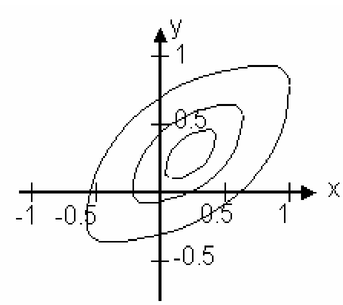

Fig. 5. Contour lines of MC prediction error surface in Model 2

$$\begin{bmatrix} f(1) \\ f(2) \\ f(3) \\ f(4) \\ f(5) \\ f(6) \\ f(7) \\ f(8) \\ f(9) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & -1 & -1 & 1 \\ 0 & 0 & 1 & 0 & -1 & 1 \\ 1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 \\ 1 & -1 & 1 & -1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \end{bmatrix} \qquad (6)$$

This over-determined equation is a typical least square problem and can be solved

$$\begin{aligned} A \cdot c &= f \\ c &= \left(A^T A\right)^{-1} A^T \cdot f \end{aligned} \qquad (7)$$

where $f(n)$ denotes the MC prediction errors at each position.

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \end{bmatrix} = \begin{bmatrix} 1/6 & -1/3 & 1/6 & 1/6 & -1/3 & 1/6 & 1/6 & -1/3 & 1/6 \\ 1/4 & 0 & -1/4 & 0 & 0 & 0 & -1/4 & 0 & 1/4 \\ 1/6 & 1/6 & 1/6 & -1/3 & -1/3 & -1/3 & 1/6 & 1/6 & 1/6 \\ -1/6 & 0 & 1/6 & -1/6 & 0 & 1/6 & -1/6 & 0 & 1/6 \\ -1/6 & -1/6 & -1/6 & 0 & 0 & 0 & 1/6 & 1/6 & 1/6 \\ -1/9 & 2/9 & -1/9 & 2/9 & 5/9 & 2/9 & -1/9 & 2/9 & 1/9 \end{bmatrix} \begin{bmatrix} f(1) \\ f(2) \\ f(3) \\ f(4) \\ f(5) \\ f(6) \\ f(7) \\ f(8) \\ f(9) \end{bmatrix} \qquad (8)$$

The pseudo inverse matrix in Eq. (8) can be easily found. To further reduce computational time, each polynomial term of Eq. (5) can be pre-calculated as follows.

$$f(x,y) = c_1 x^2 + c_2 xy + c_3 y^2 + c_4 x + c_5 y + c_6$$

$$\begin{bmatrix} f(-1/2,-1/2) \\ f(\;\;0,-1/2) \\ f(\;1/2,-1/2) \\ f(-1/2,\;\;0) \\ f(\;\;0,\;\;0) \\ f(\;1/2,\;\;0) \\ f(-1/2,\;1/2) \\ f(\;\;0,\;1/2) \\ f(\;\;0,\;1/2) \end{bmatrix} = \begin{bmatrix} 1/4 & 1/4 & 1/4 & -1/2 & -1/2 & 1 \\ 0 & 0 & 1/4 & 0 & -1/2 & 1 \\ 1/4 & -1/4 & 1/4 & 1/2 & -1/2 & 1 \\ 1/4 & 0 & 0 & -1/2 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 1/4 & 0 & 0 & 1/2 & 0 & 1 \\ 1/4 & -1/4 & 1/4 & -1/2 & 1/2 & 1 \\ 0 & 0 & 1/4 & 0 & 1/2 & 1 \\ 1/4 & 1/4 & 1/4 & 1/2 & 1/2 & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \end{bmatrix} \qquad (9)$$

C. Model 3 – Nonsingular case, Separable solution

Model 3 further simplifies Model 2 by eliminating the *xy* term.

$$f(x,\,y) = c_1 x^2 + c_2 x + c_3 y^2 + c_4 y + c_5 \qquad (10)$$

Eq. (10) represents MC prediction errors directionally separable.

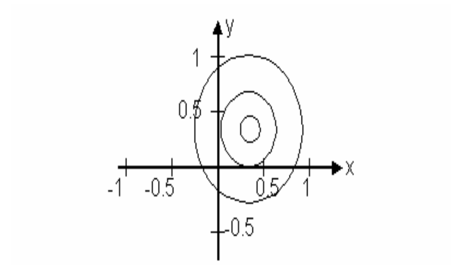

Fig 6. Contour lines of MC prediction error surface in Model 3

In this case, four neighboring positions such as (0,-1), (-1,0), (1,0), (0,1) around (0,0) are used together to find the 5 coefficients. It can be easily seen that this Model 3 is identical to those of [8, 9, 10]. In Model 3, the horizontal and vertical refinements can be carried out separately. Thus we simply need to consider one-dimensional model for MC prediction error surface. Assuming we carry out the horizontal refinement first, let the one-dimensional MC prediction error model be simplified as

$$E(x) = a|x-b|^{\gamma} + c \qquad (\gamma = 2,\, a > 0,\, |b| < 1,\, c \geq 0) \quad (11)$$

where b is the exact MV and x is a vector near b. Let Y(m, n) and Y'(m, n) be luminance values of current and previous frames, respectively. Let P_0 be the MC prediction error at (0, 0).

$$P_0 = \frac{1}{256}\sum_{m=0}^{15}\sum_{n=0}^{15}\left|Y(m,\,n) - Y'(m+m_0,\,n+n_0)\right|^2 \qquad (12)$$

That is, P_0 is the mean-square MC prediction error at integer-pixel MV (m_0, n_0). In the same manner, we define P_1 and P_{-1} as mean-square MC prediction errors adjacent to (0, 0). Then we have (see [8])

$$\frac{P_1 - P_0}{P_{-1} - P_0} = \frac{|1-b|^{\gamma} - |b|^{\gamma}}{|1+b|^{\gamma} - |b|^{\gamma}} = g(b) \qquad (13)$$

For half-pixel refinement, (13) can be expressed as.

$$\begin{aligned} &\text{MV'} = (m_0-0.5,\, n_0) \quad \text{if} \quad b = g^{-1}\left(\frac{P_1 - P_0}{P_{-1} - P_0}\right) < -\frac{1}{4} \\ &\text{MV'} = (m_0+0.5,\, n_0) \quad \text{if} \quad b = g^{-1}\left(\frac{P_1 - P_0}{P_{-1} - P_0}\right) > \frac{1}{4} \\ &\text{MV'} = (m_0,\, n_0) \quad \text{if} \quad -\frac{1}{4} \leq b \leq \frac{1}{4} \end{aligned} \qquad (14)$$

where MV' is a horizontal component of new half-pixel accuracy MV. The vertical refinement can be done in the same manner. This method can be easily applicable to other sub-pixel accuracy ME such as quarter-pixel ME.

When $\gamma = 2$, Eq. (14) can be simply expressed as.

$$
\begin{aligned}
&MV' = (m_0-0.5, n_0) && \text{if } 3(P_{-1} - P_0) \langle (P_1 - P_0) \\
&MV' = (m_0+0.5, n_0) && \text{if } (P_{-1} - P_0) \rangle 3(P_1 - P_0) \\
&MV' = (m_0, n_0) && \text{otherwise}
\end{aligned} \qquad (15)
$$

When $\gamma = 1$, Eq. (14) can be simply expressed as.

$$
\begin{aligned}
&MV' = (m_0-0.5, n_0) && \text{if } 2(P_{-1} - P_0) \langle (P_1 - P_0) \\
&MV' = (m_0+0.5, n_0) && \text{if } (P_{-1} - P_0) \rangle 2(P_1 - P_0) \\
&MV' = (m_0, n_0) && \text{otherwise}
\end{aligned} \qquad (16)
$$

D. Modified Model 2 – Weighted least square solution

In solving for the coefficients in Model 2, weights are given depending on the distance between (0,0) and the other 9 points. The closer points such as (0,-1), (-1,0), (0,1), (1,0) are rather heavily weighted. The basic idea, here, is that the closer to the origin (0, 0), the more effect to the model accuracy and half-pixel refinement. Using different weights we have

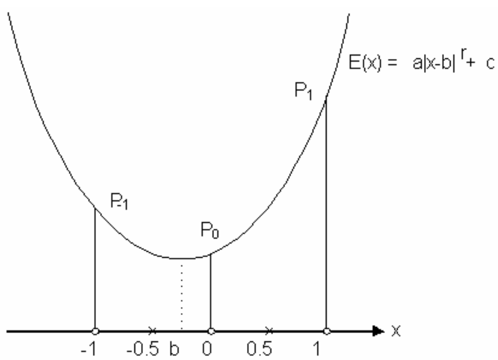

Fig. 7. 1-D model of MC prediction error

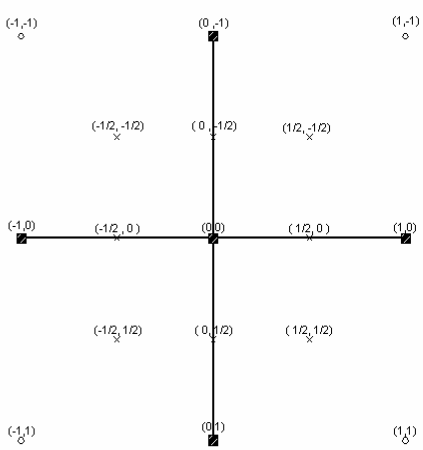

Fig. 8. 5 weighted positions including (0,0) (■ is weighted point)

$$
W = \begin{bmatrix} 1 &&&&&&&& \\ & s &&&&&&& \\ && 1 &&&&&& \\ &&& s &&&&& \\ &&&& c &&&& \\ &&&&& s &&& \\ &&&&&& 1 && \\ &&&&&&& s & \\ &&&&&&&& 1 \end{bmatrix} \qquad (17)
$$

$$
\begin{aligned}
&W \cdot b = (W \cdot A)x \\
&\Rightarrow x = (A^T W^T W A)^{-1} A^T \cdot W^T \cdot W \cdot b
\end{aligned} \qquad (18)
$$

E. Modified Model 3 – Weighted fast solution

All the 9 coordinates in (10) of Model 3 are used but with heavier weights on the 5 positions such as (0,-1), (-1,0), (0,0), (0,1), (0,0). Except for this weighting, the other operations are the same as Modified Model 2.

III. EXPERIMENTAL RESULTS AND CONSIDERATION

The proposed methods were tested using some image sequences such as "flower garden," "table tennis," and "football." Only the luminance component was used for this ME purpose. Each image sequence consists of 30 frames of 352×240 pixels. The experimental results are summarized in Table 1. All proposed models have PSNRs between that of integer-pixel ME and that of half-pixel interpolation-and-search ME. Among the three models of Model 1 through Model 3, in general Model 1 showed the best result and Model 3 showed the lowest performance. The two modified models have better results than their original versions, respectively. Of course, the complexity of Model 3 is the lowest. As for weights in the modified models, s=2, c=2 was applied to 5 positions close to the origin. Table 2 shows comparison of the computational complexity of the proposed methods. This comparison is calculated under CCIR 601 format (740×480) and 29.97 Hz frame rate. The search area is assumed to be -16

Table 1. Image quality comparison (PSNR)

(MSE)

	flower garden	table tennis	football
integer full search	24.48dB	32.61dB	23.46dB
half full search (using interpolation)	25.27dB	33.43dB	24.13dB
Model 1	25.23dB	33.18dB	23.97dB
Model 2	25.19dB	32.99dB	23.88dB
Model 3	25.16dB	32.97dB	23.83dB
Modified Model 2 (s : 2 c : 2)	25.21dB	33.12dB	23.91dB
Modified Model 3 (s : 2 c : 2)	25.17dB	32.97dB	23.85dB

Table 2. Computational complexity

	add./sec.	mult./sec.
Integer pel full search	21,212,430,000	10,606,215,000
Half pel full search	222,486,790	82,861,056
Model 1	2,751,246	0
Model 2	2,670,327	890,109
Model 3	161,838	0
Modified Model 2	2,670,327	890,109
Modified Model 3	2,184,813	525,974

(MSE, CCIR601:720×480, 29.97 Hz)

~ +15 (integer-pixel accuracy) and -16 ~ +15.5 (half-pixel accuracy). Because MSE is used in Table 1, Table 2 includes the increased number of multiplication that is required for calculation of MSE. Although MSE is used in Table 1 and Table 2, the proposed methods have no assumption regarding the error criterion. Thus, SAD also can be used for these methods as the error criterion. The number of multiplication that can be expressed by shift operation was excluded. Model 2 requires more multiplication than Model 1 or Model 3 because the result of pseudo inverse matrix has a number of entries that cannot be replaced by shift operation. Modified Model 2 has the same numbers of multiplication and addition with those of Model 2 because MC prediction errors are multiplied by pseudo inverse matrix that was already multiplied by weight factors.

IV. CONCLUSIONS

We have proposed sub-pixel accuracy ME methods and associated models of MC prediction errors. The proposed methods simply use MC prediction errors around the integer-pixel accuracy MV and directly extend ME precision from integer-pixel accuracy to sub-pixel accuracy. We have proposed mathematical models of several different degrees of freedom. Starting from the polynomial with 9 coefficients, we gradually simplified the model of MC prediction errors by eliminating higher order terms. Using these models we can estimate sub-pixel accuracy MVs. We have shown from experiments that the proposed methods have lower computational complexity while keeping their performance close to that of the conventional interpolation-and-search method. The proposed method can, therefore, contribute to reduce complexity of the ME process which is regarded as a major bottleneck in video encoders of e.g., MPEG-2, MPEG-4, H.264 [14], etc.

V. REFERENCES

[1] J. S. Lim, Two-Dimensional Signal and Image Processing, McGraw-Hill, 1991.

[2] ISO/IEC JTC1/SC29/WG11 MPEG-2 Standard TM 5, 1995.

[3] ISO/IEC JTC1/SC29/WG11 MPEG-4 Standard VM 6, 2000.

[4] P. Pirsch and H. J. Stolberg, “VLSI implementations of image and video multimedia processing systems”, IEEE Trans. Circuits and Systems for Video Tech, vol 8, pp. 878-891, Nov. 1998

[5] S. Kang, H.Hwang, J.W. Suh and Y. Lee, “Reliable and Flexible Video Codec Structure Implemented on a RISC Processor”, pp. 243-246, in *Proc*. PROMS2000, Oct., 2000

[6] J. R. Jain, and A. K. Jain, "Displacement measurement and its application in interframe image coding, " IEEE trans. on comm., Vol. COM-209, No. 12, Dec. 1981.

[7] T. Koga, et al, "Motion compensated interframe coding for video conferencing," National Telecommunication Conference, Nov. 29- Dec. 3, 1981, New Orleans, LA, USA

[8] J. Jeong, and W. Ahn, "Subpixel-accuracy Motion Estimation Using a Model for Motion Compensated Error," in *Proc. PCS'93*, 13.4. March. 1993.

[9] X. Li and C. Gonzales, " A Locally Quadratic Model of the Motion Estimation Error Criterion Function and its Application to Subpixel Interpolations," IEEE Trans. Circuits and Systems for Video Tech. Vol. 6. No. 1, pp. 118-122, Feb., 1996.

[10] Cheng Du, Yun He, and Junli Zheng, "PPHPS: A parabolic prediction-based, fast half-pixel search algorithm for very low bit-rate moving-picture coding," IEEE Trans. Circuits Syst. Video Technol., June 2003, pp. 514-518.

[11] Y. Senda, H. Harasaki, and M. Yano, " A Simplified Motion Estimation Using an Approximation for the MPEG-2 Real-Time Encoder," ICASSP'95, Vol. 4, pp. 2273-2276, 1995.

[12] K. T. Choi, S. C. Chan and T. S. Ng, " A New Fast Motion Estimation Algorithm using Hexagonal Subsampling Pattern and Multiple Candidates Search," in *Proc.* ICIP'96, Vol. 2, pp. 497-500, 1996.

[13] Yuzo Senda, Hidenobu Harasaki and Mitsuhara Yano, "Theoretical Background and Improvement of a simplified Half-Pel Motion Estimation," in *Proc.* ICIP'96, Vol. 3, pp. 263-266, 1996.

[14] ITU-T Recommendation and international standard of joint video specification [ITU-T Rec. H.264, ISO/IEC 14496-10 AVC]

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