Using MMX™ Instructions to Implement a Video Loop Filter

Information for Developers and ISVs

From Intel® Developer Services
www.intel.com/IDS

March 1996

Information in this document is provided in connection with Intel® products. No license, express or implied, by estoppel or otherwise, to any intellectual property rights is granted by this document. Except as provided in Intel's Terms and Conditions of Sale for such products, Intel assumes no liability whatsoever, and Intel disclaims any express or implied warranty, relating to sale and/or use of Intel products including liability or warranties relating to fitness for a particular purpose, merchantability, or infringement of any patent, copyright or other intellectual property right. Intel products are not intended for use in medical, life saving, or life sustaining applications. Intel may make changes to specifications and product descriptions at any time, without notice.

Note: Please be aware that the software programming article below is posted as a public service and may no longer be supported by Intel.

Copyright © Intel Corporation 2004
* Other names and brands may be claimed as the property of others.

CONTENTS

1.0. INTRODUCTION
2.0. LOOP FILTER
    2.1. row_filter Core
    2.2. col_filter Core
3.0. PERFORMANCE GAINS
4.0. LOOP FILTER FUNCTION CODE LISTING

1.0. INTRODUCTION

The Intel Architecture (IA) media extensions include single-instruction, multi-data (SIMD) instructions. This application note presents the basics of a loop filter implementation using MMX instructions.

Filtering or smoothing operations are used to reduce noise in imagery that is often characterized by high frequency components. In the loop filter calculation described here, smoothing in YUV space is performed over each frame.

2.0. LOOP FILTER

The 2-D convolution kernel for the loop filter is shown in Figure 1. This 2-D convolution kernel of size 3x3 is equivalent to a 1-D convolution kernel along the rows with coefficients [1 2 1] and a 1-D convolution kernel along the columns with the same coefficients [1 2 1].

Figure 1. 2-D Convolution Kernel

$$\frac{1}{16}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

Notice that the convolution kernel is normalized by the factor 1/16. Normalization is necessary since the sum of all coefficients in the filter must equal one to preserve scaling.

The 2-D loop filter is implemented as two smaller 1-D filters, namely a [1 2 1] filter along the rows ("row_filter") and a [1 2 1] filter along the columns (" col_filter"). Each of these filters is basically an inner product of the data with the [1 2 1] kernel.

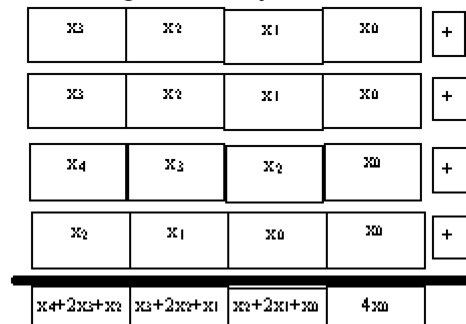
The data is processed in blocks; each block is 8 pixels by 8 pixels in size. Each block passes first through the row_filter and then through the col_filter.

2.1. row_filter Core

Before data passes through the row_filter, it is unpacked from bytes to words for precision. Figure 2 illustrates how the row_filter operates on the lower four words
(0-3). The data element is copied three times. One copy is unchanged, one is shifted left; and one is shifted right. Finally the four resulting data elements are added together. The result is the inner product of the data with the [1 2 1] kernel.

Notice that a boundary condition occurs at the zeroth element that requires special handling. If there were no boundary, the sum for the zeroth element would be x1 + 2x0 + x-1 However, since there is no neighboring data, x_{-1} , we weight the value by a factor of 41 instead. This is achieved by adding a masked out version of $2x_0$ (line 26 of the code, see Example 1).

Figure 2. row_filter Flow



The operation shown in Figure 2 must be repeated for the higher four words (4-7), with similar treatment for the upper boundary condition at the seventh element. Then, the entire process must be repeated for each row of 8 pixels.

Example 1. row_filter Code

```
row_loop:
  1 movq         mm0, [esi]                       ; get a row
  2 pxor         mm7, mm7                 ; clear for unsigned unpacking
  3 movq         mm1, mm0                 ; copy row
  4 psrlq                mm0, 32                          ; align
  5 movq         mm2, mm1                 ; copy row
  6 punpcklbw            mm0, mm7                 ; bytes to word [7 6 5 4]
  7 movq         mm3, mm2                 ; copy row
  8 punpcklbw            mm1, mm7                 ; bytes to word [3 2 1 0]
  9 movq         mm4, mm0                 ; copy half row [7 6 5 4]
 10 psrlq                mm2, 24                          ; align [_ _ _ 7 6 5 4 3]
 11 movq         mm5, mm1                 : copy half row [3 2 1 0]
 12 psrlq                mm3, 8                           ; align [_ 7 6 5 4 3 2 1]
 13 paddw                mm0, mm0                 ; double [7 6 5 4]
 14 punpcklbw            mm2, mm7                 ; bytes to word [6 5 4 3]
 15 paddw                mm1, mm1                 ; double [3 2 1 0]
 16 punpcklbw            mm3, mm7                 ; bytes to word [4 3 2 1]
 17 pand         mm2, DWORD PTR _MASK7            ; make  [_ 5 4 3]
 18 psrlq                mm4, 16                          ; align [_ 7 6 5]
 19 pand         mm3, DWORD PTR _MASK0            ; make  [4 3 2 _]
 20 psllq                mm5, 16                          : align [2 1 0 _]
 21 paddw                mm2, mm4                 ; make [___ 5+7 4+6 3+5]
 22 paddw                mm3, mm5                 ; make [2+4 1+3 0+2]
 23 paddw                mm2, mm0                 ; make [2*7 5+7+2*6 4+6+2*5 3+5+2*4]
 24 pand         mm0, DWORD PTR _NOT_MASK7 ; make [2*7    -       -       -    ]
 25 paddw                mm3, mm1                 ; make [2+4+2*3 1+3+2*2 0+2+2*1 2*0]
 26 pand         mm1, DWORD PTR _NOT_MASK0 ; make [    -       -       -    2*0]
 27 paddw                mm2, mm0                 ; make [4*7 5+7+2*6 4+6+2*5 3+5+2*4]
 28 paddw                mm3, mm1                 ; make [2+4+2*3 1+3+2*2 0+2+2*1 4*0]
 29 movq         _lf_blk[edi], mm3                ; Store first half of the row
 30 movq         _lf_blk+8[edi], mm2              ; Store second half of the row
 31 add                  edi, 16
 32 add                  esi, 176
 33 dec                  ecx
 34 jnz                  row_loop                 ; Process 8 rows of data
 35 ret
```

The row_filter code is listed in Example 1. Within the loop, one row of pixels is processed. First, the data is unpacked from bytes to words (lines 6 and 8). Register MM0 contains the higher four words; register MM1 contains the lower four words.

Next, the inner product is calculated as follows:

$$x_i = x_{i-1} + 2x_i + x_{i+1}$$

Look at this calculation for the higher four words. Line 13 calculates the values 2xi (stored in MM0). Lines 9 and 18 compute the values xi+1 by copying the data and shifting right (stored in MM4). Lines 5, 10, and 14 compute values xi-1 by copying the data, shifting right, and then unpacking (stored in MM2).

The code handles the boundary condition at the seventh and zeroth elements by preparing registers with doubled boundary values (lines 24 and 26, respectively).

The inner product of the four upper words is formed by adding the three registers together (lines 21 and 23).

Similar calculations are made for the inner products of both the higher and lower halves of the row. Then, the loop is repeated eight times for eight rows of data.

col_filter Core

Figure 3 illustrates how the col_filter performs an inner product of the results of the row_filter with the [1 2 1] kernel. This time, the rows are added together, forming the [1 2 1] results along the columns (i.e., across the rows). Figure 3 shows the flow of the summation across the rows. As before, boundary conditions exist for the first and last rows, so they are handled in a similar fashion as in the case of the row_filter.

Figure 3. col_filter Flow

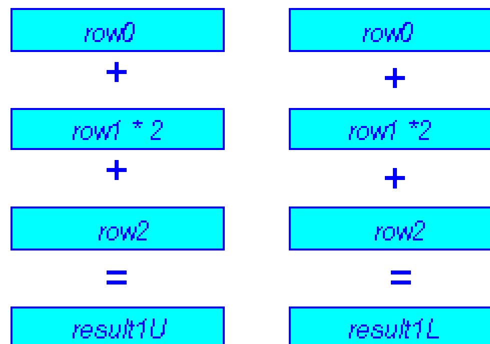
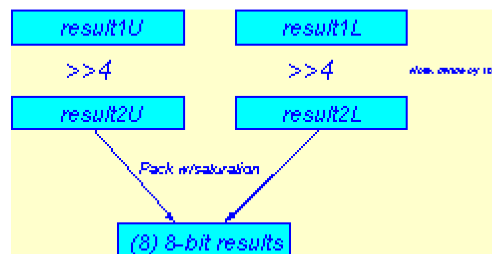


Figure 4 shows how the results are normalized and packed before they are stored in memory. The results are normalized by shifting the result right by 4 places (i.e., dividing by 16). Then the upper and lower results are packed into bytes (with saturation). Packing is necessary because the resulting data elements must be the same size as the input, even though the intermediate calculations were done at twice the precision. As before, boundary conditions are handled separately for the first and last rows in the filter.

Figure 4. Normalizing and Packing the Results



Example 2 lists a small segment of the col_filter code (the loop is completely unrolled for the col_filter). In this code, registers MM2 and MM3 accumulate the rows (lines 4 and 6-10). Lines 11 and 12 normalize the results by shifting right 4 places. Finally, line 9 packs the words back into bytes. Since the col_filter loop has been unrolled, code from different iterations overlaps due to scheduling.

Example 2. col_filter Code

```
1  movq          mm6, _lf_blk+48          ; load row i+1 into mm6
2  packuswb      mm0, mm1        ; row 1 calculation
3  movq          mm7, _lf_blk+56          ; load row i+2 into mm7 (row 3 iter)
4  paddw mm2, mm4          ; accumulate row i-1 + row i
5  movq          frame_y+176[edi], mm0    ; Store results in row 1
6  paddw mm3, mm5
7  paddw mm2, mm4          ; add row i again
8  paddw mm3, mm5
9  paddw mm2, mm6          ; add row i+1
10 paddw mm3, mm7
11 psrlw mm2, 4                  ; normalize result
12 psrlw mm3, 4
```

```
13 movq           mm0, _lf_blk+64
14 packuswb       mm2, mm3         ; pack results back to bytes
15 movq           mm1, _lf_blk+72
16 paddw mm4, mm6
17 mov            frame_y+352[edi], mm2     ; Store results in row 2
```

3.0. PERFORMANCE GAINS

Table1 indicates that the video loop filter coded with MMX instructions performed 1.9X faster than the scalar version of the filter. The data represents the simulation of scalar code and MMX code on a Pentium® processor. The simulation processed 30 blocks of data; each block was 8 pixels by 8 pixels.

The performance increase is due primarily to the ability to exploit the parallelism within the filter. That is, the process is separated into two 1-D filters that are performed in parallel using paddw (with only 1 clock latency for four additions, in parallel). First, the calculation is performed along each row, in conjunction with shifts to form a [1 2 1] filter. Then the calculation is performed along the columns (i.e. across the rows) to form a [1 2 1] filter in the orthogonal direction.

Table . TT_PerfGains Performance Gains

	Scalar Code	**MMX™ Code**
Instructions	20315	11675
Cycles	20003	10549
CPI	0.98	0.90

4.0. LOOP FILTER FUNCTION CODE LISTING

```
        .486P
 ASSUME ds:FLAT, cs:FLAT, ss:FLAT
_TEXT SEGMENT DWORD PUBLIC USE32 'CODE'
_TEXT ENDS
_DATA SEGMENT PARA  PUBLIC USE32 'DATA'
        ALIGN4
_DATA ENDS
_DATA SEGMENT PARA  PUBLIC USE32 'DATA'
        ALIGN    16
_zero_quad      db 0, 0, 0, 0, 0, 0, 0, 0
_MASK0  db 0, 0, 0ffh, 0ffh, 0ffh, 0ffh, 0ffh, 0ffh
_MASK7  db 0ffh, 0ffh, 0ffh, 0ffh, 0ffh, 0ffh, 0, 0
_NOT_MASK0      db 0ffh, 0ffh, 0, 0, 0, 0, 0, 0
_NOT_MASK7      db 0, 0, 0, 0, 0, 0, 0ffh, 0ffh
EXTRN    _frame_y:DWORD
EXTRN    _lf_blk:DWORD
_DATA ENDS
_TEXT SEGMENT DWORD PUBLIC USE32 'CODE'
row_filter Proc C Public uses esi edi ecx, array_offset:DWORD
;Row loop of 121 Filter */
;mem array_offset
  mov           esi, array_offset
  xor           edi, edi
  mov           ecx, 8
  lea           esi, _frame_y[esi]
row_loop:
  movq          mm0, [esi]                          ; get a row
  pxor          mm7, mm7
  movq          mm1, mm0                    ; copy row
  psrlq         mm0, 32                             ; align
  movq          mm2, mm1                    ; copy row
  punpcklbw     mm0, mm7                    ; bytes to word [7 6 5 4]
  movq          mm3, mm2                    ; copy row
  punpcklbw     mm1, mm7                    ; bytes to word [3 2 1 0]
  movq          mm4, mm0                    ; copy half row [7 6 5 4]
  psrlq         mm2, 24                             ; align [_ _ _ 7 6 5 4 3]
  movq          mm5, mm1                    ; copy half row [3 2 1 0]
  psrlq         mm3, 8                              ; align
  paddw         mm0, mm0                    ; double [7 6 5 4]
  punpcklbw     mm2, mm7                    ; bytes to word [6 5 4 3]
  paddw         mm1, mm1                    ; double [3 2 1 0]
  punpcklbw     mm3, mm7                    ; bytes to word [4 3 2 1]
  pand          mm2, DWORD PTR _MASK7               ; make  [_ 5 4 3]
  psrlq         mm4, 16                             ; align [_ 7 6 5]
  pand          mm3, DWORD PTR _MASK0               ; make  [4 3 2 _]
  psllq         mm5, 16                             ; align [2 1 0 _]
  paddw         mm2, mm4                    ; make [___ 5+7 4+6 3+5]
  paddw         mm3, mm5                    ; make [2+4 1+3 0+2]
  paddw         mm2, mm0                    ; make [2*7 5+7+2*6 4+6+2*5 3+5+2*4]
  pand          mm0, DWORD PTR _NOT_MASK7 ; make [2*7     -       -       -    ]
  paddw         mm3, mm1                    ; make [2+4+2*3 1+3+2*2 0+2+2*1 2*0]
  pand          mm1, DWORD PTR _NOT_MASK0 ; make [    -       -       -     2*0]
  paddw         mm2, mm0                    ; make [4*7 5+7+2*6 4+6+2*5 3+5+2*4]
  paddw         mm3, mm1                    ; make [2+4+2*3 1+3+2*2 0+2+2*1 4*0]
  movq          _lf_blk[edi], mm3                   ; Store first half of the row
  movq          _lf_blk+8[edi], mm2                 ; Store second half of the row
  add           edi, 16
  add           esi, 176
  dec           ecx
```

```
  jnz             row_loop                  ; Process 8 rows of data
  ret
row_filter EndP
col_filter Proc C Public uses edi, array_offset:DWORD
;121 Filter kernel for column section
;mem array_offset
  mov             edi, array_offset
  movq            mm0, _lf_blk
  movq            mm1, _lf_blk+8
  psrlw           mm0, 2
  movq            mm2, _lf_blk+16
  psrlw           mm1, 2
  movq            mm3, _lf_blk+24
  movq            mm7, mm0
  movq            mm4, _lf_blk+32
  packuswb        mm7, mm1
  movq            mm5, _lf_blk+40
  psllw           mm0, 2
  movq            _frame_y[edi], mm7                ; Store results in row 0
  psllw           mm1, 2
  paddw           mm0, mm2
  paddw           mm1, mm3
  paddw           mm0, mm2
  paddw           mm1, mm3
  paddw           mm0, mm4
  paddw           mm1, mm5
  psrlw           mm0, 4
  psrlw           mm1, 4
  movq            mm6, _lf_blk+48
  packuswb        mm0, mm1
  movq            mm7, _lf_blk+56
  paddw           mm2, mm4
  movq            _frame_y+176[edi], mm0    ; Store results in row 1
  paddw           mm3, mm5
  paddw           mm2, mm4
  paddw           mm3, mm5
  paddw           mm2, mm6
  paddw           mm3, mm7
  psrlw           mm2, 4
  psrlw           mm3, 4
  movq            mm0, _lf_blk+64
  packuswb        mm2, mm3
  movq            mm1, _lf_blk+72
  paddw           mm4, mm6
  movq            _frame_y+352[edi], mm2    ; Store results in row 2
  paddw           mm5, mm7
  paddw           mm4, mm6
  paddw           mm5, mm7
  paddw           mm4, mm0
  paddw           mm5, mm1
  psrlw           mm4, 4
  psrlw           mm5, 4
  movq            mm2, _lf_blk+80
  packuswb        mm4, mm5
  movq            mm3, _lf_blk+88
  paddw           mm6, mm0
  movq            _frame_y+528[edi], mm4    ; Store results in row 3
  paddw           mm7, mm1
  paddw           mm6, mm0
  paddw           mm7, mm1
  paddw           mm6, mm2
  paddw           mm7, mm3
  psrlw           mm6, 4
  psrlw           mm7, 4
```

```
  movq          mm4, _lf_blk+96
  packuswb      mm6, mm7
  movq          mm5, _lf_blk+104
  paddw         mm0, mm2
  movq          _frame_y+704[edi], mm6    ; Store results in row 4
  paddw         mm1, mm3
  paddw         mm0, mm2
  paddw         mm1, mm3
  paddw         mm0, mm4
  paddw         mm1, mm5
  psrlw         mm0, 4
  psrlw         mm1, 4
  movq          mm6, _lf_blk+112
  packuswb      mm0, mm1
  movq          mm7, _lf_blk+120
  paddw         mm2, mm4
  movq          _frame_y+880[edi], mm0    ; Store results in row 5
  paddw         mm3, mm5
  paddw         mm2, mm4
  paddw         mm3, mm5
  paddw         mm2, mm6
  paddw         mm3, mm7
  psrlw         mm2, 4
  psrlw         mm3, 4
  packuswb      mm2, mm3
  movq          _frame_y+1056[edi], mm2   ; Store results in row 6
  psrlw         mm6, 2
  psrlw         mm7, 2
  packuswb      mm6, mm7
  movq          _frame_y+1232[edi], mm6   ; Store results in row 7
  ret
col_filter EndP
_TEXT ENDS
END
```