Using MMX™ Instructions to Compute a 16-Bit Vector

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1.0. INTRODUCTION

Calculating the dot-product of two vectors requires executing a large number of multiply-accumulate operations. This application note shows how to use the MMX technology PMADDWD instruction to significantly speed up 16-bit vector dot-product calculation. The PMADDWD instruction multiplies four pairs of 16-bit numbers and produces partial sums of the results - and can do so once per clock (with a three-clock latency). A throughput of up to two 16-bit multiply-accumulates per clock can be achieved if the instructions are correctly scheduled. The results are accumulated with 32-bit precision.

2.0. VDPMMX16 FUNCTION

The vector dot-product operation is an basic building block of many common linear algebra and DSP operations, such as matrix multiplication and FIR filters. The VDPMMX16 function, illustrated in Figures 1 and 2, is an MMX technology implementation of the vector dot-product operation. VDPMMX16 performs a dot-product on two 16-bit vectors, calculating the result with 32-bit precision.

The MMX technology PMADDWD instruction is used on four elements from each vector. The results are two 32-bit numbers; the sum of the first two products and the sum of the second two products. These are accumulated into an MMX register by using PADDD. This operation is repeated on the next four elements until all the elements have been multiplied. This is the basic loop of the MMX technology vector dot-product implementation - it can be unrolled to achieve better performance.
At this point the accumulator register contains two (doubleword) partial sums. The actual result of the vector dot-product is the sum of these partial sums. That is, the low and high doublewords must be added together. To do this:

Copy the accumulator register.

Shift the duplicated accumulator register 32 bits to the right, so that the doubleword which was in the high half of the accumulator is in the low half of the duplicated accumulator.

Sum the registers.

Now the desired result is in the low half of the register and it can be written to memory with one MOVQ instruction.

**2.1. Alternate Method**

If the routine can calculate two vector dot-products each time it is called and the data can be interleaved ahead of time without affecting performance, performance can be improved. This is because the accumulation of the partial sums at the end of the loop can be avoided in this case, thereby saving three clocks at the end of the loop (see Figure 3). If the vectors are relatively short, this may be significant.
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**Figure 3. Alternate Method**

With the input data interleaved, the main loop calculates two separate vector dot-products instead of calculating two partial sums of one vector dot-product. Though this method is quicker in specific cases (short vectors, dot-products can be calculated two at a time, vectors can be interleaved ahead of time), in this document the VDPMMX16 function shows the more general case, and will use the first method illustrated in Figures 1 and 2.

**Interleaving the Data**

The two sets of vectors can be interleaved using the PUNPCKLDQ and PUNPCKHDQ instructions (see Figure 4). This can be done without affecting performance if the routine which creates the input data has a few available pairing slots, or the same data is created once and used many times.

**Figure 4. Interleaving Two Vectors**

**2.1. vdpmmx16 Core**

The core of the VDPMMX16 function is listed in Example 1.

**Example 1. vdpmmx16 Core**

1  PXOR mm4, mm4 ; prepare for 1st iteration (SW pipelining)
2  PXOR mm6, mm6 ; prepare for 1st iteration (SW pipelining)
3  PXOR mm7, mm7 ; initialize accumulator
   ;.align 16
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```assembly
vdpl6:
  4  MOVQ mm0,0[eax]  ; first 4 source1 elements
  5  PADDD mm7, mm4  ; accumulate (from prev. iteration)
  6  MOVQ mm1,0[ebx]  ; first 4 source2 elements
  7  PADDD mm7, mm6  ; accumulate (from prev. iteration)
  8  MOVQ mm2,8[eax]  ; next 4 source1 elements
  9  PMADDWD mm0, mm1
      ; s1[0]*s2[0] + s1[1]*s2[1]::s1[2]*s2[2] + s1[3]*s2[3]
 10  MOVQ mm3,8[ebx]  ; next 4 source2 elements
      ; V-pipe empty - memory can be accessed only in U-pipe
 11  MOVQ mm4,16[eax]  ; next 4 source1 elements
 12  PMADDWD mm2, mm3
 13  MOVQ mm5,16[ebx]  ; next 4 source2 elements
 14  PADDD mm7, mm0  ; accumulate
 15  MOVQ mm6,24[eax]  ; last 4 source1 elements
 16  PMADDWD mm4, mm5
 17  PMADDWD mm6, 24[ebx]
 18  PADDD mm7, mm2  ; accumulate
 19  ADD eax, 32  ; increment source1 index
 20  ADD ebx, 32  ; increment source2 index
 21  SUB ecx, 16
 22  JNZ vdp16
 23  PADDD mm7, mm4  ; accumulate from last iteration
      ; (SW pipelining)
 24  PADDD mm7, mm6  ; accumulate from last iteration
      ; (SW pipelining)
```

The **EAX** register contains a pointer to one source vector, the **EBX** register to the other source vector and **ECX** contains the number of elements (words) in the vectors. At the end of this section of code **MM7** contains two partial sums which are later added to generate the final result.

Several changes were made from the flow shown in Figures 1 and 2 to improve performance. One is that the core loop was unrolled four times; it operates on 16 elements each iteration, instead of four. This yields more scheduling opportunities and improves pairing, in addition to reducing loop overhead.

Also software pipelining (scheduling together instructions from different operations or loop iterations) has been used to achieve maximum pairing. The instructions **PADDD MM7, MM4** and **PADDD MM7, MM6** were moved from the bottom of the loop to the top (they were also copied below the loop). Two instructions have been added above the loop to initialize **MM4** and **MM6** for the first loop iteration.

### Memory Operands

The **PMADDWD** instructions operate on data which is be loaded from memory. There are two possible instruction sequences to do this:

```assembly
MOVQ reg1, mem1
MOVQ reg2, mem2
PMADDWD reg1, reg2
```

This sequence uses register operands only.

```assembly
MOVQ reg1, mem1
```
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PMADDWD reg1, mem2

In this sequence, the PMADDWD instruction uses a memory operand.

Unlike scalar IA instructions, MMX instructions with a memory operand suffer no penalty (if the operand is present in the L1 cache). Therefore the choice between the two options is not trivial and should be made on a case-by-case basis. Usually the second sequence is faster, since it contains one less instruction, but in some cases the first sequence can enable better pairing and lower clock counts. This is because the PMADDWD REG1, MEM2 instruction is restricted in pairing both by being a memory-access instruction and by being dependent on REG1. Splitting this into two instructions, each of which has only one of these restrictions, may facilitate pairing. In this code section, three out of four PMADDWD instructions use register operands; one uses a memory operand.

The loop overhead (four instructions) requires two clocks. It could be done with two less instructions (if we use ECX as an index register in addition to the EAX/EBX base register, the incrementation of EAX and EBX can be eliminated). However, since the first loop instruction would then have a one-clock AGI delay, no speed would be gained. If desired, the loop overhead can be reduced by further loop unrolling.

**Data Alignment**

Note that VDPMMX16 does not align the input vectors. The input vectors should both be aligned to eight bytes beforehand to avoid losing significant performance due to misaligned accesses (an additional three clocks per memory access). Note also that since the loop has been unrolled, VDPMMX16 can only operate on vectors if their size is a multiple of 16 words. For applications where this is not always the case, two possible solutions are:

- Pad the vectors with zeros until their size is a multiple of 16 before calling VDPMMX16.
- Alter VDPMMX16 to operate on vectors of all lengths. One way to do this is to add additional loops before and after the core loop. For an example of adding loops to handle vectors of arbitrary size and alignment, see application note AP-560, "Vector Arithmetic and Logic Operations".
3.0. PERFORMANCE GAINS

This section details the performance improvement as compared with traditional scalar code. There is approximately a 5X speedup for the MMX technology version. The results presented here assume all data is in the L1 cache and aligned to eight bytes - gains are reduced if there are cache misses or misaligned accesses.

3.1. Scalar Performance

Since the floating-point multiplication is significantly faster, the fastest scalar implementation is in floating-point. (Unless the vector is short enough for the overhead of converting between formats to be larger than the gain). Ignoring conversion overhead, a well-optimized implementation should be able to issue one multiplication, add or load per clock, so 16 elements + two clocks loop overhead should take about 50 clocks per iteration for a loop which operates on 16 elements.

3.2. MMX™ Code Performance

The inner loop executes in 10 clocks, which is five times faster than the scalar loop. For vectors which are much longer than 16 elements, the total performance improvement for the vector dot-product operation should be close to 500%, assuming all data is in the cache and that both vectors are aligned to eight bytes. If there is significant overhead for converting the data from integer to floating point, the speedup will be higher. The speedup is mostly attributable to the MMX instructions which perform operations on multiple data elements and can be paired, unlike the scalar instructions.

Peak MMX technology rate for multiply-accumulate operations is two 16-bit multiply-accumulate operations per clock. Peak scalar rate for multiply-accumulate operations is one per three clocks, so the peak speedup is 600%. This is reduced to 500% by the loop overhead. To achieve higher speedups the loop can be further unrolled. Though this reduces the loop overhead, care must be taken that the performance loss caused by code size increase is not larger than the gain.
4.0. VDPMMX16 FUNCTION: CODE LISTING

```assembly
.486P
.model FLAT
PUBLIC _vprod_mmx
.DATA SEGMENT
_DATA ENDS
.TEXT SEGMENT
_vprod_mmx PROC NEAR
src1 EQU [esp+16]
src2 EQU [esp+20]
vecsize EQU [esp+24]
result EQU [esp+28]
push ebx
push esi
push edi
mov eax, src1 ; src1 pointer (1 clock AGI delay)
mov ebx, src2 ; src2 pointer
mov ecx, vecsize ; size of src1 and src2 arrays
mov edx, result ; pointer to the result
pxor mm4, mm4 ; prepare for early use (SW pipelining)
pxor mm6, mm6 ; prepare for early use (SW pipelining)
pxor mm7, mm7 ; initialize accumulator
; .align 16
vdp16:
  movq mm0, 0[eax] ; first 4 source1 elements
  paddd mm7, mm4 ; accumulate (from prev. iteration - SW pipelining)
  movq mm1, 0[ebx] ; first 4 source2 elements
  paddd mm7, mm6 ; accumulate (from prev. iteration - SW pipelining)
  movq mm2, 8[eax] ; next 4 source1 elements
  pmaddwd mm0:mm1 ; s1[0]*s2[0] + s1[1]*s2[1]::s1[2]*s2[2] + s1[3]*s2[3]
  movq mm3, 8[ebx] ; next 4 source2 elements
  movq mm4, 16[eax] ; next 4 source1 elements
  movq mm5, 16[ebx] ; next 4 source2 elements
  paddd mm7, mm0 ; accumulate
  pmaddwd mm5:mm5 ; s1[12]*s2[12] + s1[13]*s2[13]::s1[14]*s2[14] + s1[15]*s2[15]
  paddd mm7, mm2 ; accumulate
  add eax, 32 ; increment source1 index
  add ebx, 32 ; increment source2 index
  sub ecx, 16 ; (NOTE: could elim. prev. pair, but AGI)
  jnz vdp16
  paddd mm7, mm4 ; accumulate ; V-pipe empty (mm6 locked because of pmaddwd)
  paddd mm7, mm6 ; accumulate ; V-pipe empty (data dependency)
  movq mm0, mm7 ; copy accumulator ; V-pipe empty (data dependency)
  psrlq mm0, 32 ; shift high order 32 bits of accumulation ; V-pipe empty (data dependency)
  paddd mm7, mm0 ; add high and low order 32 bits of accumulation ; V-pipe empty (data dependency)
  movd [edx],mm7 ; store result ; V-pipe empty (integer inst. does not pair w/ MM memory reference)
  pop edi
  pop esi
  pop ebx
  ret 0
_vprod_mmx ENDP
_TEXT ENDS
END
```

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