

Efficient Multiplication and Division Using MSP430

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MSP430

ABSTRACT

Multiplication and division in the absence of a hardware multiplier require many instruction cycles, especially in C. This report discusses a method that does not need a hardware multiplier and can perform multiplication and division with only shift and add instructions. The method described in this application report is based on Horner's method. The MSP430 microcontroller CPU can perform a register shift or add in one instruction cycle. This allows fast execution of multiplications and divisions using Horner's method. This method not only produces accurate results but also provides a very good dynamic range as it does not totally depend on finite word length effects like some of the conventional methods. Also discussed is the Canonical Signed Digit (CSD) representation of numbers which further reduces the computational load when used with this method for multiplication and division. Note that Horner's method requires the multiplier or the divisor to be known in advance to function.

1 Introduction

Numbers can be broadly classified as fixed point and floating point. The fixed-point number representation is limited to positive and negative integers, whereas the floating-point number representation can accommodate fractions as well. Microcontrollers are fixed-point machines and deal with only fixed-point arithmetic. Hence, alternate methods need to be devised to handle floating-point arithmetic. This also leads to a loss in precision due to finite word length effects. Most microcontrollers do not have a hardware multiplier and rely on algorithms based on repeated addition to perform multiplication and division operations. This consumes a lot of instruction cycles and also exhibits limited precision. The Horner's method discussed here is tailor-made for such machines without much loss in precision.

2 Horner's Method

The Horner's method requires the multiplier or the divisor to be known in advance. This is not a serious limitation, since few applications perform multiplication or division of numbers that change at runtime. Once this is established, the multiplication or division can be performed efficiently with just shift and add operations. The operand is denoted by X, the multiplier by M, and the divisor by D.

2.1 Multiplication

In explaining this method, first is considered the multiplication of two unsigned fractions.

2.1.1 Example 1: Unsigned Multiplication of Two Fractions

Let the number 0.12345 be multiplied by the constant 0.14325. The 12-bit binary representations of these numbers are:

$$X = 0.12345 = 0.000111111001_b$$

$$M = 0.14325 = 0.001001001010_b$$

Horner's Method

The conventional method to perform this multiplication is:

$$\begin{aligned}
 0.12345 \times 0.14325 &= (0.000111111001_b)(2^{-3} + 2^{-6} + 2^{-9} + 2^{-11}) \\
 &= 0.000000111111_b + \\
 &\quad 0.000000000111_b + \\
 &\quad 0.000000000001_b + \\
 &\quad 0.000000000000_b \\
 \hline
 0.000001000111_b &= 0.017333984375
 \end{aligned}$$

The correct result of this multiplication is 0.0176842125, and the above method results in an absolute error of 0.000350228125, which is approximately 1.5 LSB. This error can be attributed to finite word length effects due to register width limitations. As the number of bits allocated for the fractions increase this error is reduced. The Horner's method aims to reduce this error while maintaining the same register widths.

The Horner's algorithm is based on the positions of the 1s in the multiplier and their distance to the immediate 1 to their left. This is done starting from the rightmost bit position and moving left until the last 1 before the binary point.

In the binary equivalent of the multiplier $0.14325 = 0.001001001010_b$, starting from the right the first 1 occurs at bit position 2^{-11} . The difference in position of this 1 to its immediate 1 to the left is two. Similarly the difference for the 1 in bit position 2^{-9} is three and so on.

If the number to be multiplied is denoted as X , the design equations can be written as:

Step 1: Set the intermediate result equal to the operand X and start with the rightmost 1

$$X \times 2^{-2} + X = X_1 \quad \text{For the first iteration, the weight } 2^{-2} \text{ is applied to the intermediate result as the distance of the rightmost 1 (bit position } 2^{-11}) \text{ in the multiplier to its next 1 (bit position } 2^{-9}) \text{ is two. The operand } X \text{ is added to account the occurrence of the 1 at bit position } 2^{-9}. \text{ The result of this addition is now stored as the intermediate result after this step.}$$

Step 2: Proceed to the next 1 in bit position 2^{-9}

$$X_1 \times 2^{-3} + X = X_2 \quad \text{The weight } 2^{-3} \text{ is now applied to the intermediate result (updated in Step 1) since the distance of the 1 in bit position } 2^{-9} \text{ to its next 1 (bit position } 2^{-6}) \text{ is three. The operand is again added for the reason explained in Step 1.}$$

Step 3: Proceed to the next 1 in bit position 2^{-6}

$$X_2 \times 2^{-3} + X = X_3 \quad \text{The weight } 2^{-3} \text{ is applied to the intermediate result (updated in Step 2) and the operand added.}$$

Step 4: Proceed to the last 1 in bit position 2^{-3}

$$\text{Final result} = X_3 \times 2^{-3} \quad \text{The factor } 2^{-3} \text{ is applied to the intermediate result (updated in Step 3), as it is the weight at the position of the leftmost 1. The operand is not added this time, since all the 1s have been taken into account.}$$

The design equations for this division are:

Step 1: Set the intermediate result equal to the operand X and start with the rightmost 1

$X \times 2^{-1} + X = X_1$ For the first iteration, the weight 2^{-1} is applied to the intermediate result as the distance of the rightmost 1 (bit position 2^{-15}) in the multiplier to its next 1 (bit position 2^{-14}) is one. The operand X is added to account the occurrence of the 1 at bit position 2^{-14} . The result of this addition is now stored as the intermediate result after this step.

Step 2: Proceed to the next 1 in bit position 2^{-14}

$X_1 \times 2^{-1} + X = X_2$ The weight 2^{-1} is now applied to the intermediate result (updated in Step 1) since the distance of the 1 in bit position 2^{-14} to its next 1 is one. The operand is again added for the reason explained in Step 1.

Step 3: Proceed to the next 1 in bit position 2^{-13}

$X_2 \times 2^{-1} + X = X_3$ The weight 2^{-1} is applied to the intermediate result (updated in Step 2) and the operand added.

Step 4: Proceed to the next 1 in bit position 2^{-12}

$X_3 \times 2^{-5} + X = X_4$ The weight 2^{-5} is applied to the intermediate result (updated in Step 3) and the operand added.

Step 5: Proceed to the next 1 in bit position 2^{-7}

$X_4 \times 2^{-1} + X = X_5$ The weight 2^{-1} is applied to the intermediate result (updated in Step 4) and the operand added.

Step 6: Proceed to the last 1 in bit position 2^{-6}

Final result = $X_5 \times 2^{-6}$ The factor 2^{-6} is applied to the intermediate result (updated in Step 5) as it is the weight at the position of the leftmost 1. The operand is not added this time, since all the 1s have been taken into account.

The correct result for this division is 10.5407827, and the result obtained is 10 with the fractional part discarded with an error of 0.5407827, similar to the error in conventional methods.

All types of operands and multipliers shown in the previous section and Appendix A can be extended to the process of division to produce the desired results.

2.3 Canonical Signed Digit Representation (CSD)

The efficiency of Horner's method can be further improved by using the Canonical Signed Digit (CSD) format to represent the multiplier or divisor. The CSD format aims to reduce the number of add operations during multiplication and division. The CSD format has a ternary set as opposed to a binary set in number representation. The symbols used in this format are $\{0, 1, \bar{1}\}$, with $\bar{1}$ representing -1 . The goal is to group consecutive 1s and change them to a ternary representation from binary representation. This is done starting from the rightmost 1 and proceeding left until the last 1. By doing so, the final CSD representation never has adjacent 1s or $\bar{1}$ s. This representation is effective when there are many adjacent 1s in the binary representation.

Table 1. Observations for the Methods Discussed

Type	Methods	Instruction Cycles	Code Size (bytes)	Results	Absolute Error
Integer-Integer Multiplication (41 × 441)	CLIB ⁽¹⁾	77	50	18081	0
	Existing methods ⁽²⁾	107	54	18081	0
	Horner	15	32	18081	0
	Horner+CSD	13	30	18081	0
Integer-Integer Division (9280/41)	CLIB	183	80	226	0
	Existing methods	191	28	226	0
	Horner	23	48	226	0
	Horner+CSD	21	44	226	0
Integer-Float Multiplication (41 × 441.8375)	CLIB	427 ⁽³⁾	322	18115.3375	0
	Existing methods	107	54	18081	34.3375
	Horner	32	66	18115	0.3375
	Horner+CSD	29	60	18115	0.3375
Integer-Float Division (1500/37.12345)	CLIB	476	500	40.4057	0
	Existing methods	191	28	40	0.4057
	Horner	24	50	40	0.4057
	Horner+CSD	22	46	40	0.4057

(1) The C library is part of the IAR Embedded Workbench Ver. 3.41A, written for MSP430 family of devices.

(2) The algorithms have been explained in the book *Computer Organization*, Carl Hamacher, Zvonko Vranesic, and Safawat Zaky, 3rd Edition, McGraw Hill Publication, 1990.

(3) Includes cycles for type conversion from float to integer as part of a requirement of the algorithm used.

2.4.2 Tradeoffs

Table 1 results are used as a comparison of speed, accuracy and memory requirements. The MSP430 CPU implements Horner's algorithms extremely quickly with its single cycle shift and add operations. The Horner's method, when compared to the existing methods, is extremely fast and maintains the same level of accuracy for integer-integer multiplications and better accuracy for integer-float multiplications. Division is also performed extremely fast with limited accuracy. The error in Horner's method is similar to existing methods for integer-integer division. The results for integer-float divisions can be improved by representing the divisor by a higher number of bits, with an insignificant increase in cycle count. There is no provision to obtain the remainder during division in Horner's method, which is not the case with the existing algorithms. The most important benefit of Horner's method is the multipliers and divisors suffer very little from finite word length effects. Although the examples considered had only 12- or 16-bit word lengths, each of them can be implemented with large precision with proportional increase in the number of shift and add operations. The memory requirement is much higher for Horner's method since, for each multiplier or divisor, the code is different. In cases where speed is of prime concern, this is not a serious limitation. Also Horner's method requires the multiplier or the divisor to be known in advance, which is not the case with the other methods. This does not pose any limitation to filtering operations and other standard conversions, where the multipliers and divisors do not change during runtime.

Appendix A

In this appendix, several numerical examples are given for better understanding of Horner's method for various types of operands and multipliers.

A.1 Example 4: Signed Multiplication of Fractions With Multiplicand Negative

Consider the example when -0.12345 is multiplied by the constant 0.14325 . The representation of this negative fraction in the 2s complement format is:

$$X = -0.12345 = \bar{1}.111000000111_b$$

$$M = 0.14325 = 0.001001001010_b$$

where $\bar{1}$ is the sign bit representing -1 .

The design equations for this numerical example are shown.

$$X_1 = X \times 2^{-2} + X = \begin{array}{r} 1.111110000001_b + \\ 1.111000000111_b \\ \hline \end{array}$$

$$X_1 \rightarrow 1.110110001000_b$$

$$X_2 = X_1 \times 2^{-3} + X = \begin{array}{r} 1.111110110001_b + \\ 1.111000000111_b \\ \hline \end{array}$$

$$X_2 \rightarrow 1.110110111000_b$$

$$X_3 = X_2 \times 2^{-3} + X = \begin{array}{r} 1.111110110111_b + \\ 1.111000000111_b \\ \hline \end{array}$$

$$X_3 \rightarrow 1.110110111110_b$$

Final result $= X_3 \times 2^{-3} = 1.111110110111_b = -0.017822265625$, which has an absolute error of 0.000138053125 , which is just 0.565466 LSB.

The above example shows that the method is accurate, regardless of the sign of the operand X . If the multiplier were a negative number, the above procedure remains exactly the same, except that in the end the operand X is subtracted due to the sign bit of the multiplier. The design equations for this are shown in Example 5.

A.2 Example 5: Signed Multiplication of Fractions With Multiplier Negative

If the multiplier is now considered to be -0.12345 and the operand X to be 0.14325 . The binary representations are:

$$M = -0.12345 = \bar{1}.111000000111_b$$

$$X = 0.14325 = 0.001001001010_b$$

where $\bar{1}$ is the sign bit representing -1 .

$$X \times 2^{-1} + X = X_1$$

$$X_1 \times 2^{-1} + X = X_2$$

$$X_2 \times 2^{-1} + X = X_3$$

$$X_3 \times 2^{-1} + X = X_4$$

$$X_4 \times 2^{-1} + X = X_5$$

Final result = $X_5 \times 2^{-1} - X$.

With the present operands the absolute error obtained is 0.000138053125, which is 0.565466 LSB.

The previous examples considered fraction-fraction multiplication exhibiting the better accuracy of this method over others. This method can also be employed when the multiplier is any integer or real number. The procedure for this is very similar to the previous method, with a slight change. In microcontrollers, the operand X is usually data coming from the analog-to-digital converter (ADC), which is a fixed-point number. Typical examples are considered with the operand X a fixed point and the multiplier an integer or a real number.

A.3 *Example 6: Unsigned Multiplication of Integers*

Consider the value of X to be 41 and the multiplier is 441.

$$X = 41 = 0101001_b$$

$$M = 441 = 0110111001_b$$

The only change when the multiplier is an integer is the algorithm starts looking for 1s starting from the leftmost bit and moves right. Similar to the approach for fractions the difference in bit positions of the neighboring 1s is used as weights. Since the direction is from left to right the weights all become positive powers of 2 rather than negative. The design equation for this example is:

$$X \times 2^1 + X = X_1$$

$$X_1 \times 2^2 + X = X_2$$

$$X_2 \times 2^1 + X = X_3$$

$$X_3 \times 2^1 + X = X_4$$

$$X_4 \times 2^3 + X = X_5$$

Final result = $X_5 \times 2^0$.

The final result becomes the result X_5 weighted by 2^0 (the bit position of the rightmost 1).

The absolute error obtained for this multiplication is zero.

A.4 *Example 7: Signed Multiplication of Integers With Multiplier Negative*

The design equations would slightly change if the multiplier was negative. Consider the multiplier to be -441 instead for the same X .

$$X = 41 = 0101001_b$$

$$M = -441 = \bar{1}001000111_b$$

Example 8: Unsigned Integer-Float multiplication

The design equations now become:

$$\begin{aligned}
 -X \times 2^3 + X &= X_1 && \text{The sign bit causes the operand to be negative in the first equation.} \\
 X_1 \times 2^4 + X &= X_2 \\
 X_2 \times 2^1 + X &= X_3 \\
 X_3 \times 2^1 + X &= X_4
 \end{aligned}$$

Final result = $X_4 \times 2^0$.

The absolute error obtained for this multiplication is zero.

If the multiplier is a real number with an integer part and fractional part, the method is just a combination of the two types discussed so far. The algorithm is now divided into two parts, one for the integer part of the multiplier and the other for the fractional part of the multiplier. This approach is explained in Example 8.

A.5 Example 8: Unsigned Integer-Float multiplication

Consider the multiplier to be defined as 441.8375 and the operand X is 41.

$$\begin{aligned}
 X &= 41 = 0101001_b \\
 M &= 441.8375 = 0110111001.1101011001_b
 \end{aligned}$$

The fact to note here is that this method is independent of word length for the multiplier. The overhead would only be in the number of shifts and adds to be done.

The design equations for this example is given by:

$$\begin{aligned}
 X \times 2^1 + X &= X_1 \\
 X_1 \times 2^2 + X &= X_2 \\
 X_2 \times 2^1 + X &= X_3 \\
 X_3 \times 2^1 + X &= X_4 \\
 X_4 \times 2^3 + X &= X_5
 \end{aligned}$$

Intermediate result due to integer part = $X_5 \times 2^0$.

$$\begin{aligned}
 X \times 2^{-3} + X &= X_1 \\
 X_1 \times 2^{-1} + X &= X_2 \\
 X_2 \times 2^{-2} + X &= X_3 \\
 X_3 \times 2^{-2} + X &= X_4 \\
 X_4 \times 2^{-1} + X &= X_5
 \end{aligned}$$

Intermediate result due to fractional part = $X_5 \times 2^{-1}$.

Adding the above two results gives us the final solution. The absolute error obtained for this multiply is just the fractional part and is 0.3375 LSB.

The procedure is very similar if the multiplier is a negative real number, as shown in Example 9.

A.6 Example 9: Signed Integer-Float Multiplication With Multiplier Negative

Consider the multiplier to be defined as -441.8375 , and the operand X is 41.

$$X = 41 = 0101001_b$$

$$M = -441.8375 = \bar{1}001000110.0010100111_b$$

The design equations for this example is given by:

$$-X \times 2^3 + X = X_1$$

$$X_1 \times 2^4 + X = X_2$$

$$X_2 \times 2^1 + X = X_3$$

Intermediate result due to integer part = $X_3 \times 2^1$.

$$X \times 2^{-1} + X = X_1$$

$$X_1 \times 2^{-1} + X = X_2$$

$$X_2 \times 2^{-3} + X = X_3$$

$$X_3 \times 2^{-2} + X = X_4$$

Intermediate result due to fractional part = $X_4 \times 2^{-3}$.

Adding the above two results gives us the final solution. The absolute error obtained for this multiply is just the fractional part and is 0.6625 LSB.

A.7 Example 10: Unsigned Integer Multiplication With CSD

Consider the example of an integer-integer multiplication using Horner's method using the CSD format, with the operand X being 41 and multiplier 441.

$$X = 41 = 0101001_b$$

$$M = 441 = 0110111001_b = 100\bar{1}00\bar{1}001_{CSD}$$

The design equations are

$$X_1 = X \times 2^3 - X = \begin{array}{r} 00101001000_b - \\ \underline{00000101001_b} \\ X_1 \rightarrow 00100011111_b \end{array}$$

$$X_2 = X_1 \times 2^3 - X = \begin{array}{r} 100011111000_b - \\ \underline{000000101001_b} \\ X_2 \rightarrow 100011001111_b \end{array}$$

$$X_3 = X_2 \times 2^3 + X = \begin{array}{r} 100011001111000_b + \\ \underline{000000000101001_b} \\ X_3 \rightarrow 100011010100001_b \end{array}$$

Example 11: Unsigned Integer-Float Multiplication With CSD Format

Final result = $X_3 = (100011010100001)_b = 18081$.

The absolute error obtained for this multiplication is zero.

The design equations remain the same if the operand X were a negative number.

A.8 Example 11: Unsigned Integer-Float Multiplication With CSD Format

When the multiplier is a real number say 441.8375 and the operand X is a positive integer say 41, the design equations become:

$$X = 41 = 0101001_b$$

$$M = 441.8375 = 0110111001.1101011001_b = 100\bar{1}00\bar{1}010.00\bar{1}0\bar{1}0\bar{1}001_{\text{CSD}}$$

The design equations for this example is given by:

$$X \times 2^3 - X = X_1$$

$$X_1 \times 2^3 - X = X_2$$

$$X_2 \times 2^2 + X = X_3$$

Intermediate result due to integer part = $X_3 \times 2^1$.

$$X \times 2^{-3} - X = X_1$$

$$X_1 \times 2^{-2} - X = X_2$$

$$X_2 \times 2^{-2} - X = X_3$$

Intermediate result due to fractional part = $X_3 \times 2^{-3}$

Adding the above two results gives us the final solution. The absolute error obtained for this multiplication is just the fractional part and is 0.3375 LSB.

A point to be noted here is if the rightmost bit is $\bar{1}$, the design equations start with a negative X weighted and added or subtracted with X depending on the next bit being 1 or -1 , respectively.

A.9 Example 12: Signed Integer-Float Multiplication With Multiplier Negative in CSD Format

Consider the example if the multiplier was negative and the operand X a positive number 41 with the multiplier -441.8375 .

$$X = 41 = 0101001_b$$

$$M = -441.8375 = \bar{1}001000110.0010100111b = \bar{1}0010010\bar{1}0.001010100\bar{1}_{\text{CSD}}$$

The design equations are:

$$-X \times 2^3 + X = X_1$$

$$X_1 \times 2^3 + X = X_2$$

$$X_2 \times 2^2 - X = X_3$$

Intermediate result due to integer part = $X_3 \times 2^1$.

$$-X \times 2^{-3} + X = X_1$$

$$X_1 \times 2^{-2} + X = X_2$$

$$X_2 \times 2^{-2} + X = X_3$$

Intermediate result due to fractional part = $X_3 \times 2^{-3}$.

Adding the above two results gives the final solution. The absolute error obtained for this multiplication is just the fractional part and is 0.6625 LSB.

Appendix B MSP430 Code

B.1 MSP430 Code

The MSP430 codes that implement multiplication and division are shown below. For some of these examples, it can be assumed that the incoming operand is a 12-bit sample from the ADC. The codes used and their functionality are given below.

multiply_int.c – source file calling four math functions. All the functions perform multiplication of two 16-bit integers to give a 16-bit integer result. The "main()" function calls each of these functions.

mul.s43 – assembly source file containing an existing scheme for integer-integer multiplication using only shift and add operations. This source file is called by function "main()" in the source file multiply_int.c and multiply_float.c.

horner_mul_int.s43 – assembly source file containing the Horner's scheme for integer-integer multiplication. This source file is called by function "main()" in the source file multiply_int.c.

csd_mul_int.s43 – assembly source file containing the Horner's scheme using the CSD format for integer-integer multiplication. This source file is called by function "main()" in the source file multiply_int.c.

multiply_float.c – source file calling four math functions. All the functions perform multiplication of a 16-bit integer with a floating point number to give a 16-bit integer or float result. The "main()" function calls each of these functions.

horner_mul_float.s43 – assembly source file containing the Horner's scheme for integer-float multiplication. This source file is called by function "main()" in the source file multiply_float.c.

csd_mul_float.s43 – assembly source file containing the Horner's scheme using the CSD format for integer-float multiplication. This source file is called by function "main()" in the source file multiply_float.c.

div_int.c – source file calling four math functions. All the functions perform division of two 16-bit integers to give a 16-bit integer result. The "main()" function calls each of these functions.

div.s43 – assembly source file containing an existing scheme for integer-integer division using only shift and add operations. This source file is called by function "main()" in the source file div_int.c and div_float.c.

horner_div_int.s43 – assembly source file containing the Horner's scheme for integer-integer division. This source file is called by function "main()" in the source file div_int.c.

csd_div_int.s43 – assembly source file containing the Horner's scheme using the CSD format for integer-integer division. This source file is called by function "main()" in the source file div_int.c.

div_float.c – source file calling four math functions. All the functions perform division of a 16-bit integer with a floating point number to give a 16-bit integer or float result. The "main()" function calls each of these functions.

horner_div_float.s43 – assembly source file containing the Horner's scheme for integer-float division. This source file is called by function "main()" in the source file div_float.c.

csd_div_float.s43 – assembly source file containing the Horner's scheme using the CSD format for integer-float multiplication. This source file is called by function "main()" in the source file div_float.c.

These files are provided as a zip file downloadable with this application report.

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