INTRODUCTION

There are various ways on how to implement the Analog-to-Digital (A/D) conversion in a circuit. For a simple and low bandwidth analog application such as DC voltmeter, it is desirable to have a low cost yet high resolution A/D converter.

This application note describes a method to implement A/D conversion on the PIC16C5X and PIC16F5X series of microcontrollers. The converter requires only five external components and is software and hardware configurable for conversion resolutions from six bits up to ten bits, and conversion times of 250 us or longer. The method is usable for both voltage and current conversion and uses a software calibration technique that compensates for time and temperature drift, as well as component errors. Following are reasons why PIC16C5X and PIC16F5X microcontroller families are ideal for simple analog applications:

- Very low cost
- Few external components required
- Fully programmable; PIC16C5X microcontrollers for One-Time-Programmable (OTP) EEPROM devices and PIC16F5X for Flash devices

THEORY OF OPERATION

Figure 1 shows a simplified schematic of the A/D converter circuit. There are two input voltages connected one at a time to op amp U1. VREF is the fixed reference voltage used in calibration and VMEAS is the unknown voltage to be converted. Resistor R1 and Capacitor C1 form a charging circuit used to convert input voltage to time. The existence of U1 in the circuit removes the logarithmic characteristic that would occur if the input voltage is directly applied to R1 and C1. The microcontroller controls the U1 operation by turning ON/OFF the four switches, S1-S4 of Analog Switch IC, at different conversion stages. Additionally, the microcontroller measures the time and calculates the digital representation of the unknown input voltage.

The circuit can also be used as a Current mode A/D converter. In this case, the input voltage to the current converter is not needed and the reference current and input current are both routed via analog switches directly into the capacitor.
In order to visualize the different stages of conversion, let us refer to U1 output voltage $V_O$ waveform shown in Figure 2.

**FIGURE 2:** OPERATIONAL AMPLIFIER OUTPUT VOLTAGE WAVEFORM

At $t_0-t_1$, S1 and S3 are ON, S2 and S4 are OFF and RA0 is pulled to ground by the software. This yields the equivalent circuit in Figure 3. $V_O$ is equal to $V_{REF}$ since $V_{IN}$ is equal to $V_{REF}$ and S3 force unity gain feedback. C1 is discharging or is initially discharged after the Reset state. In any case, this stage ensures that C1 is fully discharged before going to the next stage. At the end of $t_1$, S1 remains ON, S2 remains OFF, S3 is OFF, S4 is ON and RA0 is configured as an input pin. This yields the equivalent circuit in Figure 4. As a function of $V_{REF}$, $V_O$ is started to ramp-up linearly while C1 is charging. The $V_O$ ramp-up continues until the threshold voltage input $V_{th}$ of the microcontroller trips. This generates a software calibration value equal to $t_{ref}$. This calibration value is measured and used to calibrate out most circuit errors, including inaccuracies in the resistor and capacitor, changes in the $V_{th}$, and temperature variation.

**FIGURE 3:** EQUIVALENT CIRCUIT DURING DISCHARGING

After the software calibration value is measured at $t_2$, S2 and S3 are ON, S1 and S4 are OFF and RA0 is pulled to ground again by the software. This yields the same equivalent circuit in Figure 3. However, $V_O$ is equal to $V_{MEAS}$ since $V_{IN}$ is equal to $V_{MEAS}$ and S3 force unity feedback. C1 is discharging from $t_2$ to $t_3$. At the end of $t_3$, S2 remains ON, S1 remains OFF, S3 is OFF, S4 is ON and RA0 is configured as an input pin. This yields the same equivalent circuit in Figure 4. As a function of $V_{MEAS}$, $V_O$ is started to ramp-up linearly while C1 is charging. The $V_O$ ramp-up continues until the $V_{th}$ of the microcontroller trips. This generates a software $V_{MEAS}$ value equal to $t_{meas}$. This value is compared to the software calibration value to determine the actual digital representation of $V_{MEAS}$. 
A/D CONVERTER EQUATIONS

Based on the circuit operation, equation is used by the microcontroller in order to calculate the final conversion result.

In Figure 4, current through R1 is equal to the current through C1.

When input voltage $V_{IN}$ is equal to $V_{REF}$, the relation between the two currents are represented as (see Equation 1):

**EQUATION 1: R1 AND C1 CURRENT EQUATION WHEN INPUT VOLTAGE IS $V_{REF}$**

$$\frac{V_{ref}}{R1} = C1 \frac{dV_0}{dt}$$

and when $V_{IN}$ is equal to $V_{MEAS}$, the relation between the two currents are represented as (see Equation 2):

**EQUATION 2: R1 AND C1 CURRENT EQUATION WHEN INPUT VOLTAGE IS $V_{MEAS}$**

$$\frac{V_{meas}}{R1} = C1 \frac{dV_0}{dt}$$

Integrating Equation 1 and 2 results (see Equation 3 and Equation 4):

**EQUATION 3: INTEGRATION RESULT OF EQUATION 1**

$$V_0 = \frac{1}{R1C1} \int_{0}^{t_{ref}} V_{ref} dt$$

and

**EQUATION 4: INTEGRATION RESULT OF EQUATION 2**

$$V_0 = \frac{1}{R1C1} \int_{0}^{t_{meas}} V_{meas} dt$$

Since $V_{REF}$ and $V_{MEAS}$ is constant input, Equation 3 and Equation 4 can be reduced further to:

**EQUATION 5: U1 VOLTAGE OUTPUT EQUATION AS A FUNCTION OF $V_{REF}$**

$$V_0 = \frac{V_{ref} t_{ref}}{R1C1}$$

and

**EQUATION 6: U1 VOLTAGE OUTPUT EQUATION AS A FUNCTION OF $V_{MEAS}$**

$$V_0 = \frac{V_{meas} t_{meas}}{R1C1}$$

At the end of each measurement, $V_O$ of Equation 5 and Equation 6 are both equal to $V_{th}$, therefore, equating both equations yields:

**EQUATION 7: RESULT OF EQUATIONS 5 AND 6**

$$V_{ref} t_{ref} = V_{meas} t_{meas}$$

In Equation 7, R1 and C1 can be eliminated and solved for $V_{MEAS}$, the unknown input voltage.

**EQUATION 8: FINAL CONVERSION**

$$V_{meas} = \frac{V_{ref} t_{ref}}{t_{meas}}$$

In Equation 8, it is apparent that the measurement is independent of the value of circuit elements R1 and C1. This makes the conversion insensitive to errors in R1 and C1 value, due to the inaccuracy or temperature variation. However, this does not mean that the value of R1 and C1 is unimportant in the design of the A/D converter. The values of R1 and C1 should be selected based upon the number of bits of resolution. Looking back at Equation 6 and solving $R1C1$ (see Equation 9):
EQUATION 9: CALCULATION OF R1C1 VALUE

\[
R1C1 = \frac{V_{\text{meas}} \cdot t_{\text{meas}}}{V_0}
\]

where

- \( V_{\text{meas}} \) = Lowest voltage to be measured (at least ten LSBs)
- \( t_{\text{meas}} \) = Time to do the number of bits of resolution desired
  \( (2^N \times fosc \times 4 \text{ clock/cycle} \times \text{instruction cycles per count} \times \text{desired bits per count}) \)
- \( V_0 = V_{\text{th}} \) = Threshold Voltage input of the PIC16C5x/PIC16F5x being used (3V estimated)

The actual value for R1C1 should be slightly smaller than calculated, to ensure that the PIC16C5X or PIC16F5X does not over count during the measurement.
CIRCUIT CONFIGURATIONS

C and Assembly code implementing the circuit of Figure 1 is listed in Appendix A: “Source Code in C” and Appendix B: “Source Code in Assembly”.

These codes measure the time up to 16 bits. The full implementation of algorithm can be seen in the flowchart shown in Figure 5.

FIGURE 5: A/D CONVERSION FLOWCHART

There is a difference between the R1C1 value when implementing in Assembly and C. This is because the instruction cycles per count, when using C, is greater than the Assembly.

Using the 4 MHz external RC clock oscillator, the value of R1C1 can be calculated as follows (see Equation 10):

For the C code:

EQUATION 10: R1C1 CALCULATION IN C

\[ R1C1 = \frac{100 mV \times 2^{16} \times \frac{1}{4 MHz} \times 4 \times \text{clocks per cycle} \times 16 \text{ cycles per count}}{3V} \]

For the Assembly code (see Equation 11):

EQUATION 11: R1C1 CALCULATION IN ASSEMBLY

\[ R1C1 = \frac{100 mV \times 2^{16} \times \frac{1}{4 MHz} \times 4 \times \text{clocks per cycle} \times 6 \text{ cycles per count}}{3V} \]
In actual applications, if measurement accuracy permits, it may be advantageous to use lower resolution bits and higher clock source. The math code can be substantially reduced and the measure time is reduced by the simpler code and shorter count.

CIRCUIT PERFORMANCE

The calibration value removes all first order errors (offset, gain, R and C inaccuracy, power supply voltage and temperature) except the reference voltage drift. Any change in the reference voltage, including noise, may result in measurement errors. Other error sources may be analog switch leakage, resistor and capacitor non-linearities, input threshold uncertainty and time measurement uncertainty (± one instruction cycle time). Measured performance shows the converter to be accurate within ±1% of full scale.

FIGURE 6: PERCENT ERROR AT FULL-SCALE CONVERSION

V_{REF} = 2.5V; R1 = 33K ohm; C1 = 1uF

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<tr>
<th>V_{IN}</th>
<th>Computed</th>
<th>Actual</th>
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<tr>
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<td>HEX</td>
<td>DEC</td>
</tr>
<tr>
<td>2.5</td>
<td>9A3</td>
<td>2467</td>
</tr>
<tr>
<td></td>
<td>9A1</td>
<td>2465</td>
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</table>

<table>
<thead>
<tr>
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<th>%ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.081%</td>
</tr>
</tbody>
</table>

CONCLUSION

For a simple and low bandwidth analog application, it usually requires a low cost yet high resolution A/D converter. By using the PIC16C5X and PIC16F5X baseline family of microcontrollers, this application note demonstrates how to meet such requirements. The A/D converter does not only use fewer components but also has a capability to calibrate out most circuit errors.
APPENDIX A: SOURCE CODE IN C

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EXAMPLE A-1: A/D CONVERTER PROGRAM IN C

/******************************************************************************
File Name:
PIC16F5xADC.c

Summary:
This is the main file used for the Application Note AN00513

Hardware implementation requires:
R1 = 33K ohm
C1 = 1uF
RC oscillator value are 4.7K ohm and 22pF, respectively.
Vref = 2.5V

Generation Information :
Device : PIC16F57
Compiler : XC8 v1.21
MPLAB : MPLAB X 1.90
******************************************************************************/

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********************************************************************************/

#include <xc.h>

// CONFIG
#pragma config OSC = RC      // Oscillator selection bits (RC oscillator)
#pragma config WDT = OFF     // Watchdog timer enable bit (WDT disabled)
#pragma config CP = OFF      // Code protection bit (Code protection off)

void initPORTS()
{
    PORTA = 0x00;   //set RA0 low (on when activated)
    TRISB = 0x00;   //set all pins in PORTB as output
    OPTION = 0x28; //select positive edge for TMRO
}
EXAMPLE A-2: A/D CONVERTER PROGRAM IN C

```c
void DSCHRG_CAP()
{
    TRISA = 0x00;  // RA0 on
    _delay(5000);  // RC discharging time
    TRISA = 0x01;  // set RA0 to have high impedance
}

void main()
{
    unsigned int Tcount, Tmeas, Tref, Vref, Vmeas;
    unsigned long mpy;

    Vref = 0x09A3;  // Digital Equivalent of Vref voltage
    Vmeas = 0;      // Initiate Vmeas to 0
    initPORTS();   // Initialize I/O pin
    while(1)
    {
        PORTB = 0x05;  // S1 and S3 activated (Vref)
        DSCHRG_CAP();  // discharge capacitor charge
        PORTB = 0x09;  // S1 and S4 activated
        TMR0 = 0x00;   // reset counter and TMR0
        Tcount = 0;
        while(!TMR0)  // increment Tcount until TMR0 trips
        {
            Tcount++;
        }
        Tref = Tcount;
        PORTB = 0x06;  // S2 and S3 activated (Vmeas)
        DSCHRG_CAP();  // discharge capacitor charge
        PORTB = 0x0A;  // S2 and S4 activated
        TMR0 = 0x00;   // reset counter and TMR0
        Tcount = 0;
        while(!TMR0)  // increment Tcount until TMR0 trips
        {
            Tcount++;
        }
        Tmeas = Tcount;
        mpy = (long) Tref*Vref;  // perform mathematical operation to get Vin
        Vmeas = mpy / Tmeas;    // result
    }
}
```
APPENDIX B: SOURCE CODE IN ASSEMBLY

EXAMPLE B-1: A/D CONVERTER PROGRAM IN ASSEMBLY

;****************************************************************************
; Revision Date:
; 12-10-2013
;
; File Name:
; PIC16F5xADCasm.asm
;
; Summary:
; This is the main file used for the Application Note AN00513
;
; Hardware implementation requires:
; R1 = 13K ohm
; C1 = 1uF
; RC oscillator value are 4.7K ohm and 22pF, respectively.
;
; Generation Information :
; Device : PIC16F54
; Compiler : MPASM v5.52
; MPLAB : MPLAB X 1.90
;****************************************************************************

#INCLUDE <P16F54.INC>

__config 0xFFFFB ; configuration setting:
; OSC_RC, WDT_OFF, CP_OFF

; Digital Equivalent of Vref voltage

#define VCALMS 009 ; VCAL MSB VALUE IN HEX
#define VCALLS 02E ; VCAL LSB VALUE IN HEX
EXAMPLE B-2: A/D CONVERTER PROGRAM IN ASSEMBLY

```
ACCA EQU  8
ACCB EQU  0A
ACCC EQU  0C
ACCD EQU  0E
ACCE EQU  10
TMEAS EQU  12
TEMP EQU  14

TEMP1 EQU  16
TEMP2 EQU  17
TEMP3 EQU  18

ORG  0
GOTO VOLTS ;PROGRAM CODE

MADD    MOVF    ACCA+1,W
       ADDWF   ACCB+1, F ;ADD LSB
       BTFSC   3,0       ;ADD IN CARRY
       INCF    ACCB, F
       MOVF    ACCA,W
       ADDWF   ACCB, F ;ADD MSB
       RETLW   0
NOP

MPY      CALL    SETUP ;RESULTS IN B(16 MSB'S) AND C(16 LSB'S)
MLOOP    RRF     ACCD, F ;ROTATE D RIGHT
       RRF     ACCD+1, F
       SKPNC                   ;NEED TO ADD?
       CALL    MADD
       RRF     ACCB, F
       RRF     ACCB+1, F
       RRF     ACCC, F
       RRF     ACCC+1, F
       DECFSZ  TEMP, F         ;LOOP UNTIL ALL BITS CHECKED
       GOTO    MLOOP
       RETLW   0
NOP

SETUP    MOVLW   10
       MOVWF   TEMP
       MOVF    ACCB,W         ;MOVE B TO D
       MOVWF   ACCD
       MOVF    ACCB+1,W
       MOVWF   ACCD+1
       MOVF    ACCC,W
       MOVWF   ACCE
       MOVF    ACCC+1,W
       MOVWF   ACCE+1
       CLRIF   ACCB
       CLRIF   ACCB+1
       RETLW   0
```
EXAMPLE B-3:    A/D CONVERTER PROGRAM IN ASSEMBLY

NOP
DIV    CALL    SETUP
MOV1W  20
MOVWF  TEMP
CLRF   ACCC
CLRF   ACCC+1
DLOOP  CLC
RLF    ACCE+1, F
RLF    ACCE, F
RLF    ACCD+1, F
RLF    ACCD, F
RLF    ACCC+1, F
MOVF   ACCC, W
SUBWF  ACCC, W ;CHECK IF A>C
SKPZ   GOTO    NOCHK
MOVF   ACCA+1, W
SUBWF  ACCC+1, W ;IF MSB EQUAL THEN CHECK LSB
NOCHK  SKPC    ;CARRY SET IF C>A
GOTO    NOGO
MOVF   ACCA+1, W
SUBWF  ACCC+1, F
BTFSS  3,0
DECF   ACCC, F
MOVF   ACCA, W
SUBWF  ACCC, F
SETC    ;SHIFT A 1 INTO B (RESULT)
NOGO   RLF     ACCB+1, F
RLF    ACCB, F
DECSFSZ    TEMP, F ;LOOP UNTILL ALL BITS CHECKED
GOTO    DLOOP
RETLW   0
DSCHRG MOV1W  B'00001110' ;DISCHARGE C (RA0 ON)
TRIS    5
MOV1W  0FF
MOVWF  TEMP1
MOVWF  TEMP2
MOVWF  TEMP3
LOOP1   DECSFSZ    TEMPI, F ;WAIT
GOTO    LOOP1
LOOP2   DECSFSZ    TEMP2, F ;WAIT
GOTO    LOOP2
LOOP3   DECSFSZ    TEMP3, F ;WAIT
GOTO    LOOP3
MOV1W  B'00001111' ;ALL RA HIGH Z
TRIS    5
RETLW  0
M_TIME  CLRF   1    ;CLEAR RTCC REGISTER
CLRF   ACCA+1    ;CLEAR 16 BIT COUNTER
CLRF   ACCA
EXAMPLE B-4: A/D CONVERTER PROGRAM IN ASSEMBLY

```assembly
TLOOP  INCFSZ ACCA+1, F
      GOTO ENDCHECK
      INCFSZ ACCA, F
      GOTO ENDCHECK
      GOTO END_M
ENDCHECK BTFSS 1,0             ;CHECK FOR RTCC TRIP
      GOTO TLOOP
END_M   MOVF 1,W
        RETLW 0

VOLTS    MOVLW B'00000110'     ;SET S2 AND S3 HIGH(ON WHEN ACTIVATED)
          MOVWF 6
          MOVLW B'00000000'     ;ACTIVATE SWITCHES S1-S4
          TRIS 6
          MOVLW B'00101000'     ;SELECT POSITIVE EDGE FOR RTCC
          OPTION
          MOVLW B'00000000'
          MOVWF 5               ;SET RA0 LOW (ON WHEN ACTIVATED)
          CALL DSCHRG           ;CHARGE CAPACITOR TO VIN
          MOVLW B'00001010'     ;S2 AND S4 ON
          MOVWF 6
          CALL M_TIME           ;MEASURE TIME
          MOVF ACCA+1,W
          MOVWF TMEAS+1         ;STORE LSB
          MOVF ACCA,W
          MOVWF TMEAS           ;STORE MSB
          CALL DSCHRG           ;CHARGE CAPACITOR TO VREF
          MOVLW B'00001001'     ;S1 AND S4 ON
          MOVWF 6
          CALL M_TIME           ;MEASURE TIME
          MOVLW VCALLS
          MOVWF ACCB+1
          MOVLW VCALMS
          MOVWF ACCB
          CALL MPY               ;MULTIPLY ACCA(TCAL) * ACCB(VREF)
          MOVF TMEAS+1,W
          MOVWF ACCA+1
          MOVF TMEAS,W
          MOVWF ACCA
          CALL DIV               ;DIVIDE ACCB(TCAL * V) BY ACCA(TMEAS)
          GOTO VOLTS

END
```

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