AN624

PIC14000 A/D Theory and Implementation

Author: *Brian Dellacroce*
Design Consultant

INTRODUCTION

This application note presents an implementation of a data acquisition system based on a PIC14000 micro-controller. The PIC14000's analog front end will perform signal conditioning and analog to digital conversion of signals used in a battery monitoring application. Battery voltage, current, and temperature data will be acquired. This data will then be transmitted via RS-232 to a remote PC host.

SLOPE A/D CONVERSION

With the addition of an external capacitor, the analog front end of the PIC14000 can be used as a slope A/D converter. The slope A/D is formed when a constant current source (CDAC pin) drives a capacitor. From basic capacitor theory, the voltage across this capacitor is described by the equation:

EQUATION 1: CAPACITOR VOLTAGE

$$V(t) = 1/C \times \int_{t0}^{t1} i(t)\,dt$$

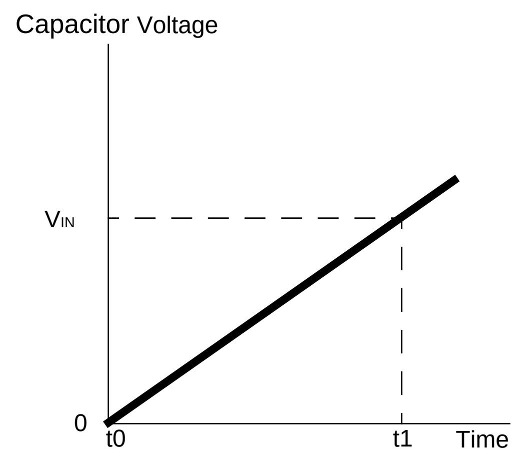
Since the current i(t) is constant, this reduces to:

EQUATION 2: VOLTAGE RAMP

$$V1 - V0 = 1/C \times I(t1 - t0)$$

This relationship describes a basic linear voltage ramp. The conversion from analog to digital occurs by measuring the time from the start of the linear ramp (t0) to the time (t1) that the voltage across the capacitor equals the analog input voltage to be converted. This time is measured by a digital counter circuit. Thus, the delta time (t1 - t0) value represents the magnitude of the analog voltage being converted. In this application note, the measured delta time value will simply be referred to as the "count" for the particular analog voltage being converted.

FIGURE 1: LINEAR VOLTAGE RAMP A/D CONVERSION



V_{IN} = Analog voltage to be measured
t1 = ramp time to V_{IN}

The magnitude of the measured analog voltage can be determined if the capacitance and the charging current are known. However, in practice, these values cannot be exactly determined. Therefore, a known reference voltage is used instead. This reference voltage is supplied by a very stable circuit known as a bandgap reference. The analog input voltage is determined ratiometrically by performing two successive A/D conversions, the first on the analog input voltage, and the second on the reference voltage. The analog voltage being measured can be calculated using the equation below.

EQUATION 3: VOLTAGE MEASURE

$$V_{IN} = \frac{N_{IN}}{N_{BG}} \times K_{BG}$$

N_{IN}	=	A/D count value for selected input.
N_{BG}	=	A/D count value for bandgap reference.
K_{BG}	=	Absolute voltage value of the bandgap reference voltage, stored in calibration space EPROM.

Equation 3 assumes that the starting voltage of the linear ramp (V_0) in both the analog input and reference voltage conversions is zero. In practice, however, the capacitor cannot be discharged completely from the prior conversion and a few millivolts worth of charge, referred to as offset voltage, may remain on the capacitor. This effect is called capacitor dielectric absorption, and varies depending on the capacitor's dielectric material, the voltage to which it was charged during the last charge cycle, and the amount of time the capacitor has had to discharge. While teflon capacitors exhibit the lowest dielectric absorption, polystyrene and polyethylene are also very good. Ceramic, glass and mica are fair, and tantalum and electrolytic types are poor choices for A/D applications.

Additionally, the comparator (that compares the ramp voltage to the input voltage and stops the timer when the voltages are equal) usually has a few millivolts of offset error in its comparison. This comparator offset voltage adds (or subtracts) to the dielectric absorption offset. Finally, the counter that times the conversion may have a very small constant turn-on or turn-off delay that affects the measurement in the same manner as offset voltage.

In order to calculate an exact value for the analog input voltage, the various offset voltages must be factored into the equation. To do this, they are combined and measured.

The PIC14000 provides two slope reference voltages for this purpose: upper and lower. The ratio of the magnitudes of these references is known and can be used to calculate the combined offset voltage.

This is done by performing conversions on both slope references, and using the supplied calibration constant for the ratio of their magnitudes, and calculating the offset voltage as an offset count. This offset count is then used in the other equations.

The equation used is that of calculating the x-intercept of a straight line when the slope of the line and two x coordinates are known.

EQUATION 4: OFFSET COUNT

$$N_{OFFSET} = N_{REFLO} - K_{REF}(N_{REFHI} - N_{REFLO})$$

Where:

N_{REFLO}	=	A/D count value low reference point.
N_{REFHI}	=	A/D count value high reference point
K_{REF}	=	S_{REFLO} / (S_{REFHI} - S_{REFLO}), stored in calibration space in EPROM.
S_{REFHI}	=	See PIC14000 Data Sheet, section 8.
S_{REFLO}	=	See PIC14000 Data Sheet, section 8.

This offset term and its measurement are illustrated graphically in Figure 2. Applying this offset term to the calculation of Vin compensates the count obtained for both the input channel and the reference channel, to yield the counts as if each conversion did start from zero, instead of some offset voltage. Thus, the following equation may be used to determine the voltage at any input:

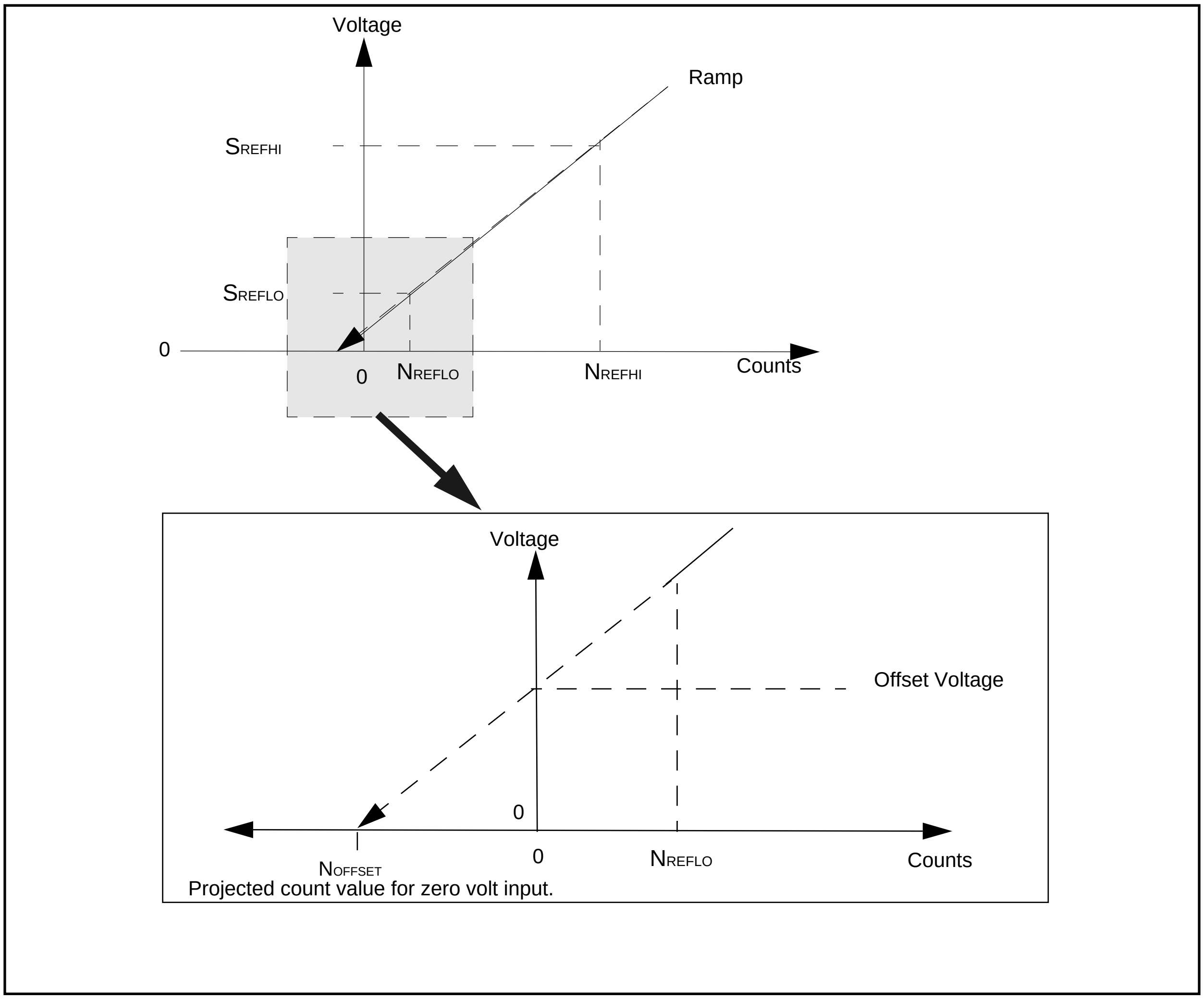
EQUATION 5: VOLTAGE AT ANY INPUT

$$V_{IN} = \frac{N_{IN} - N_{OFFSET}}{N_{BG} - N_{OFFSET}} \times K_{BG}$$

RA1/AN1 and RD5/AN5 Analog Input Pins

The AN1 and AN5 inputs pins have a special input offset feature that can allow these inputs to measure voltages that are either above or below chip ground potential. This is accomplished with a summing junction that adds 0.5V to the signal at the pin before it reaches the A/D comparator. In order to determine the absolute voltage at the pin if the offset feature is turned on, two A/D conversions must be made. First, the input combined with the summing signal (0.5V) is converted. Then, a second conversion is performed with the AN1/AN5 side of the summing junction disconnected, resulting in just the 0.5V summing signal being converted. To compute the value of the voltage at the AN1/AN5 pin, the result from the second conversion is subtracted from the result of the first conversion.

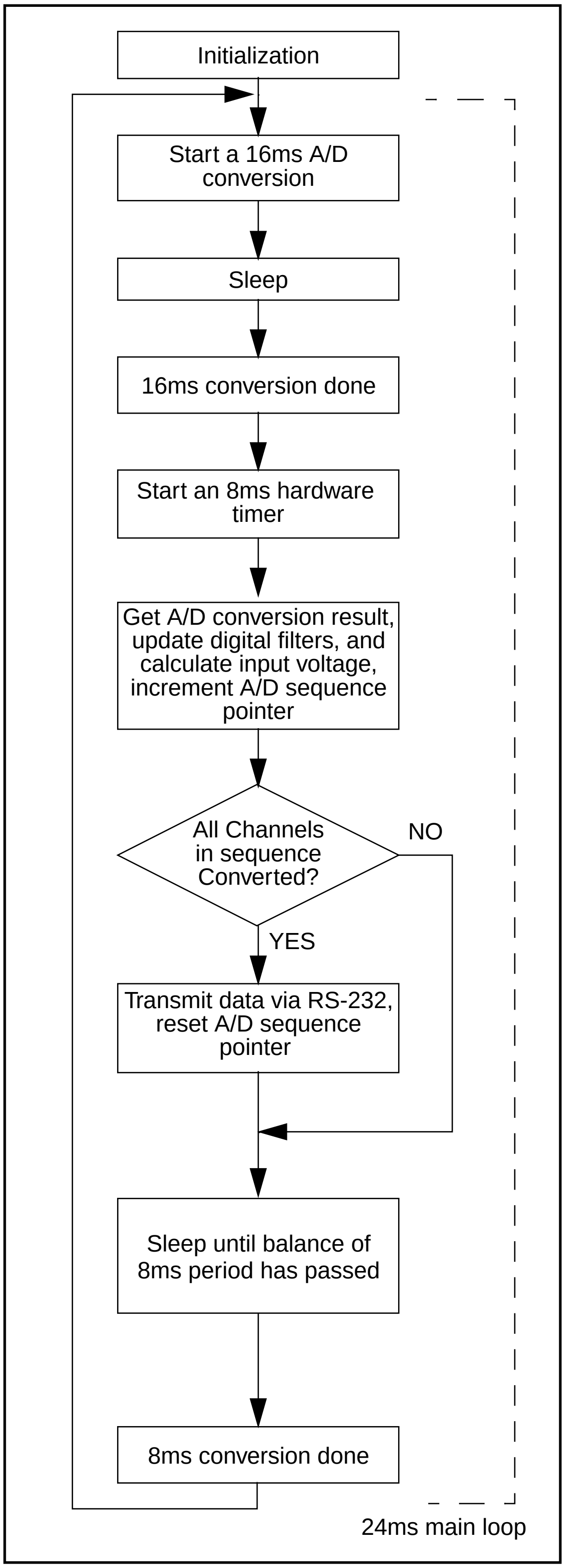
FIGURE 2: FINDING THE ZERO VOLTAGE COUNT FROM SREFHI AND SREFLO



IMPLEMENTATION

After initilization, the program continuously executes a 24ms main loop. 16ms is allocated for each A/D conversion, and 8ms is allotted for calculations and other tasks. In order to conserve power and reduce noise in the A/D conversions, the CPU is put to sleep during each A/D conversion and during any unused portion of the 8ms calculation time (see Figure 3). This timing scheme allows both the charging time and the discharging time of the voltage ramp capacitor to be constant. This aids in achieving accurate A/D conversions by keeping the offset voltage due to capacitor dielectric absorption constant.

FIGURE 3: PROGRAM FLOW



Hardware Allocation

For this application note, three external analog input channels are used. RA1/AN1, RA2/AN2, and RA3/AN3 are assigned to battery current measurement, battery voltage measurement, and external voltage measurement (in this case a potentiometer), respectively.

Since the A/D converter measures voltage, and not current, the battery current measurement is obtained by measuring the voltage drop across a low value resistor (in this case 0.1 ohm). Actual battery current is then calculated by the firmware using the value of the resistor and Ohms law.

Battery voltage measurement requires that an external resistive voltage divider be used to lower the voltage input into the A/D converter's range. A divider that results in an A/D input voltage that is as near as possible to the bandgap reference voltage is normally selected, since it reduces ratiometric errors during the calculation of the voltage. The firmware calculates the actual battery voltage from the voltage measured at the AN3 pin by multiplying the measured value by the external voltage divider ratio.

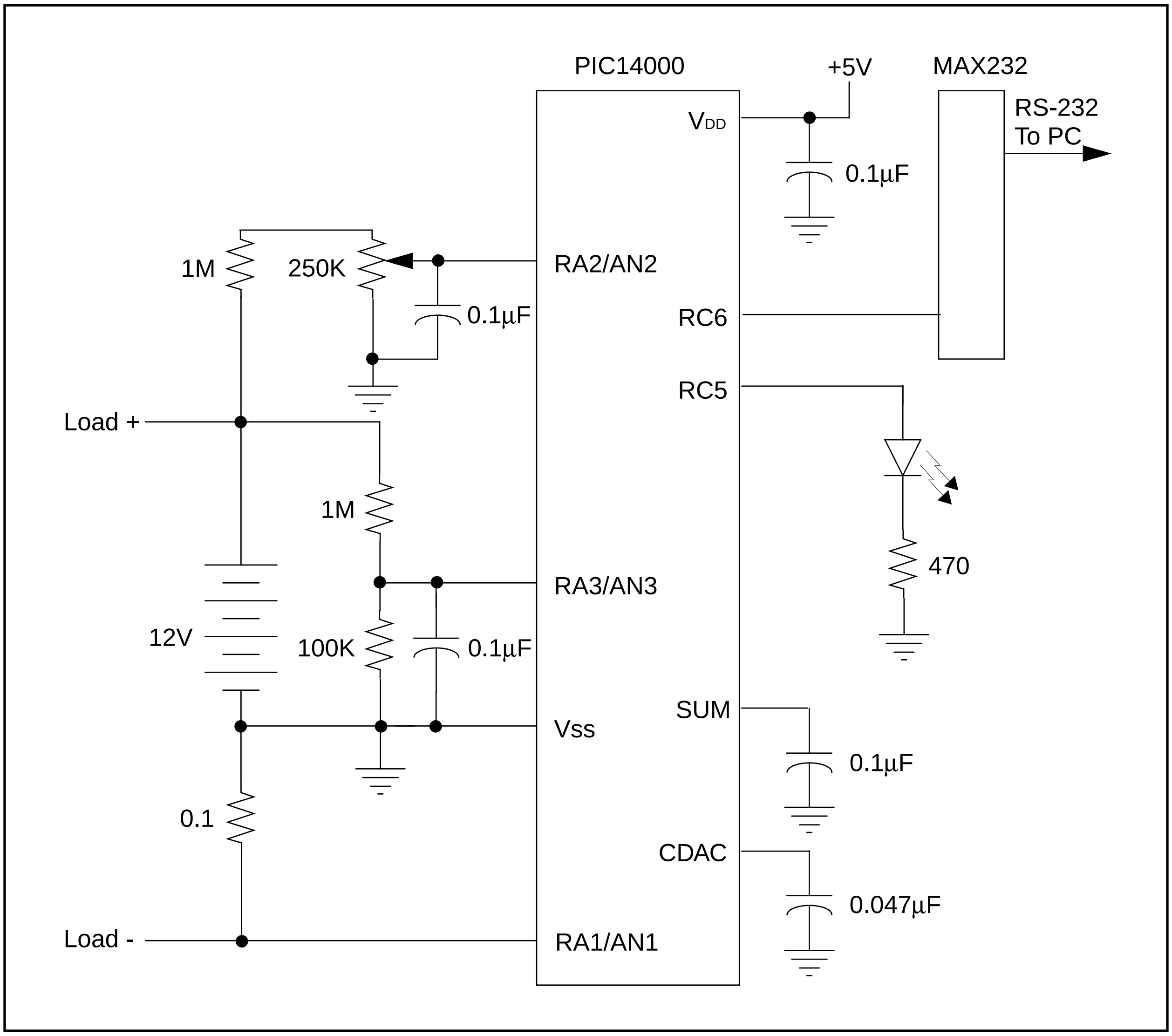
The external potentiometer voltage measurement is an auxiliary measurement, and could be used for measuring a thermistor, individual cell voltages, or other parameters. No scaling of this voltage is performed. The program simply reports the voltage sensed at the AN2 pin.

This program assumes that a 0.047µF capacitor is connected between the CDAC pin of the chip and ground. It is used for creating the ramp voltage for the A/D conversion process. Optionally, a 0.1µF capacitor can be connected between the SUM pin and ground to allow for increased filtering of the battery current (AN1) input.

Port RC6 is used to transmit four parameters: battery current, battery voltage, internal temperature, and AN3 voltage. The format is 9600 baud (8,N,1) RS-232. Each parameter consists of four bytes and is in PIC 16/17 32-bit floating point format. Refer to AN575 for more information on floating point format.

For monitoring purposes, the program will toggle the RC5 output every ~384ms. It will drive RC5 high just prior to starting the RS-232 data transmission, and drive it low after completing the transmission. If an LED and current limiting resistor are connected to RC5, a visible "heartbeat" indication will appear when the program is running in a normal manner.

FIGURE 4: HARDWARE SCHEMATIC



A/D Conversion

The analog to digital conversion firmware modules control the operation of the analog to digital converter hardware. They convert the raw data received from the hardware into physical voltage values. This is accomplished by obtaining readings from the external inputs, the on-chip bandgap reference, and the on-chip A/D reference circuits. The physical voltages at the external inputs are computed based on these readings.

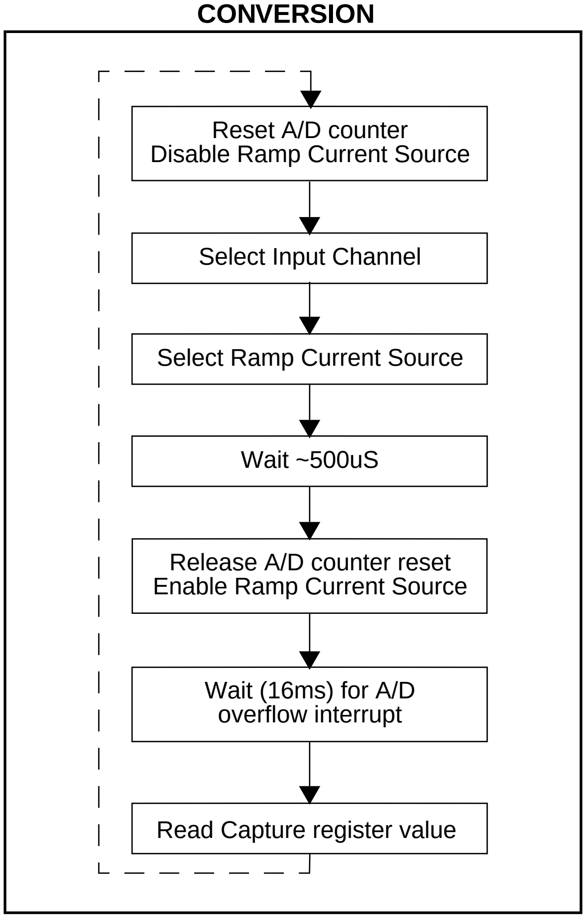
A/D Input Interleaving Sequence

Interleaving the selection of analog inputs scheduled for conversion maximizes the sampling rate for high priority signals such as the battery current, and reduces the sampling rate for low priority signals (that change at relatively slow rates), such as temperature inputs. The following interleaving scheme places the inputs in priority order from highest to lowest. Battery current is the highest priority with eight samples in 16 A/D cycles (~384ms). Battery voltage is sampled two times in 16 A/D cycles. Battery temperature, via the external thermistor input and internal temperature, is sampled once each during 16 A/D cycles. Current network zero voltage, bandgap voltage, the A/D lower reference voltage, and the A/D upper reference voltage, are each sampled once for every 16 conversion cycles.

Conversions are scheduled at fixed intervals based upon the maximum conversion time to overflow (16ms). This fixed scheduling method maintains determinism in the overall system.

Conv #	T_{REL}	T_{ABS}	Interleave Channel	A/D Channel
0	16ms	ms	Run sequence on current input channel	AN1: Ibat
1	16ms	ms	Run sequence on V_{REFHI} channel	S_{REFHI}
2	16ms	ms	Run sequence on current input channel	AN1: Ibat
3	16ms	ms	Run sequence on V_{REFLO} channel	S_{REFLO}
4	16ms	ms	Run sequence on current input channel	AN1: Ibat
5	16ms	ms	Run sequence on Bandgap channel	V_{BG}
6	16ms	ms	Run sequence on current input channel	AN1: Ibat
7	16ms	ms	Run sequence on V_{IN} channel	AN3: Vbat
8	16ms	ms	Run sequence on current input channel	AN1: Ibat
9	16ms	ms	Run sequence on current zero channel	AN1: I_{ZERO}
10	16ms	ms	Run sequence on current input channel	AN1: Ibat
11	16ms	ms	Run sequence on internal thermistor channel	T_{INT}
12	16ms	ms	Run sequence on current input channel	AN1: Ibat
13	16ms	ms	Run sequence on external voltage channel	AN2: V_{EXT}
14	16ms	ms	Run sequence on current input channel	AN1: Ibat
15	16ms	ms	Run sequence on V_{IN} channel	AN3: Vbat

FIGURE 5: SEQUENCE FOR PERFORMING A SINGLE A/D CONVERSION



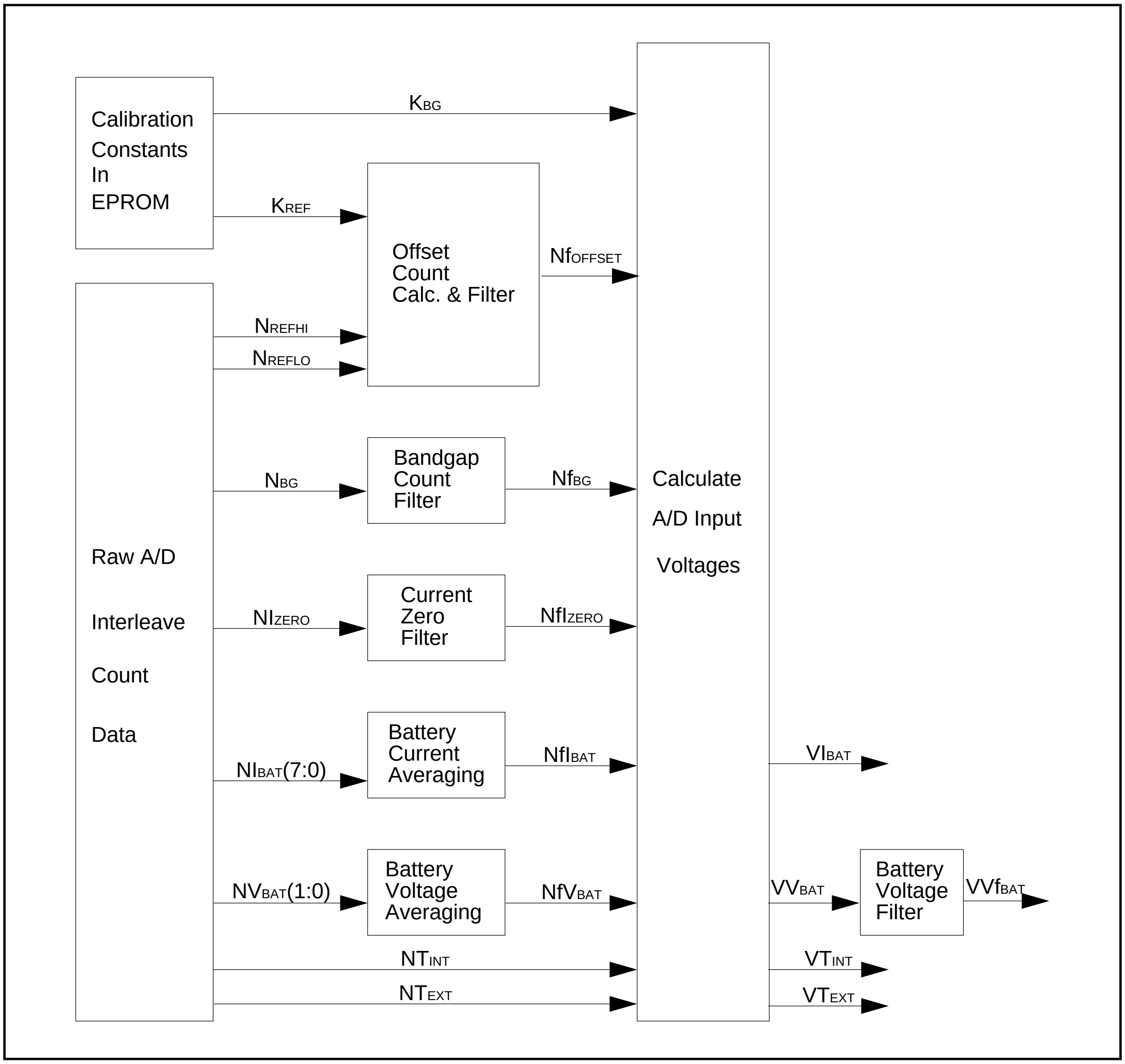
A/D Filtering

Due to the high resolution of the PIC14000 A/D converter, digital filtering of the A/D count data is performed. This will reduce noise in the A/D readings, and enhance performance.

A/D count data is converted to PIC16/17 floating point format prior to being used in any calculation. All results are retained in floating point format as well. DC inputs such as bandgap reference voltage, slope reference high, slope reference low, and current zero offset voltage are filtered with long time-constant filters. Dynamic signals, such as battery voltage and current, are filtered less. Internal temperature and AN3 external voltage are not filtered at all. All calculated outputs are in voltage units. Figure 6 diagrams the data flow through the filtering and calculation task.

The formulas on the following page are used to filter the raw count data obtained from the A/D converter prior to calculating the actual voltage values for the A/D inputs. This filtering stabilizes the reference values to enhance A/D accuracy. The bandgap and offset reference are DC signals, so no information is lost by the filtering process.

FIGURE 6: CLTASK DATA FLOW



The count value for the bandgap voltage reference is filtered by calculating the rolling average of the last 16 count values obtained. This filtered value of bandgap count is then used to calculate the input voltages. The subscript i denotes the interleave sequence number, not the conversion number within the interleave sequence.

EQUATION 6: FILTERED BANDGAP COUNT

$$Nf_{BG} = \frac{N_{BG_i} + 15 \times N_{BG_{i-1}}}{16}$$

The count offset value is filtered by calculating the rolling average of the last 16 count values obtained. The filtered value of the offset count is then used in Equation 6 to calculate the input voltages.

EQUATION 7: FILTERED OFFSET COUNT

$$Nf_{OFFSET} = \frac{N_{OFFSET_i} + 15 \times N_{OFFSET_{i-1}}}{16}$$

where:

$$N_{OFFSET_i} = N_{REFLO_i} - K_{REF}(N_{REFHI_i} - N_{REFLO_i})$$

The current-input zero offset value is filtered by calculating the rolling average of the last 16 count values obtained. This filtered value of the current-input zero offset is used in the equation to calculate the input voltages.

EQUATION 8: FILTERED ZERO-CURRENT

$$NfI_{ZERO} = \frac{NI_{ZERO_i} + 15 \times NI_{ZERO_{i-1}}}{16}$$

The following formulas are used to filter the raw count data obtained from the battery voltage and current input channels. These filtered values are then used for communication and control functions.

The battery current value is filtered by taking the average of the eight samples of the input channel from the interleave sequence.

EQUATION 9: FILTERED CURRENT COUNT

$$NfI_{BAT} = \left(\frac{1}{8}\right) \sum_{s=0}^{7} (NI_{BAT_s})$$

The count value for the battery voltage input is filtered by calculating the average of two samples of the input channel from the interleave sequence.

EQUATION 10: FILTERED VOLTAGE COUNT

$$NfV_{BAT} = \left(\frac{1}{2}\right) \sum_{s=0}^{1} (NV_{BAT_s})$$

Calculation of Input Voltage Values.

The following formulas are used to calculate the digital value for each of the input voltages.

EQUATION 11: VOLTAGE AT AN1

$$VI_{BAT} = \frac{NI_{BAT} - NfI_{ZERO}}{Nf_{BG} - Nf_{OFFSET}} \times K_{BG}$$

VI_{BAT} refers to the voltage at the battery current input, AN1. Note that there is no Nf_{OFFSET} term in the numerator. The Nf_{OFFSET} components of the NfI_{BAT} and NfI_{ZERO} terms are canceled out by the subtraction. The equations for the remaining inputs all follow the general form given in Equation 5.

EQUATION 12: VOLTAGE AT AN0

$$VV_{BAT} = \frac{NfV_{BAT} - Nf_{OFFSET}}{Nf_{BG} - Nf_{OFFSET}} \times K_{BG}$$

VV_{BAT} refers to the voltage at the battery voltage input, AN0. Additional filtering is added to the computed VV_{BAT} signal using the equation:

EQUATION 13: FILTERED VOLTAGE

$$VVf_{BAT} = \frac{VV_{BAT_i} + 7 \times VV_{BAT_{i-1}}}{8}$$

Temperature terms are calculated directly without any added filtering.

EQUATION 14: INTERNAL TEMPERATURE

$$VT_{INT} = \frac{NT_{INT} - Nf_{OFFSET}}{Nf_{BG} - Nf_{OFFSET}} \times K_{BG}$$

VT_{INT} refers to the voltage at the internal temperature sensor.

EQUATION 15: EXTERNAL TEMPERATURE

$$VT_{EXT} = \frac{NT_{EXT} - Nf_{OFFSET}}{Nf_{BG} - Nf_{OFFSET}} \times K_{BG}$$

VT_{EXT} refers to the voltage at the external temperature sensor input.

Conversion to Physical Units

The physical unit values (i.e., temperature, battery voltage, battery current) for the input voltages are computed prior to being transmitted via RS-232. To reduce data storage requirements, these values are not maintained in memory, but are destroyed after they are transmitted. Scaling constants read from EPROM are used to convert the voltage values measured at the pin into the appropriate physical value. The voltage at the AN2 pin is not scaled prior to transmission; the actual voltage at the pin is transmitted.

Current

$$I_{BAT} = \frac{V_{IBAT}}{R_{ISENSE}}$$

I_{BAT} = Battery current.

V_{IBAT} = measured voltage at RA1/AN1 pin.

R_{ISENSE} = External current sense resistor value (stored in user EPROM).

Voltage

$$V_{BAT} = VVf_{BAT} \times V_{BAT} R_{DIV}$$

V_{BAT} = Battery voltage.

VVf_{BAT} = Filtered measured voltage at RA3/AN3 pin.

R_{DIV} = External resistor divider ratio for RA2/AN2 pin (stored in user EPROM).

Temperature

$$T_{EMPINT} = \frac{VT_{INT} - V_{THERM}}{K_{TC}} + 298.15$$

T_{EMPINT} = Temperature in degrees Kelvin.

VT_{INT} = measured temperature sensor voltage value.

Vtherm = Factory calibrated voltage value of the temperature sensor at 298 Kelvin (stored in calibration place in EPROM)

K_{TC} = Factory calibrated temperature constant of temperature sensor in volts per degrees Kelvin (stored in calibration space in EPROM).

RS-232 COMMUNICATION

The physical battery current, voltage, temperature, and RA3/AN3 voltage values are transmitted on the RC6 pin in 8,N,1 RS-232 format.

The transmit routine is designed to make use of the PIC14000's calibrated internal (IN) oscillator. The oscillator frequency, stored in the factory calibration EPROM, is used as an index into a bit-delay lookup table. The bit-delay value controls the number of instructions executed during the software delay routine and is used to generate the time between bits being transmitted. The time resolution of this lookup table method results in a worst- case bit time error of less than two percent.

Several look up tables for baud rate are included as assembly time options. Normally the 9600 baud option is used.

ASSEMBLY FILES

The program code for this application note is available on the Microchip BBS as the AN624.ZIP file. Once the file is unzipped, the user should read the readme file for further instructions.

NOTES:

WORLDWIDE SALES & SERVICE

AMERICAS

Corporate Office
Microchip Technology Inc.
2355 West Chandler Blvd.
Chandler, AZ 85224-6199
Tel: 602 786-7200 Fax: 602 786-7277
Technical Support: 602 786-7627
Web: http://www.microchip.com/

Atlanta
Microchip Technology Inc.
500 Sugar Mill Road, Suite 200B
Atlanta, GA 30350
Tel: 770 640-0034 Fax: 770 640-0307

Boston
Microchip Technology Inc.
5 Mount Royal Avenue
Marlborough, MA 01752
Tel: 508 480-9990 Fax: 508 480-8575

Chicago
Microchip Technology Inc.
333 Pierce Road, Suite 180
Itasca, IL 60143
Tel: 708 285-0071 Fax: 708 285-0075

Dallas
Microchip Technology Inc.
14651 Dallas Parkway, Suite 816
Dallas, TX 75240-8809
Tel: 214 991-7177 Fax: 214 991-8588

Dayton
Microchip Technology Inc.
Suite 150
Two Prestige Place
Miamisburg, OH 45342
Tel: 513 291-1654 Fax: 513 291-9175

Los Angeles
Microchip Technology Inc.
18201 Von Karman, Suite 1090
Irvine, CA 92715
Tel: 714 263-1888 Fax: 714 263-1338

AMERICAS *(continued)*

New York
Microchip Technology Inc.
150 Motor Parkway, Suite 416
Hauppauge, NY 11788
Tel: 516 273-5305 Fax: 516 273-5335

San Jose
Microchip Technology Inc.
2107 North First Street, Suite 590
San Jose, CA 95131
Tel: 408 436-7950 Fax: 408 436-7955

Toronto
Microchip Technology Inc.
5925 Airport Road, Suite 200
Mississauga, Ontario L4V 1W1, Canada
Tel: 905 405-6279 Fax: 905 405-6253

ASIA/PACIFIC

Hong Kong
Microchip Technology
Rm 3801B, Tower Two
Metroplaza,
223 Hing Fong Road,
Kwai Fong, N.T., Hong Kong
Tel: 852 2 401 1200 Fax: 852 2 401 3431

Korea
Microchip Technology
168-1, Youngbo Bldg. 3 Floor
Samsung-Dong, Kangnam-Ku,
Seoul, Korea
Tel: 82 2 554 7200 Fax: 82 2 558 5934

Singapore
Microchip Technology
200 Middle Road
#10-03 Prime Centre
Singapore 188980
Tel: 65 334 8870 Fax: 65 334 8850

Taiwan
Microchip Technology
10F-1C 207
Tung Hua North Road
Taipei, Taiwan, ROC
Tel: 886 2 717 7175 Fax: 886 2 545 0139

EUROPE

United Kingdom
Arizona Microchip Technology Ltd.
Unit 6, The Courtyard
Meadow Bank, Furlong Road
Bourne End, Buckinghamshire SL8 5AJ
Tel: 44 1 628 850303 Fax: 44 1 628 850178

France
Arizona Microchip Technology SARL
Zone Industrielle de la Bonde
2 Rue du Buisson aux Fraises
91300 Massy - France
Tel: 33 1 69 53 63 20 Fax: 33 1 69 30 90 79

Germany
Arizona Microchip Technology GmbH
Gustav-Heinemann-Ring 125
D-81739 Muenchen, Germany
Tel: 49 89 627 144 0 Fax: 49 89 627 144 44

Italy
Arizona Microchip Technology SRL
Centro Direzionale Colleoni
Palazzo Taurus 1 V. Le Colleoni 1
20041, Agrate Brianza, Milan Italy
Tel: 39 39 689 9939 Fax: 39 39 689 9883

JAPAN

Microchip Technology Intl. Inc.
Benex S-1 6F
3-18-20, Shin Yokohama
Kohoku-Ku, Yokohama
Kanagawa 222 Japan
Tel: 81 45 471 6166 Fax: 81 45 471 6122

5/10/96