Using ADCC Modes of PIC16F17146 and PIC16F18146 Families of Microcontrollers in Applications

TB3346

Introduction

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An Analog-to-Digital Converter (ADC) of a microcontroller converts an analog voltage signal into a digital number, which can be used in real-time monitoring and feedback control applications. Most analog sensors have the output as a single analog voltage signal (single-ended) or as a difference between two analog voltage signals (differential).

The 12-bit Analog-to-Digital Converter with Computation (ADCC) peripheral of PIC® microcontrollers has with features such as differential and single-ended measurement, channel grouping, operation in Sleep mode, continuous sampling, and threshold comparison. The ADCC has computation modes such as Accumulate, Average, Burst Average, and Low-Pass Filter modes.

This document illustrates the ADCC peripheral of the PIC16F17146 and PIC16F18146 families of microcontrollers. The document also describes how to get started with the ADCC modes and features and use them in various sensing and measurement applications.

Refer to the respective device data sheet for a detailed description of the peripheral and register level details.

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1. Relevant Devices

1.1 PIC16F17146 and PIC16F18146 Microcontroller Families

The PIC16F17146 and PIC16F18146 microcontroller families contain an enhanced mid-range 8-bit CPU core that reaches speeds up to 32 MHz. These microcontroller families support up to 28 KB of Flash, up to 2 KB of SRAM, and up to 256 Bytes of EEPROM and are available in 8-, 14-, 20-, 28-, 40- or 44-pin packages. They have a suite of analog peripherals that enable precision sensor applications. This small form factor, feature-rich device is well suited for low-cost, energy-efficient analog sensor applications with higher resolution requirements. The PIC16F17146 family of microcontrollers has one general purpose OPA, while the PIC16F18146 microcontroller family does not have OPA.

Figure 1-1. Relevant Devices

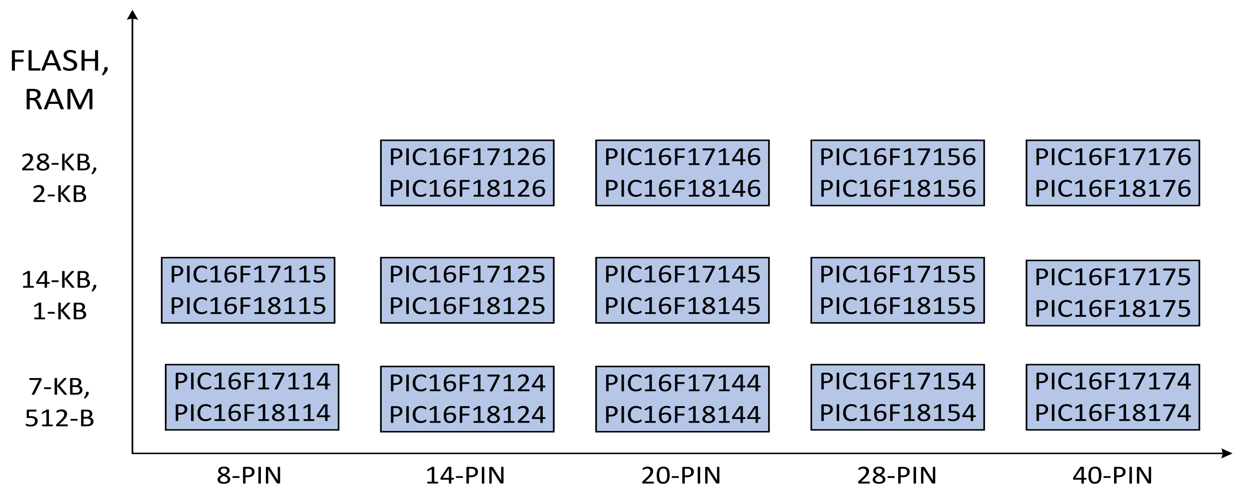

Figure 1-1 shows an overview of the PIC16F17146 and PIC16F18146 microcontroller families available in 8-pin to 40-pin (VQFN) packages with a memory range of 7 KB to 28 KB. The parts with different Flash memory typically also have different RAM and EEPROM.

- Vertical migration is possible without code modification, as these devices are pin and feature-compatible
- Horizontal migration to the left reduces the pin count and limits the available features in certain use cases

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2. Recommended ADC Clock Settings

This section illustrates recommended ADC clock settings for accurate ADC results.

2.1 Oscillator Frequency when using F_{OSC} as Clock Source

Oscillator frequency (F_{OSC}) should be 8 MHz or below when using F_{OSC} as the clock source of the ADC, irrespective of the ADC Clock Divider (ADCLK) value. The ADCRC oscillator source should be used for ADC when the application requires using F_{OSC} to be greater than 8 MHz.

2.2 ADC Clock Divider Value

ADCLK register will be loaded with odd-numbered values (e.g., 0x01, 0x03, 0x05, etc.) for accurate ADC results. The ADC Clock divider is only available if F_{OSC} is selected as the ADC Clock source, as this is not applicable when using ADCRC as the source.

The formula below gives the ADC Clock frequency:

$$ADC\ Clockfrequency = \frac{F_{osc}}{2 * (n + 1)}$$

Where n is the ADCLK value.

Table 2-1 mentions the recommended F_{OSC} division values:

Table 2-1. Recommended FOSC Clock Divider Values

$F_{OSC}/4$	$F_{OSC}/8$	$F_{OSC}/12$	$F_{OSC}/16$	$F_{OSC}/20$	$F_{OSC}/24$	$F_{OSC}/28$	$F_{OSC}/32$
$F_{OSC}/36$	$F_{OSC}/40$	$F_{OSC}/44$	$F_{OSC}/48$	$F_{OSC}/52$	$F_{OSC}/56$	$F_{OSC}/60$	$F_{OSC}/64$

2.3 ADC Clock Period

The time to complete a one-bit conversion is defined as the TAD and it is identical to 1/ADC Clock Frequency. TAD must be greater than 500 ns and less than 9 µs for the correct conversion.

Figure 2-1 illustrates the recommended combination of F_{OSC} and Clock divider values. The colored area shows a violation, and the white area recommended combinations.

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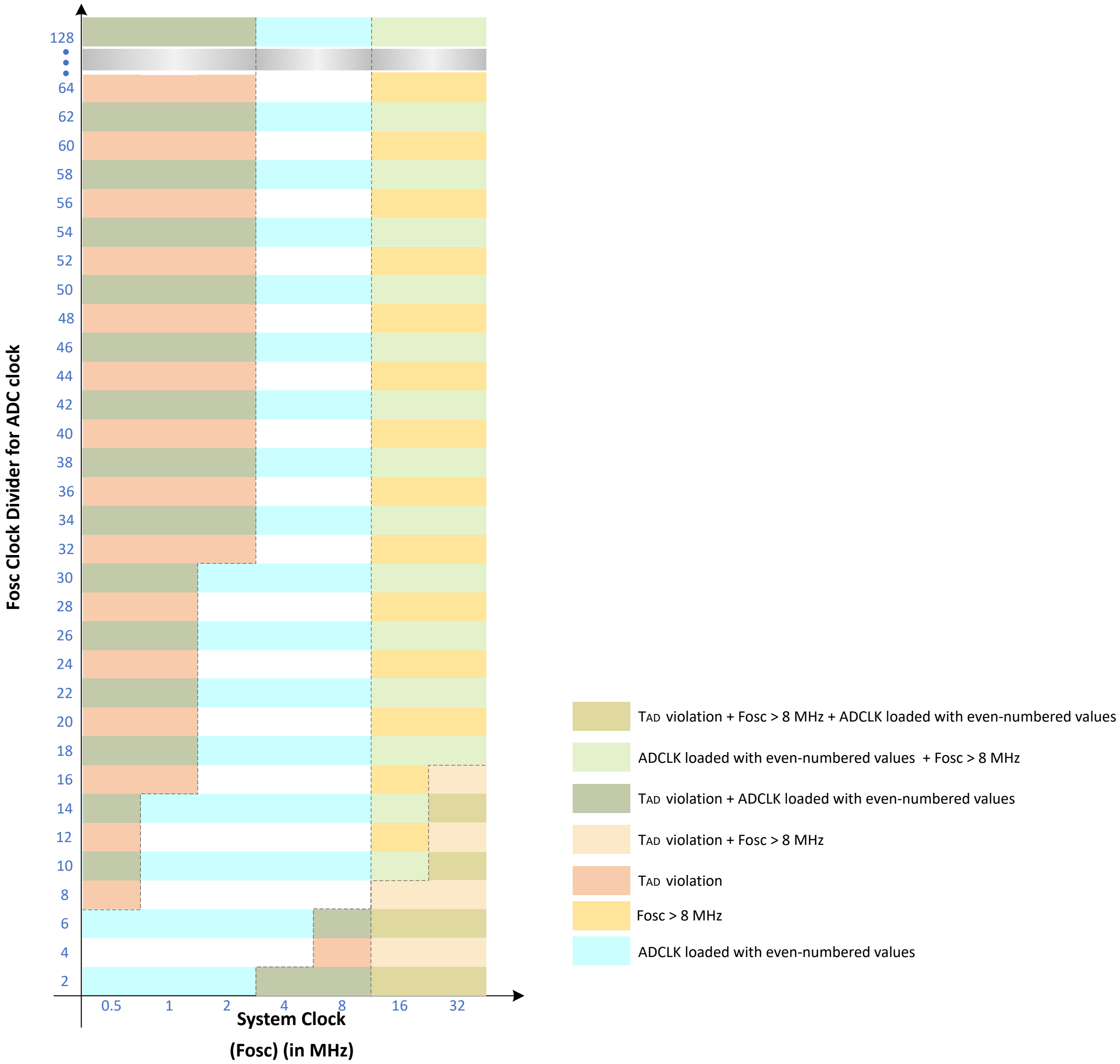
Figure 2-1. Recommended Combination of F_{OSC} and Clock Divider Values



Examples included in the next section follow all the recommended settings.

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3. Application Use Cases Using ADCC Modes and Features

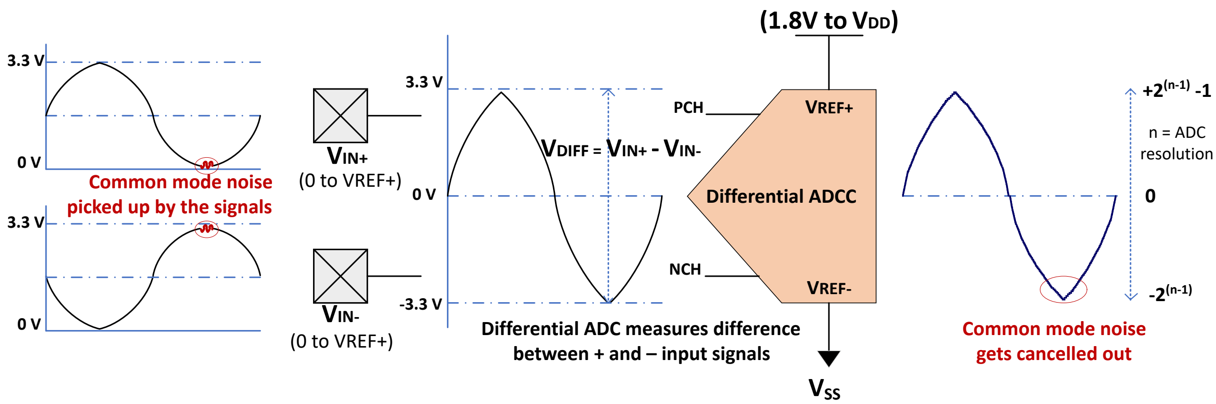
3.1 Differential Signal Measurement

The ADC peripheral of the PIC16F17146 and PIC16F18146 families of microcontrollers supports a Single-Ended and Differential Measurement mode. The modes are configured using the ADC Input Configuration (IC) bit of the ADCON0 register.

The simple and most widely used analog sensors provide single-ended signals, which occupy only one analog microcontroller input per sensor. There is a large selection of available sensors in case of single-ended measurement. The simplicity and ease of use come with a few challenges, such as the sensors being sensitive to noise along the analog signal path and to common-mode noise on the ground and reference voltage levels of the microcontroller. The signal path between the sensor and the microcontroller should be as short as possible to minimize noise and ground-level differences.

Differential inputs offer the best performance by rejecting DC and dynamic common-mode voltages. In a differential signal system, two lines carry the desired signals, and the signals run in parallel to each other. As a result, an equal amount of noise occurs on both the lines. As the differential ADC measures the difference in voltage between the positive and negative terminals, the common noise is rejected. This results in an improved signal-to-noise ratio while also removing even-order harmonics. Figure 3-1 shows the common mode noise cancellation in Differential mode configuration.

Figure 3-1. Cancellation of Common Mode Noise in Differential Mode



Refer to the Differential and Single-Ended ADCC whitepaper for more details regarding both modes.

Below are the application examples showcasing the usage of the ADC in Differential Measurement mode.

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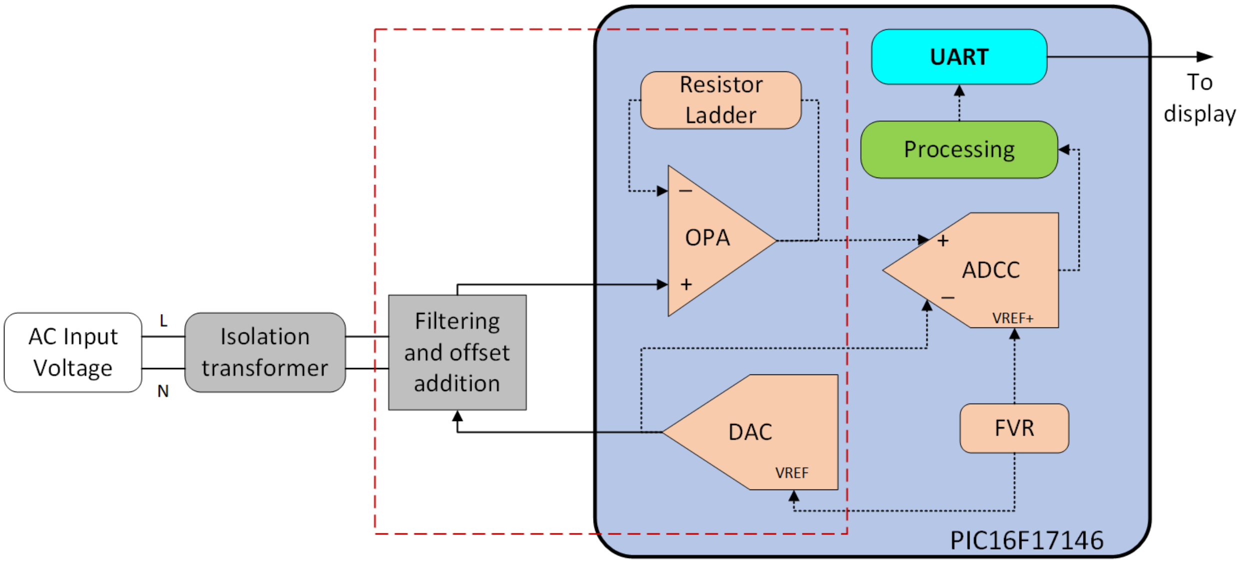
3.1.1 AC Voltage Measurement Using Differential ADC

Figure 3-2. AC Voltage Measurement Using Differential ADC



- AC voltage to be measured is fed as input to the AC voltage step-down circuit made up of an isolation transformer
- The step-down AC voltage is filtered using OPA
- An offset voltage is added to shift the step-down AC voltage using DAC, and it is made compatible with the ADC measurement range
- Then the OPA output is fed to the ADC positive channel, and the added reference offset voltage is given as input to the negative channel of differential ADCC
- Differential ADC removes the common mode noise and the effects of adding of the offset voltage. During RMS calculation, offset need not be added by the software as the Differential mode already has removed the effect

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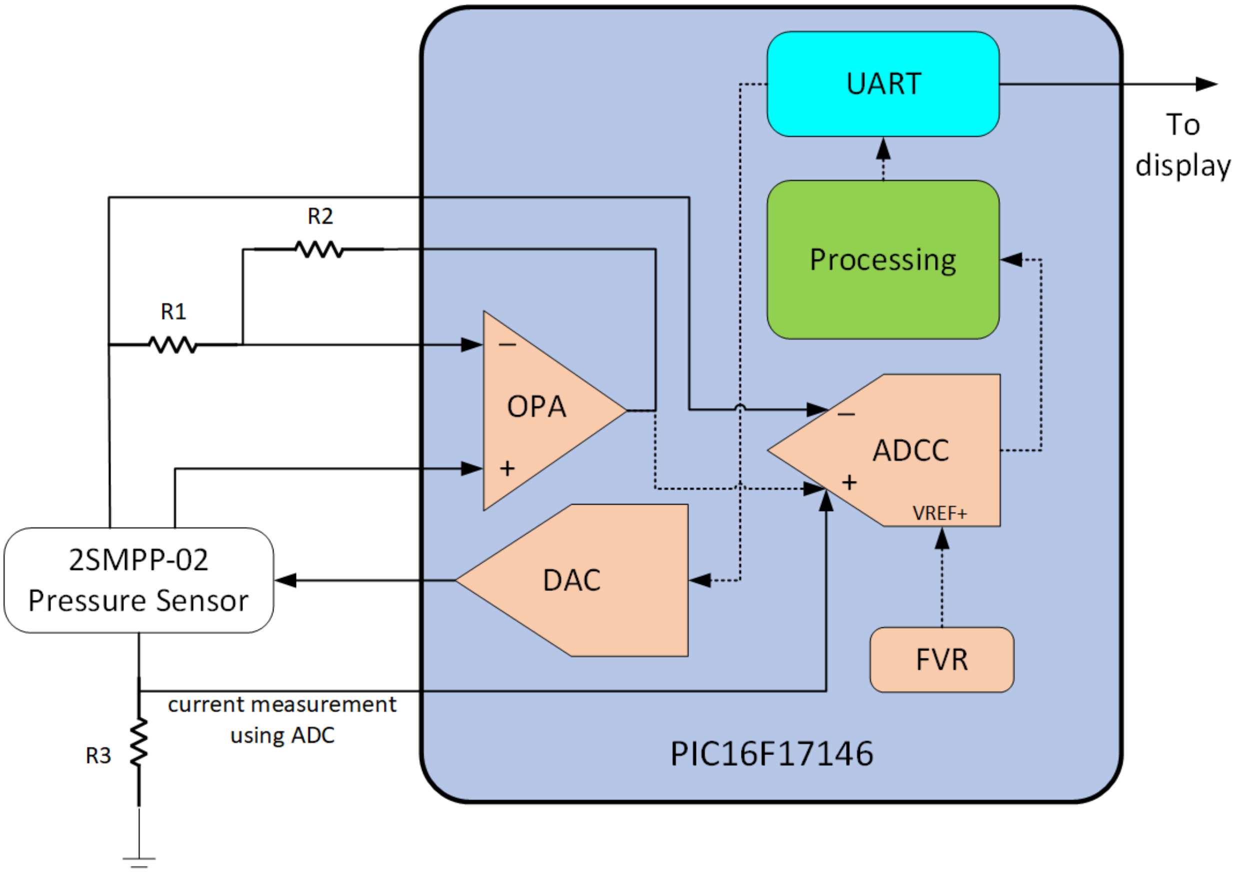
3.1.2 Differential Output Sensor Interface

Figure 3-3. Differential Output Sensor Interface



DAC provides a constant current of 100 µA for 2SMPP-02 differential output sensor excitation. OPA is configured as the gain stage, and the output of OPA provides the positive input channel of the differential ADCC.

The ADCC Differential mode interfaces with the sensor's differential output signal. The ADCC also measures the excitation current of the sensor by measuring the voltage across a resistor connected between the sensor pin ICC and circuit ground. This way, implementing a feedback loop can maintain a 100 µA constant current. Adjusting the DAC output value can modify the current.

FVR provides stable voltage reference to the ADCC and DAC modules. Ambient pressure value is displayed on the terminal window when using a UART peripheral after processing the ADC result.

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Refer to the code example above for implementation details using the PIC16F17146 microcontroller and the Getting Started with Integrated Analog Peripherals of PIC® Microcontroller technical brief.

Application examples using the ADC in Single-Ended Measurement mode are featured in the following sections.

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3.2 Making the Most Out of ADCC Channels

Configure the appropriate ADC positive and negative channels using the ADPCH and ADNCH registers for the differential ADC measurement. The input sources for the positive and negative channels could be from external sensor/signal circuitry or the outputs of microcontroller peripherals such as Temperature indicator, Fixed Voltage Reference (FVR), Operational Amplifier (OPA), Digital-to-Analog Converter (DAC).

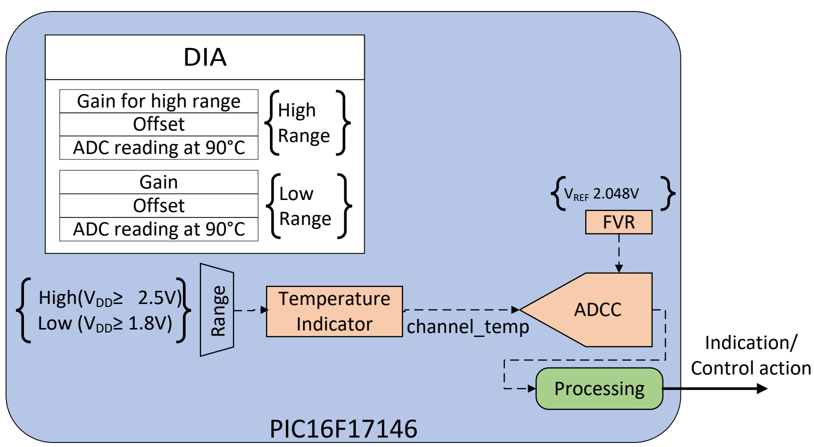
In the case of single-ended ADC measurement, the ADPCH register selects the positive input. The ADC hardware ignores any negative input selections chosen by ADNCH.

It is also possible to select one of the ADC channels (positive or negative) from an external pin and another channel from the internal peripheral output in Differential Measurement mode.

3.2.1 Temperature Indicator as ADC Internal Channel

The PIC16F17146 and PIC16F18146 families of microcontrollers contain a Temperature Indicator module designed to measure the operating temperature of the silicon die. The temperature indicator is internally connected to the input multiplexer of the ADC. Using the Temperature Indicator module along with the ADC for temperature measurement saves PCB area and the need for separate temperature sensors and microcontroller pins, thereby reducing the BOM cost in the application. The range of temperature measurement is between -40°C and +125°C.

Figure 3-4. Temperature Measurement Using Temperature Indicator



Depending on the application, the ADC result from the temperature indicator output can be either compared directly against specific trip points or used to determine the actual temperature by calculation, a look-up table, or a combination of both. The Temperature Indicator circuit can be calibrated for more accurate measurements.

Refer to AN1333 - Use and Calibration of the Internal Temperature Indicator and AN2092 - Using the Temperature Indicator Module for details on how to use and calibrate the temperature indicator module.

3.2.2 FVR as ADC Internal Channel

Battery voltage monitoring is necessary in numerous battery-powered applications where the supply voltage of a microcontroller may fall below the specified threshold level and require battery replacement or recharging for the uninterrupted operation of the system. When the microcontroller is directly powered by a battery power source, the battery voltage monitoring is possible using FVR connected internally to ADC. Hence, a microcontroller PORT pin or external passive components are not required for battery voltage measurement, as shown in Figure 3-5.

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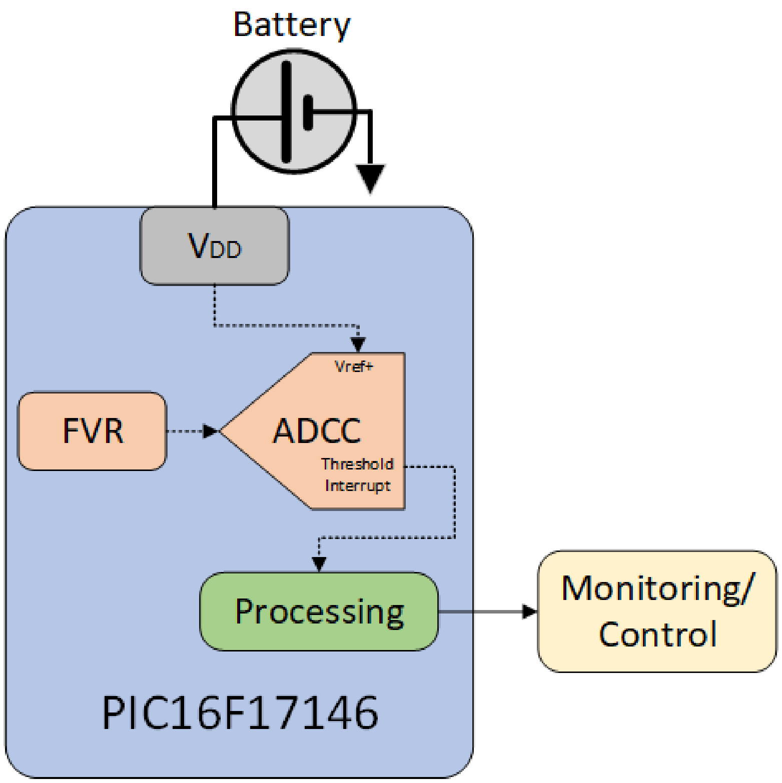
For battery voltage measurement using ADCC and FVR peripherals, use the supply voltage (V_{DD}) as positive voltage reference and FVR as input to ADCC. The ADCC conversion result for the fixed FVR output varies depending on the battery voltage. Enable the ADCC threshold comparison feature to detect the battery depletion condition.

Figure 3-5. Battery Voltage Measurement Using FVR



The ADC result is computed as shown in Equation 1 when FVR is input to the ADC channel, the battery is the power source to the microcontroller, and V_{DD} is the positive reference voltage of ADC.

Equation 1:

$$ADC_{RESULT} = \frac{V_{FVR}}{V_{BAT}} * \left(2^{12} - 1\right)$$

When the battery voltage is 3V and the FVR output is 1.024V, the ADC result count is 1398, as shown below.

Equation 2:

$$ADC_{RESULT}\left(V_{BAT} = 3V\right) = \frac{1.024}{3} * \left(2^{12} - 1\right) = 1398$$

When the battery voltage drops to 2.5V, the ADC result count for FVR (1.024V) is 1677, as shown below.

Equation 3:

$$ADC_{RESULT}\left(V_{BAT} = 2.5V\right) = \frac{1.024}{2.5} * \left(2^{12} - 1\right) = 1677$$

When the battery voltage drops to 2V, the ADC result count for FVR (1.024V) is 2097, as shown below.

Equation 4:

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$$ADC_{RESULT}\left(V_{BAT} = 2V\right) = \frac{1.024}{2} * \left(2^{12} - 1\right) = 2097$$

The 3V battery can be used as the power source to the microcontroller until its voltage drops to the recommended minimum voltage of 2V. Keep the ADC 2000 threshold to detect the depleted battery condition and take further action when its voltage goes below the recommended minimum of 2V.

3.2.3 Signal Conditioning using OPA as ADC Internal Channel

The signal condition circuit, an integral part of the sensor node, comprises OPA as its building block. The analog sensor may have a dynamic output range in millivolts or milliamperes. Depending on the operating environment in which the sensor is mounted, the sensor measurement might be affected by noise induced onto the system. Hence, the resultant sensor output signal might be noisy. Therefore, an analog sensor may require a signal conditioning circuit that converts sensor output to the required voltage range or frequency. The signal conditioning circuit, an integral part of a sensor node, comprises OPA as its building block.

The output of the signal conditioning circuit can be converted to digital form using ADCC for further processing in real-time monitoring and control applications. The PIC16F17146 family of microcontrollers has an inbuilt OPA with an internal resistor ladder and the option to connect external resistors for gain setting. This OPA has a provision to connect its output internally to the ADCC input channel. For more details on using combinations of analog peripherals in sensing and measurement applications, refer to the Getting Started with Integrated Analog Peripherals of PIC® Microcontroller technical brief.

Figure 3-6 illustrates how to interface a passive infrared (PIR) sensor using a PIC microcontroller's ADCC, OPA, DAC, FVR, and Timer Peripherals.

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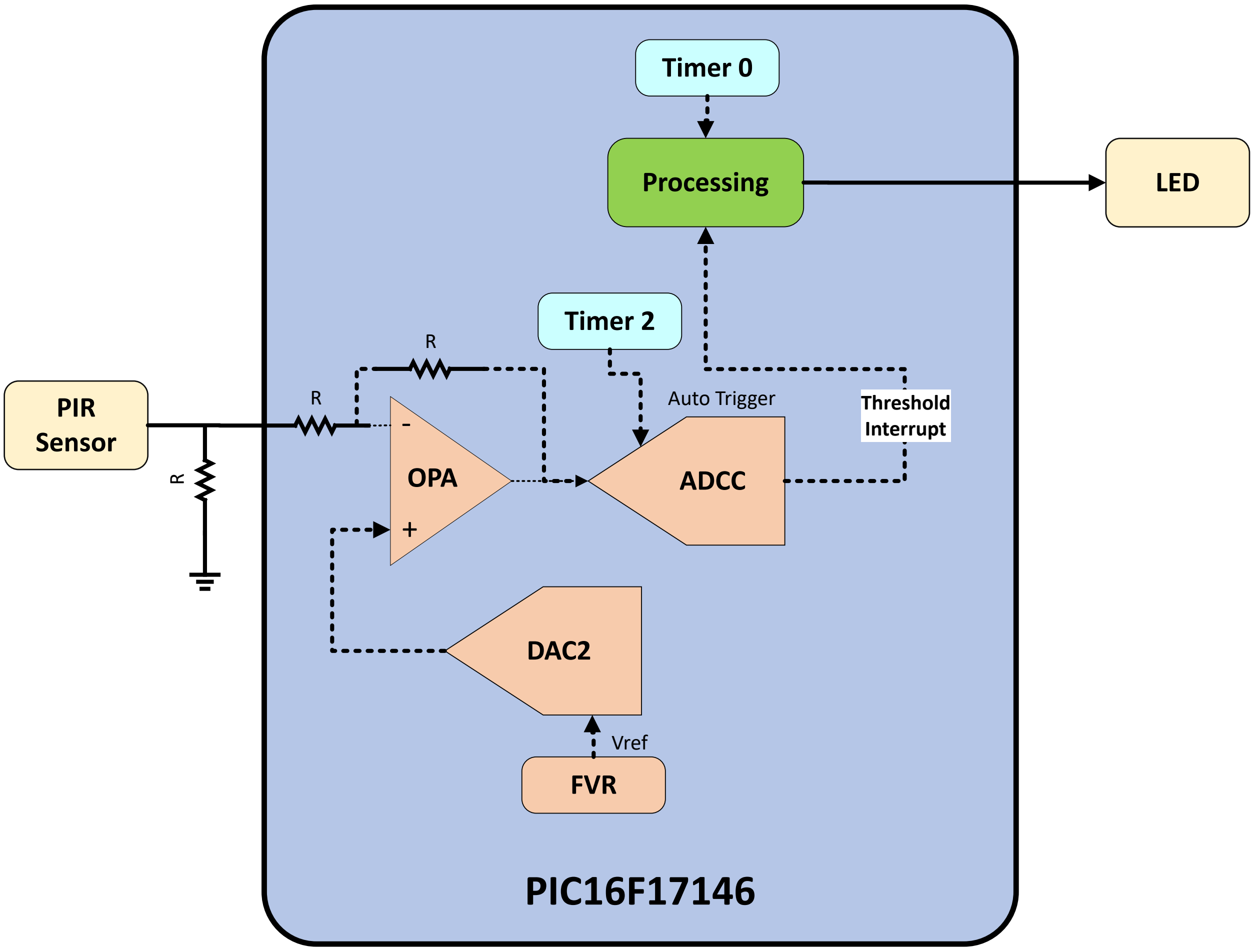
Figure 3-6. PIR Sensor Interface



- PIR sensor low output signal is fed to OPA
- OPA with Internal resistor ladder is used to provide gain (x16)
- OPA output is connected internally to the ADCC
- ADCC is used in Low-Pass Filter mode along with threshold comparison
- DAC is used to compensate the offset voltage of the PIR sensor

The application can detect movement even when the CPU is in Sleep mode. When the OPA output goes above the configured ADCC threshold, an interrupt is generated. It wakes the CPU up and indicates the movement detected by blinking the LED.

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3.1.1. AC Voltage Measurement Using Differential ADC and 3.1.2. Differential Output Sensor Interface application use cases illustrate the usage of OPA for filtering and amplification of analog signals along with ADC in sensing and measurement applications.

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3.2.4 DAC as ADC Internal Channel

The DAC of the PIC16F17146/PIC16F18146 family of microcontrollers has a provision to connect its output internally to the ADC input channel.

The 3.1.1. AC Voltage Measurement Using Differential ADC section illustrates the usage of DAC to add an offset voltage for making the analog input voltage compatible with the ADC measurement range.

3.2.5 Grouping Channels Together

The ADC channel grouping feature allows users to combine multiple input channels acting as a single sensor connected to the ADC input channel. When the channel group option of the ADPCH register is configured as ADCC 'channel', the input channels selected by the ADC Channel Group Selection registers are collectively activated for both analog signal input and a precharge operation. The ADC input is the wire-OR signal from all enabled channels.

The below application example showcases the usage of the ADC Channel Grouping feature.

3.2.5.1 Welcome Doormat with Multiple Force Sensing Resistors

When any visitor steppes on a smart doormat, it notifies the user by turning ON the buzzer, eliminating the need for the visitor to ring a doorbell. The multiple force sensors are usually placed underneath a doormat at its four corners and the center.

A pressure change will happen when any guest or visitor steps on the doormat and is detected by scanning the five force sensors placed below the doormat.

Conventionally, the ADC scans different channels periodically to detect changes in any sensor outputs from the array of multiple sensors, and the CPU takes the required control action, requiring CPU intervention and more power consumption from the microcontroller.

This feature can also be used in capacitive touch sense applications and allows the designers to apply innovative strategies to implement user interfaces, improve response time, and reduce power consumption.

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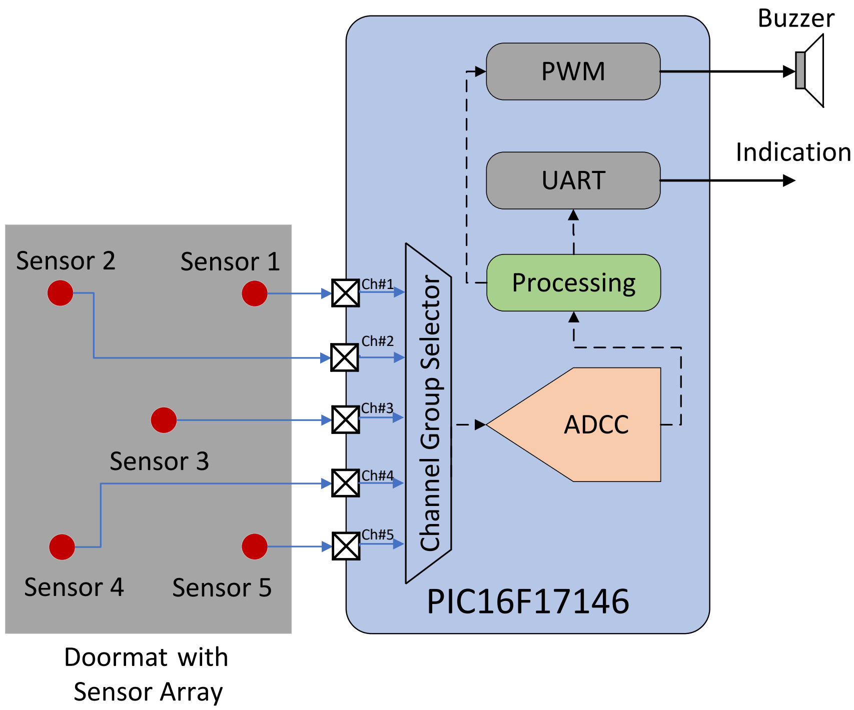
Figure 3-7. Channel Grouping Application



3.3 ADCC Continuous Operation in Sleep Mode and Threshold Comparison

Some sensor applications like automatic streetlight control systems and liquid/water level monitoring systems need continuous monitoring of the sensor output until it has reached the desired threshold limit. In battery-operated sensor nodes, low-power operation of the application is required to extend the battery life.

ADCC in the PIC16F17146/18146 family of microcontrollers can operate autonomously in Sleep mode and continuously monitor the analog sensors with the built-in threshold comparison and continuous sampling features. When working in Sleep mode, ADCC can generate an interrupt whenever the desired threshold is reached, and the CPU can wake up from Sleep mode to take appropriate action. The application described below demonstrates the usage of ADCC continuous sampling, Sleep mode operation, and threshold comparison features. Figure 3-8 shows the Street Light control system and water/liquid level monitoring system with an auto on/off feature.

To enable ADCC operation in Sleep mode, select internal ADCRC as the clock source to ADCC, enable Continuous Sampling mode, and configure ADC Upper Threshold (ADUTH) and the ADC Lower Threshold (ADLTH) registers to set lower and upper threshold values. Then, start the ADCC conversion and put the microcontroller in Sleep mode.

The ADCC peripheral starts operating autonomously in Sleep mode, and the Continuous Sampling mode retriggers automatic sampling of ADCC each time after the ADCC result has been compared with the threshold. By this, the ADCC operates in Sleep mode without CPU intervention and wakes the CPU only when the ADCC conversion result crosses above or below the threshold value. Which, in turn, lowers the microcontroller's average power consumption. If the ADCC conversion result goes below the lower threshold limit, ADCC generates a threshold interrupt and wakes the CPU from Sleep mode. The application turns on the streetlight or the pump motor to fill the tank and enable the upper threshold interrupt. The application starts the ADCC conversion with a Continuous

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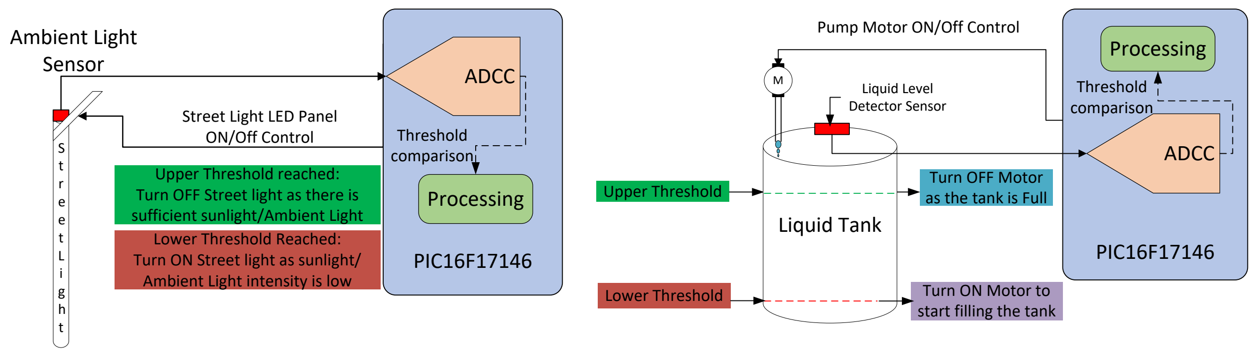
Sampling mode set and puts the CPU in Sleep mode. If the ADCC conversion result passes the upper threshold limit, ADCC generates a threshold interrupt and wakes the CPU from Sleep mode. The application turns off the streetlight as there is sufficient ambient light or turns off the pump motor as the tank is full and enables the lower threshold interrupt. The application starts the ADCC conversion with a Continuous Sampling mode set and puts the CPU in Sleep mode.

Figure 3-8. Street Light Control System and Liquid/Water Level Monitor



3.4 Using ADCC's Various Computation Modes

The ADCC module hardware contains post-conversion computation features, such as digital low-pass filtering/averaging and threshold comparison. The module can be configured to take additional samples or stop conversions, and an interrupt may be asserted based on computation results. These post-conversion computation features can be used to increase the signal-to-noise ratio in the sensor nodes by taking more samples of the signal and averaging or filtering them. The computation modes are described in detail below.

3.4.1 Coulomb Counting in Battery Using Accumulate Mode

To estimate the charging level when the battery charges, its charging current should be measured and accumulated. In the case of a battery discharge stage, for measurement of the battery state of charge (percent capacity remaining), the battery discharge current should be measured and accumulated as a coulomb counter. When combining the coulomb count and the estimated battery charge, an estimate of the battery health is calculated. ADCC with Accumulate mode can be used for the same. The timer (auto-conversion trigger feature of the ADCC) may trigger the ADC conversion of the battery current to provide a consistent sample rate.

3.4.2 Noise Suppression Using Burst Average or Average Mode

Most analog signals are affected by noise. Noise is an undesirable electrical signal which interferes with an original or desired signal. Every sample from an ADC can be a combination of signal and noise. Noise suppression is a process of reducing noise with minimal impact on the desired signal. One way to achieve this is by computing the average of many samples of a noisy signal, reducing the noise magnitude on the signal without impacting the original signal. A potential solution could be to filter the acquired samples in software. However, this would require additional CPU resources. A better option would be to use the computation modes supported by the ADCC.

The ADCC Computation modes, such as Average or Burst Average mode, can be used for averaging by configuring the ADC to accumulate several samples automatically. The ADC conversions accumulate in ADACC, and the average value of the accumulated samples (i.e., the filtered result) is available in the built-in ADFLTR. Because the sampled noise has a zero mean, the averaged result will be close to the actual signal values. In Figure 3-9, the purple line illustrates the sensor output signal with fluctuations due to noise. The red line shows the accumulation of 32 ADC samples in a short time window to get the average or filtered output.

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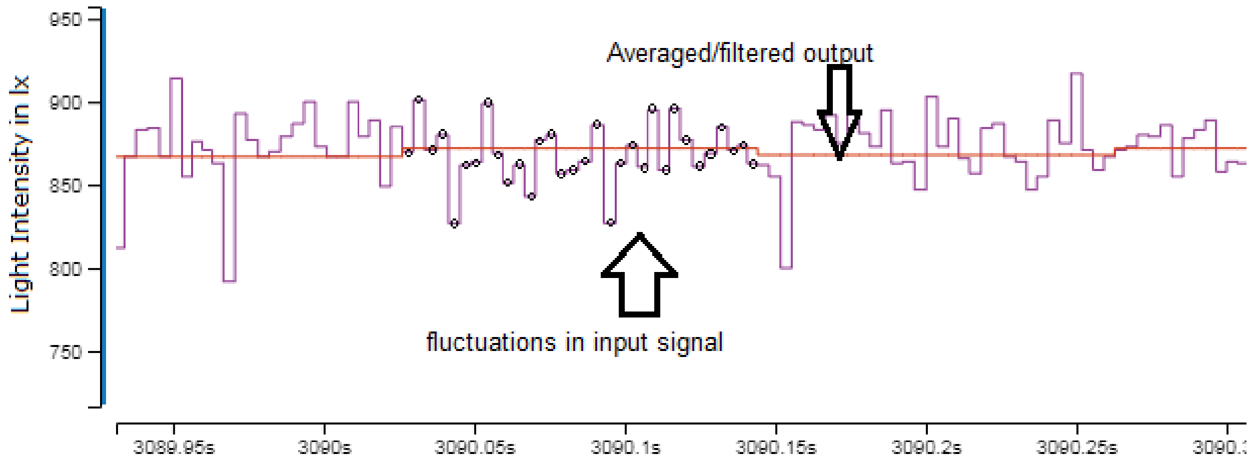
Figure 3-9. Sensor Output Signal with Fluctuations and Averaged Sensor Output



Each sample differs from zero by a random value but with an equal probability of being either positive or negative. The accumulated noise sample values will approach zero, and the noise will be successfully suppressed. If this noise is imposed on a non-zero signal, the accumulated value approaches a scaled version of this signal's average. As oversampling is done with multiple samples, the average result of all the sampled values will be approximately equal to the original DC signal, meaning zero mean noise. Increasing the burst size (accumulating more samples) helps to flatten out more peak signals and results in more noise suppression.

The Average mode can be used with low-varying signals such as temperature, humidity, and TDS sensors to remove fluctuations and noise from the signal.

The burst average can be used best for a quick, short-term averaging operation. For extended periods, Averaging mode is a better choice.

3.4.3 ADCC Low-Pass Filter Mode

The Low-Pass Filter mode can be used in systems where the control actions require a more stable signal from the input sensor. For example, in the case of a smartphone, while setting the brightness of the screen, the output of the ambient light sensor should be low-pass filtered.

Refer to AN2749 - Using PIC18F26K42's 12-bit ADC² in Low-Pass Filter Mode to understand the ADCC LPF mode in detail, which can be used for filtering noisy DC and AC signals.

Refer to the example below to understand how to use individual ADC Computation mode.

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4. References

TB3146 - Analog-to-Digital-Converter-with-Computation (DS90003146)

TB3194 - PIC16/PIC18 ADC^2 Technical Brief (DS90003194)

AN2749 - Using PIC18F26K42's 12-bit ADC^2 in Low-Pass Filter Mode (DS00002749)

Using the Analog-to-Digital Converter with Computation (ADC^2) Module (DS50002823)

TB3263 - Getting Started with ADCC on PIC18 (DS90003263)

Getting Started with Integrated Analog Peripherals of PIC® Microcontroller (DS900003320)

Differential-and-Single-Ended-ADC-WhitePaper (DS00003197)

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5. Revision History

Document Revision	Date	Comments
A	03/2024	Initial document release

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