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Getting Started with Integrated Analog Peripherals of PIC® Microcontrollers

Introduction

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In sensor node application, a sensor needs an electronic circuitry (known as signal conditioning circuit) to interface with the microcontroller. Signal conditioning circuits are designed using analog and mixed signal components such as Operational Amplifier (OPA), Comparator (CMP), Analog-to-Digital Converter (ADC) and Digital-to-Analog Converter (DAC). The 8-bit PIC® microcontrollers have these analog and mixed signal components as integrated peripherals, which can be used in sensing, signal conditioning, processing and generating analog output without the need of external components. Interconnectivity and a combination of multiple integrated analog and signal conditioning peripherals can offer significant advantages (such as configurable firmware, no external wiring, reduced circuit design complexity, PCB size and BOM cost) over other microcontrollers and external components.

This document provides an overview of sensors and signal conditioning circuits. It provides the technical details of signal conditioning circuits that can be realized using intelligent analog peripheral combinations (OPA, FVR, ADC, CMP and DAC) for various sensing and measurement applications. This document is also supported by the following sensor interfacing use cases for various real world applications:

- Force Sensing Resistor (FSR) Using PIC16F17146 Microcontroller
- Pressure Sensor Interface with Differential Output Voltage Using PIC16F17146 Microcontroller
- Water TDS Measurement Using PIC16F17146 Microcontroller

Notes:

1. The content described in this document highlights the analog peripherals of the PIC16F17146 family of microcontrollers.
2. This content is also relevant to all the other 8-bit PIC product families featuring these analog peripherals. Even though the analog peripheral features and their usage in various applications varies, the typical sensor and signal conditioning concepts described in this document are applicable to all the 8-bit PIC product families.

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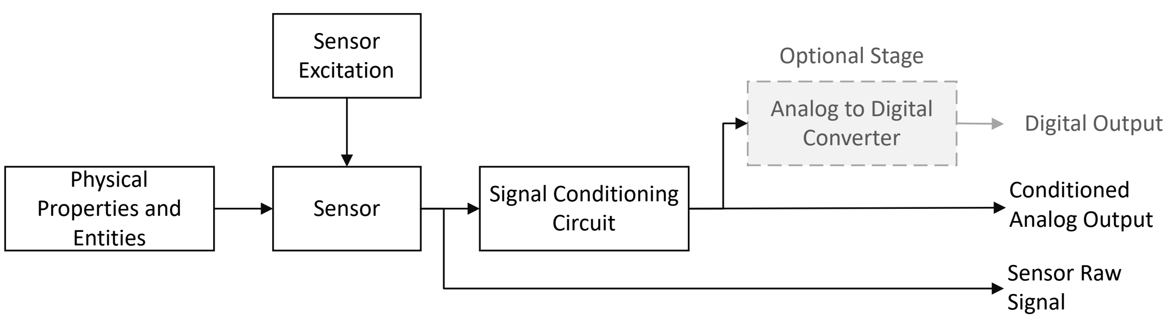
1. Sensor and Signal Conditioning Circuits

A sensor is used to sense a change within the environment it is surrounded by and produce the corresponding variation as an equivalent electrical signal. Regardless of the input, the output signal of a sensor is usually a voltage, current, charge or resistance. The dynamic output range of a sensor is typically measured in mV or mA and the output of a sensor can be a single-ended signal or a differential signal.

Depending on the system operating environment where the sensor is mounted, the sensor measurements might be affected by noise induced in the system. Therefore, the resultant sensor output signal might be noisy. Sensors require a signal conditioning circuit to remove noise (if any) from the sensor output signal and convert it to the required voltage range or frequency. The converted sensor output signal is fed to the host microcontroller so that it can be processed, displayed and utilized for feedback-controlled systems.

Few sensors have built-in signal conditioning circuitry along with an Analog-to-Digital Converter as an optional stage, referred to as digital sensors. These sensors can be interfaced directly to the host microcontroller. The host microcontroller requires a serial communication peripheral such as I^2C, SPI or UART for interfacing with digital sensors and to read data from them. Figure 1-1 shows the block diagram of a typical sensor or transducer.

Figure 1-1. A Typical Block Diagram of Sensor and Signal Conditioning Stage



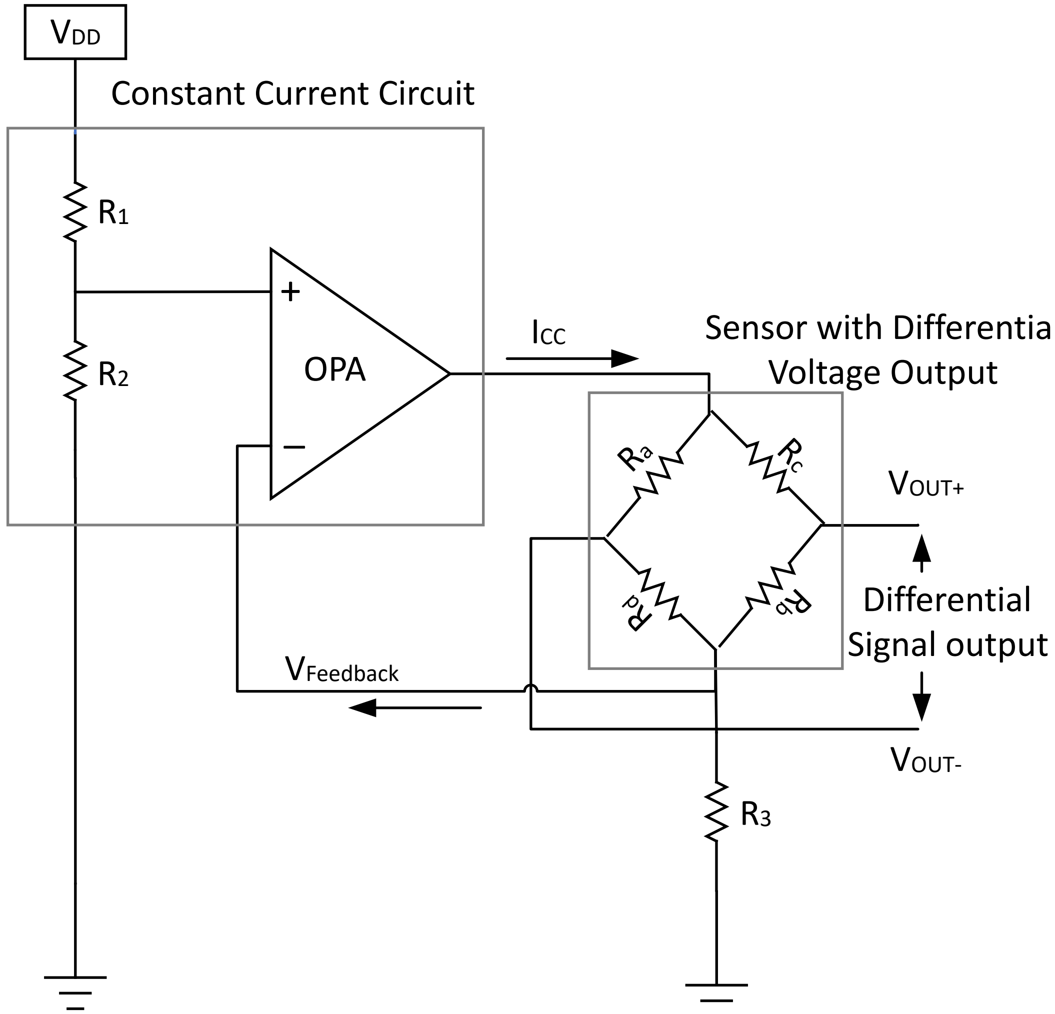
Signal conditioning circuits accept raw sensor output signals and convert them into a form that the microcontroller-based system can process further. Based on the sensor output and application use, the following are the typical circuits required for sensor interface:

- Sensor excitation (constant voltage or current supply)
- Attenuation (voltage divider circuits)
- Amplification
- Signal filtering
- Signal buffering or high-impedance stage
- Current-to-Voltage Converter
- Voltage-to-Frequency Converter

1.1 Sensor Excitation

Some sensors require an external excitation source to transform physical properties or entities into electrical signals, such as resistor-based sensors (thermistors, RTDs) and strain gauges. These sensors require current or voltage source for excitation to produce an electrical output. The accuracy in measurement of the sensor output depends upon the applied excitation. In noisy environments, current excitation is generally preferred due to its better noise immunity. Figure 1-2 shows a constant current excitation to a resistor bridge type sensor.

Figure 1-2. Constant Current Excitation



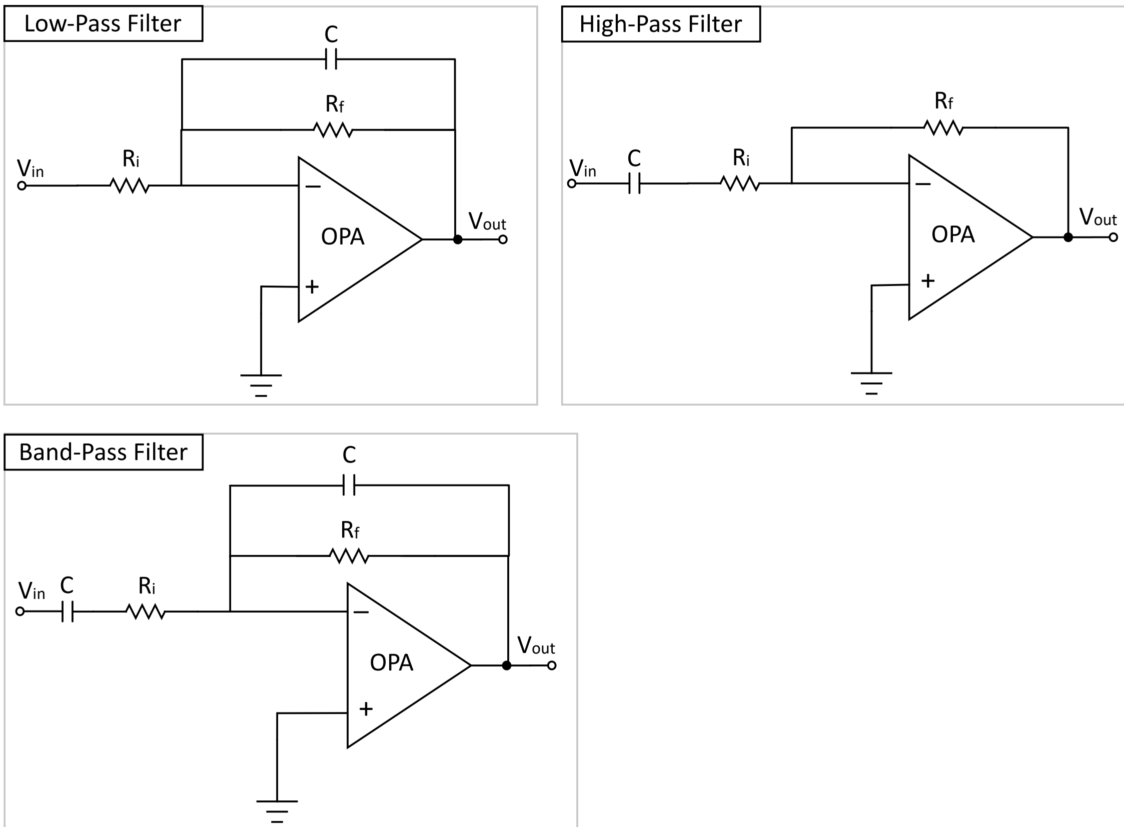
1.2 Attenuation (Voltage Divider with Buffered Stage)

The sensor output signal requires attenuation when its voltage range exceeds the input voltage range of the ADC. The resistive divider can easily attenuate any range of voltages, but it provides lower impedance to the source and higher impedance to the ADC. A unity-gain buffer provides high-input impedance (~MΩ) and very low-output impedance (< 10 KΩ) necessary for the ADC of microcontrollers. The applications such as temperature sensing and battery voltage monitoring require a sensor output signal attenuation to keep the signal within the allowed input signal range of the ADC.

1.3 Signal Filtering

The sensor output is prone to get affected by the surrounding operating environment, resulting in additional noise and fluctuations. Analog or digital signal filters are required to remove noise and fluctuations. The frequency-cutoff characteristics of passive filters can change with a change in load, whereas active filters using op amp are used to maintain stable filter characteristics. Active filters also help to attenuate/amplify signals to obtain the desired voltage range without losing signal characteristics. For example, PIR sensors, photodiodes, current measurement, flow sensors and capacitive touch sensors need filtering. Figure 1-3 shows the low-pass, high-pass and band-pass active filters, respectively.

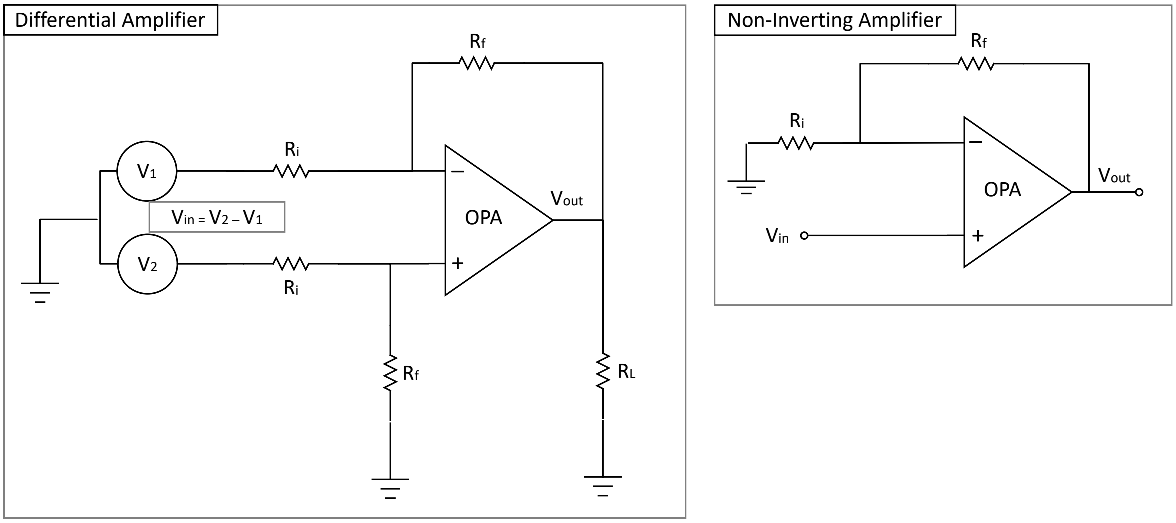
Figure 1-3. Filters



1.4 Amplification

A sensor output signal with extremely low strength cannot be directly fed to the ADC input channel. These sensors need gain and buffer stages at the output and before interfacing to the ADC channel. Op amps are required to realize gain and buffer stages. The single-ended sensor output often uses a non-inverting and unity gain follower stage, but the differential sensor output needs a difference amplifier. The major benefit of the difference amplifier is its ability to reject any common mode noise while amplifying the difference voltage. Sensors such as thermocouple, pressure sensors, ambient light sensors, Current Transformer (CT) and strain gauge sensors require amplification.

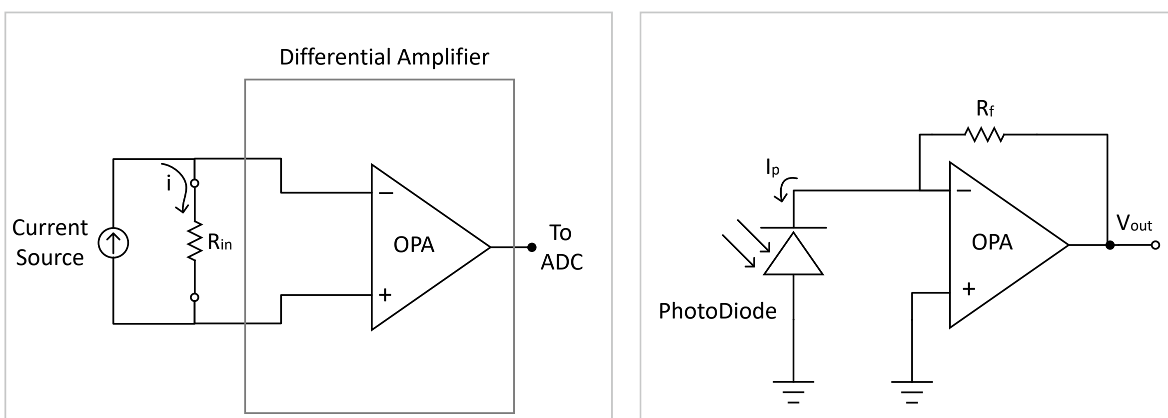
Figure 1-4. Amplification Circuit



1.5 Current-to-Voltage Converter

The Current-to-Voltage Converter is needed when the sensor gives output in terms of variation in resistance or current, such as Force Sensing Resistor (FSR), Photodiode, 4-20 mA industrial sensors, etc.

Figure 1-5. Current to Voltage Converter Circuit Examples



1.6 Voltage-to-Frequency Converter

This circuit converts the analog input signal voltage to a pulse train with the frequency proportional to the amplitude of the input signal. The pulses are counted over a fixed period to determine the frequency and the pulse counter output, in turn, represents the sensor output signal voltage. Voltage-to-Frequency Converters reject noise well and are frequently used for conditioning slow and noisy signals.

1.7 Integrated Peripherals and Sensor Interfacing

An OPA is the basic building block to implement the signal conditioning circuits. Along with the OPA, few passive components, sensor excitation and offset/bias voltages are required for a sensor interface. The ADC peripheral converts the conditioned voltage signal into digital values for further processing. If a microcontroller has built-in OPA, ADC, CMP and DAC, then interfacing a sensor to the microcontroller is easy and less time consuming.

The availability of 12-bit differential ADCC, 8-bit DAC and OPA in the PIC16F17146 family of microcontrollers helps to interface a wide range of sensors. The CPU of PIC16F17146 family of microcontrollers offers good computation capabilities and operates with a supply voltage in the range of 1.8V to 5V. Therefore, most of the sensors can be interfaced directly without any signal attenuation circuits. All the analog peripherals can be configured to connect to each other internally. Their combination makes it easy to interface a sensor with the microcontroller.

The following section highlights the intelligent analog peripherals available in the PIC16F17146 family of microcontrollers.

2. Analog Peripherals of PIC16F17146 Family

This section describes the important features of analog peripherals present in the PIC16F17146 family of microcontrollers and the various possibilities available to interconnect these peripherals. Refer to the respective device data sheet for more detailed information about these analog peripherals and the other available peripherals.

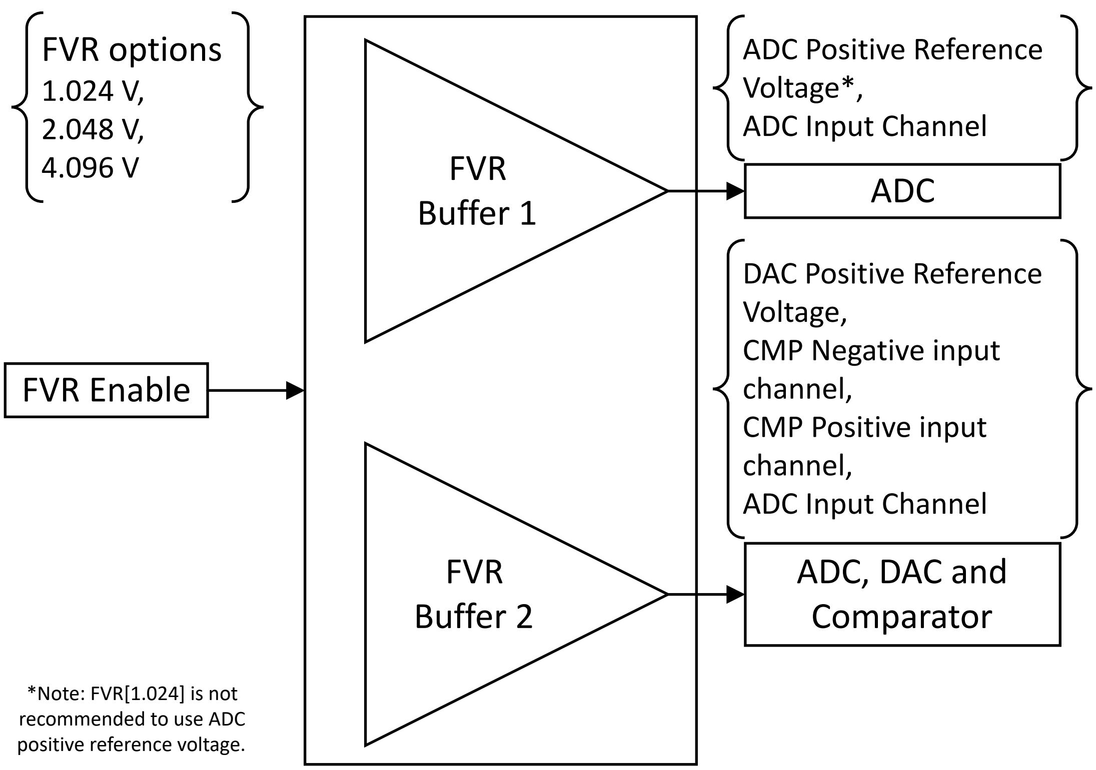
The possible internal connections of analog peripherals are described in section 3. Combinations of Analog Peripherals in PIC16F17146. The various sensor interfacing applications are briefly discussed in section 5. Use Cases.

2.1 Fixed-Voltage-Reference (FVR)

The Fixed Voltage Reference (FVR) is a stable voltage reference available in the PIC16F17146 family of microcontrollers.

Figure 2-1 shows the interconnection details of the FVR module.

Figure 2-1. FVR Module Interconnections to Other Peripherals of PIC16F17146 Family of Microcontrollers

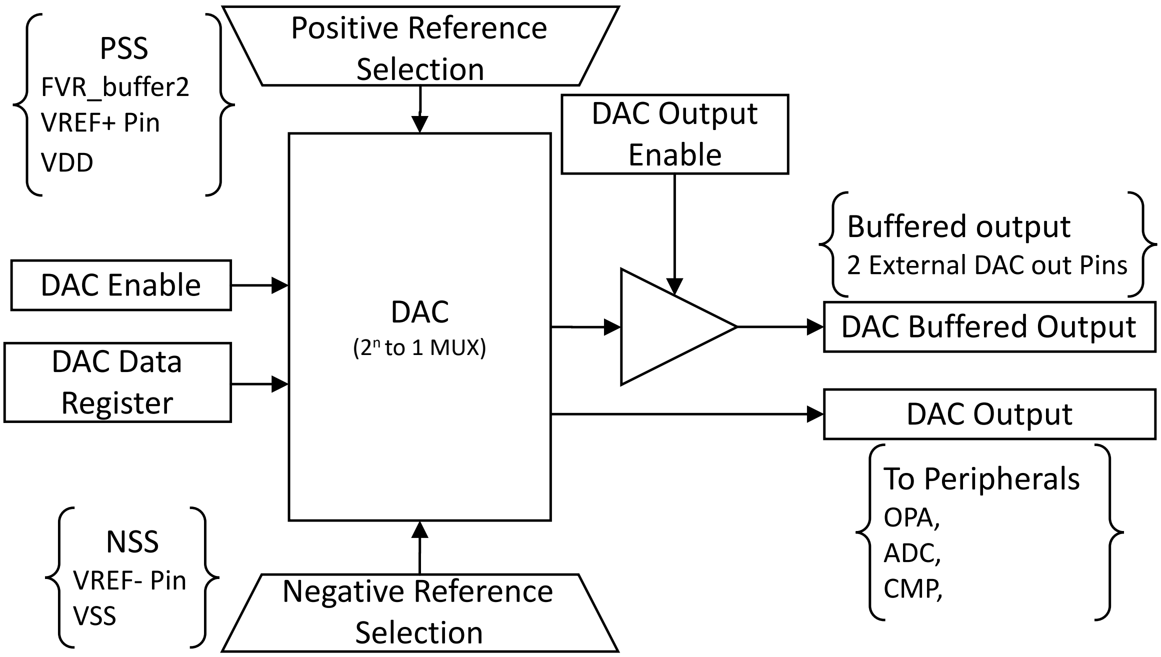


2.2 Digital-to-Analog Converter (DAC)

The Digital-to-Analog Converter (DAC) is a peripheral which converts a digital value written to the data register to an equivalent analog value. The buffered DAC output can be used as a source for sensor excitation.

Figure 2-2 shows the simplified diagram of the DAC module interconnection to the other peripherals of the PIC16F17146 family of microcontrollers.

Figure 2-2. DAC Module Interconnections to Other Peripherals of PIC16F17146 Family of Microcontrollers

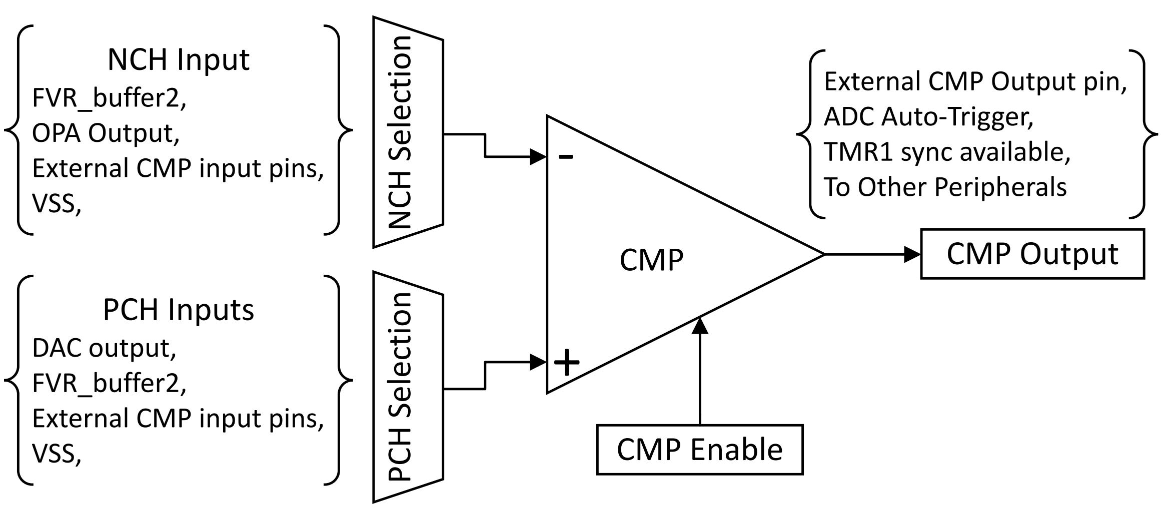


2.3 Comparator (CMP)

Comparators are used to interface analog circuits to a digital circuit by comparing two analog voltages and providing a digital indication of their relative magnitudes. Comparators are very useful mixed signal building blocks because they provide analog functionality independent of program execution.

Figure 2-3 shows simplified diagram of the CMP module interconnections to the other peripherals of PIC16F17146 family of microcontrollers.

Figure 2-3. Comparator Module Interconnections to Other Peripherals of the PIC16F17146 Family of Microcontrollers

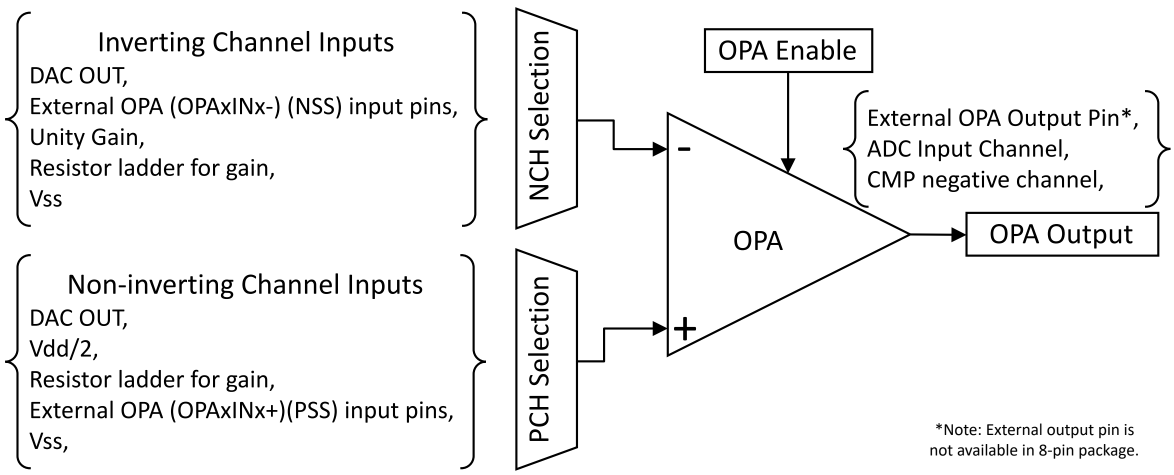


2.4 Operational Amplifier (OPA)

The Operational Amplifier (OPA) module can be used as a signal conditioning element in sensing and measurement applications. The OPA module can be used as programmable gain amplifier for the ADC input signals in low-voltage range, and the OPA module output is internally connected to the ADC input channel.

Figure 2-4 shows a simplified diagram of the OPA module interconnection to other peripherals of PIC16F17146 family of microcontrollers.

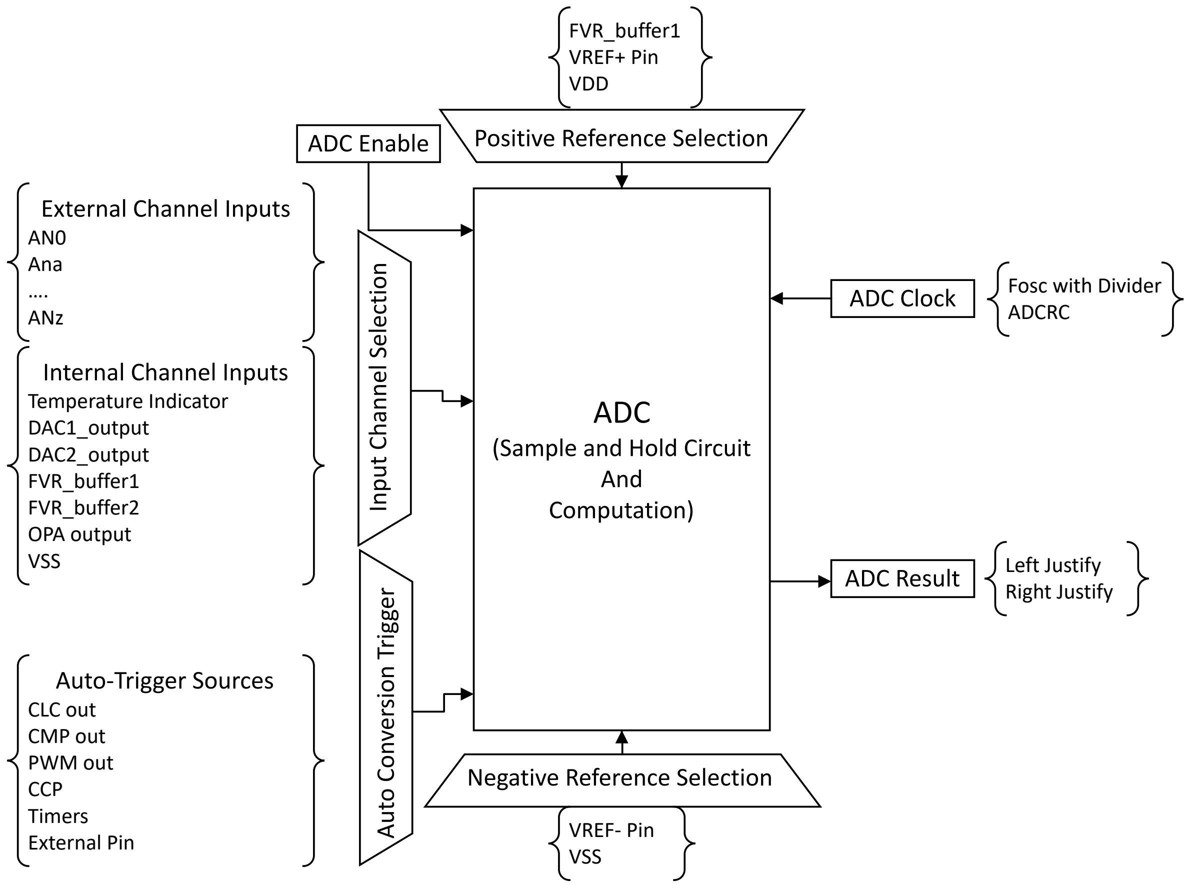
Figure 2-4. OPA Module Interconnections to Other Peripherals of PIC16F17146 Family of Microcontrollers



2.5 Analog-to-Digital Converter with Computation (ADCC)

The PIC16F17146 family of microcontrollers is equipped with 12-bit Analog-to-Digital Converter with Computation peripheral. Figure 2-5 shows a simplified diagram of the ADC module interconnections to the other peripherals of PIC16F17146 family of microcontrollers.

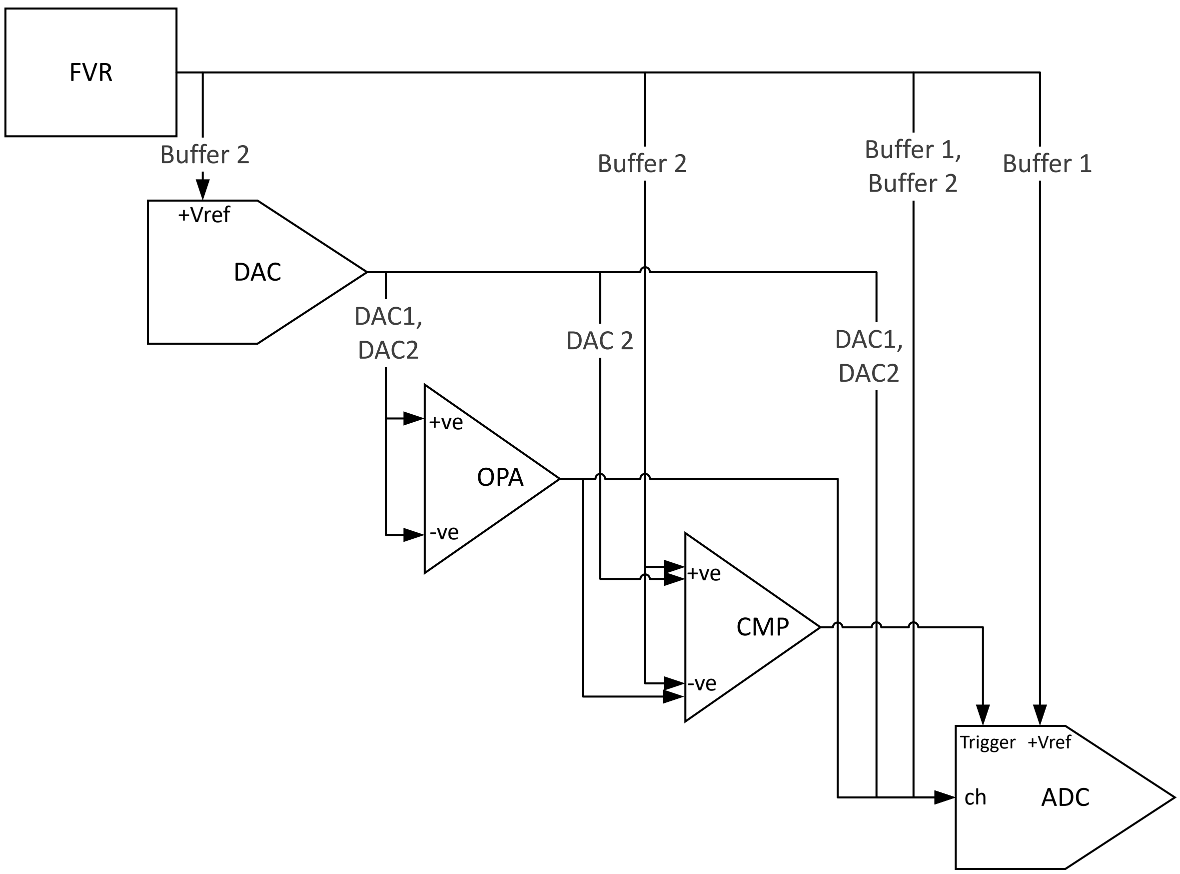
Figure 2-5. ADC Module Interconnections to Other Peripherals of the PIC16F17146 Family of Microcontrollers



3. Combinations of Analog Peripherals in PIC16F17146

This section describes the possible interconnections between intelligent analog peripherals of the PIC16F17146 family of microcontrollers and covers details on different analog peripheral combinations which are useful to develop various sensing and measurement applications.

Figure 3-1. Analog Peripheral Interconnections



The possible combinations of analog peripherals are depicted in Figure 3-1.

FVR:

- Provides 1.024, 2.048 or 4.096V of output voltage.
- The user can configure the FVR module as a positive voltage reference to the ADC module or DAC module based on the required dynamic range.
- The FVR module output can be connected to either a positive or negative input channel of the CMP module or to the ADC input channel.

DAC:

- The DAC module accepts either FVR (buffer 2) or V_{DD} as the positive reference.
- The 8-bit DAC with 1.024V reference voltage can provide an analog output resolution of 4 mV ($1.024V/2^8$).
- The buffered DAC module output can source current and be configured to connect to the external port pin.
- The DAC module output can be configured to internally connect to either the OPA module or CMP module or to the ADC input channels.

CMP:

- The CMP module can be used for auto-triggering the ADC module to start conversion upon comparator output change event.
- The DAC module or FVR module can be connected to the CMP module input channel and used as a voltage reference to compare external analog signals.

OPA:

- The OPA module output can be connected to the ADC input channels.
- Used in signal conditioning circuits. The OPA module can be used as a gain stage or high-impedance stage for an analog signal before connecting to the ADC input channel. It helps in measuring an analog signal with better voltage precision and a higher dynamic range.
- The DAC module output can be connected to the non-inverting input of the OPA and provides an offset voltage.

ADC:

- The ADC module accepts either V_{DD} or FVR or an external reference voltage at the VREF+ pin as the reference voltage (V_{REF}).
- A lower voltage reference provides a higher precision but minimizes the dynamic range of the input signal. For example, with a maximum input voltage of 2.048V and 2.048V voltage reference (V_{REF}), the step size of the 12-bit ADC module conversion result is approximately 500 µV (2.048V/ 2^{12}).
- In ADC Differential mode operation, the DAC module can add an offset voltage to the analog input signal.

4. MPLAB® MINDI™ Analog Simulator

MPLAB® MINDI™ Analog Simulator reduces circuit design time and design risk by simulating analog circuits prior to hardware prototyping. The simulation tool uses a SIMetrix/SIMPLIS simulation environment, with options to use SPICE or piecewise linear modeling, that can cover a very wide set of possible simulation needs. This capable simulation interface is paired with proprietary model files from Microchip to model-specific Microchip analog components in addition to generic circuit devices. This simulation tool installs and runs locally on your PC.

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5. Use Cases

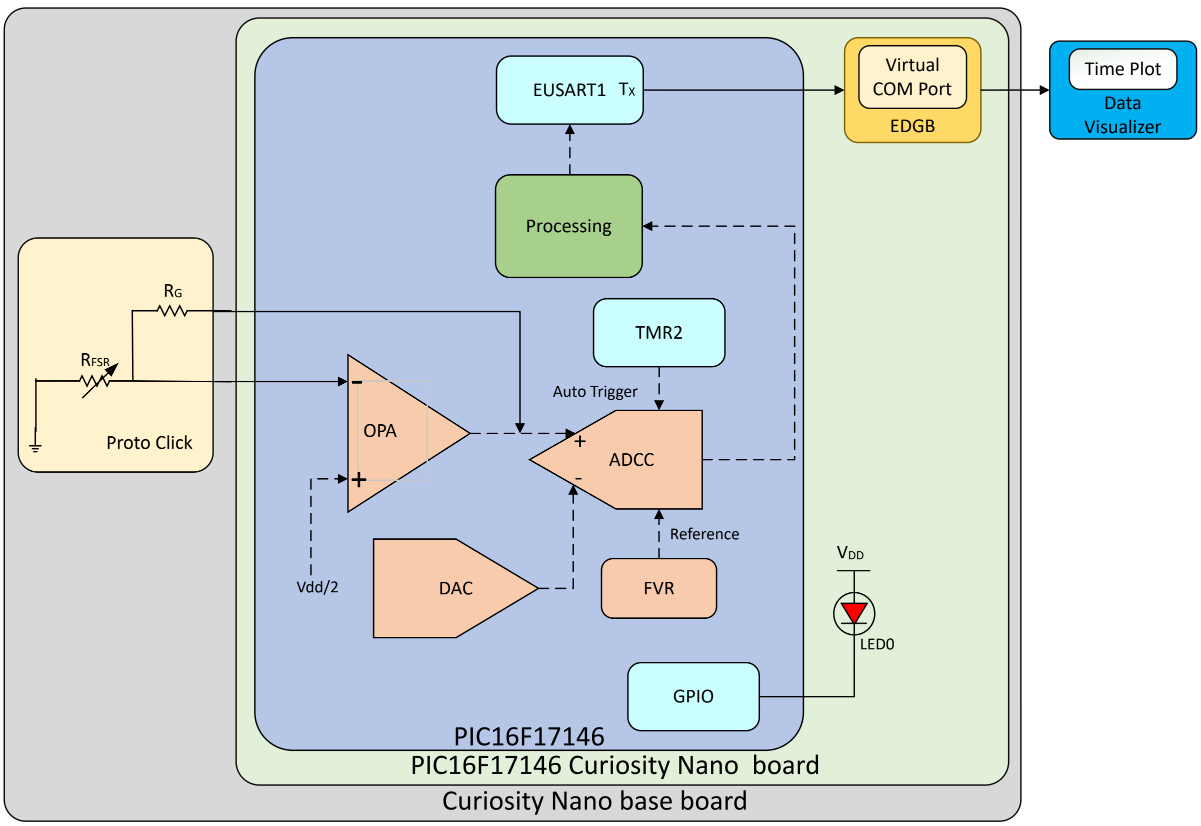
This section describes some of the use cases highlighting the possible combinations of analog peripherals of the PIC16F17146 family of microcontrollers that are useful for sensor data measurement.

5.1 Force Sensing Resistor (FSR) Interface Using PIC16F17146 Microconctroller

The Force Sensing Resistor (FSR) is a Polymer Thick Film (PTF) device which exhibits a decrease in resistance with an increase in the force applied to the active surface. A change in resistance can be measured using a current to voltage converter circuit that uses an OPA, as explained in section 1.5. Current-to-Voltage Converter . The FSR sensor can be interfaced easily using integrated OPA and ADCC available in the PIC16F17146 family of microcontrollers.

Refer to Figure 5-1 which highlights interfacing FSR sensor with PIC16F17146 family of microcontrollers.

Figure 5-1. FSR Interfaced with PIC16F17146 Microcontroller



The output voltage (V_{OUT}) of OPA in the signal conditioning circuit shown in Figure 5-1 is:

$$V_{OUT} = V_{DD}/2 \times [1 + R_G/R_{FSR}]$$

OPA: Configured as current to voltage converter and its non-inverting channel is configured to $V_{DD}/2$.

ADCC: OPA output is connected internally to ADCC.

5.1.1 Mindi Simulation (Current to Voltage Converter Circuit Using OPA)

The Mindi Simulation project is available on GitHub:

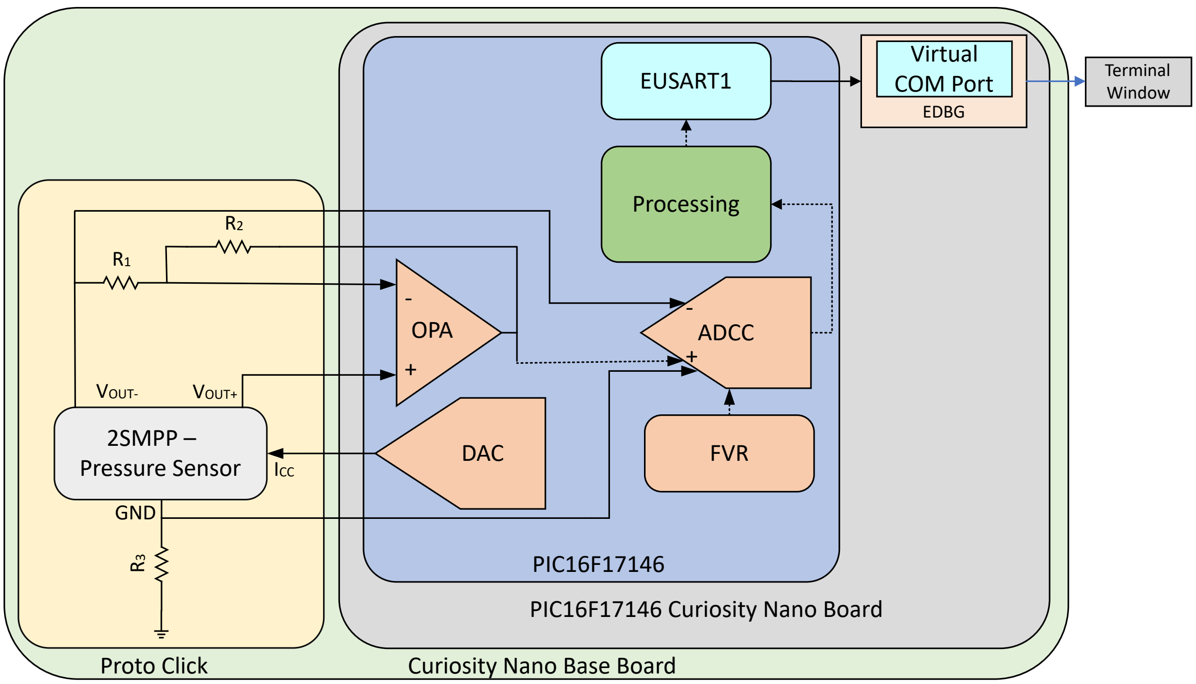
View Code Example on GitHub
Click to browse repository

5.2 Pressure Sensor Interface with Differential Output Voltage Using PIC16F17146 Microcontroller

The MEMS gauge pressure sensor 2SMPP-02 from Omron is capable of measuring air pressure till 37 Kpa and gives differential output in the range of 0 to 31 mV. This sensor requires a constant current of 100 µA for excitation.

Figure 5-2 shows a block diagram view of the necessary connections while interfacing pressure sensor to the PIC16F17146 microcontroller.

Figure 5-2. Pressure Sensor Interfaced with PIC16F17146 Microcontroller



OPA: Configured as gain stage for the signal provided at positive input channel of the differential ADCC.

DAC: Configured to provide constant current of 100 µA.

ADCC: The Differential mode of ADCC is used to interface the sensor's differential output signal. The ADCC also measures the excitation current of the sensor by measuring voltage across a resistor connected between the sensor pin I_{CC} and circuit ground. This way, a constant current of 100 µA can be maintained by implementing a feedback loop. The current can be modified by adjusting the DAC output value.

FVR: Provides stable voltage reference to the ADCC.

5.2.1 Mindi Simulation (Differential Signal Interfacing with OPA)

The Mindi Simulation project is available on GitHub:

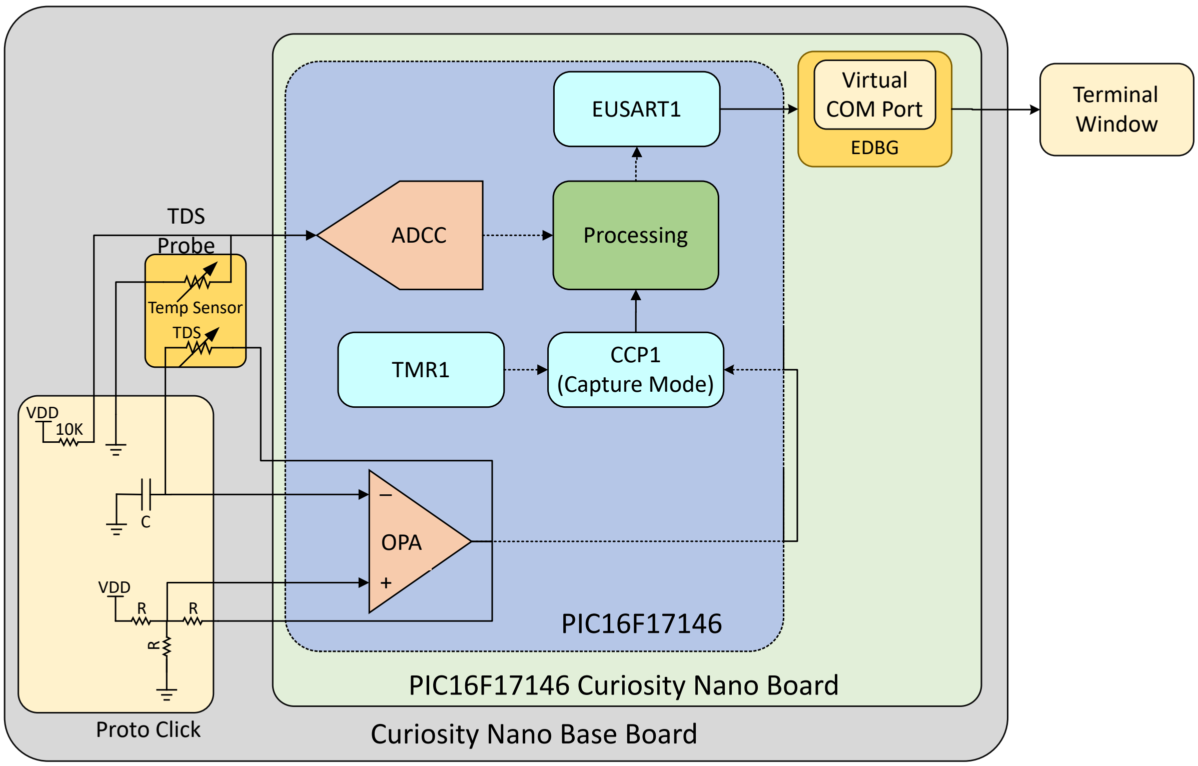
View Code Example on GitHub
Click to browse repository

5.3 Water TDS Measurement Using PIC16F17146 Microccontroller

The conductivity of water changes if its Total Dissolved Solids (TDS) value increases or decreases. A higher value of TDS means more conductivity and vice versa. Also, the conductivity of water is directly proportional to its temperature. Therefore, along with the conductivity, it is required to measure temperature for determining the correct TDS value of water.

A TDS probe can be interfaced to a PIC16F17146, as shown in the Figure 5-3.

Figure 5-3. TDS Probe Interfaced with PIC16F17146 Microcontroller



OPA: Configured as relaxation oscillator for converting voltage to frequency, where the output frequency is a function of TDS (i.e., water conductivity). Refer to section 1.6. Voltage-to-Frequency Converter for more details.

ADCC: Reads water temperature.

CCP: Configured Capture/Compare/PWM (CCP) module in Capture mode to measure the output frequency of OPA as a relaxation oscillator.

TMR1: Used along with the CCP module for frequency measurement.

5.3.1 Mindi Simulation (Relaxation Oscillator Circuit Using OPA)

The Mindi Simulation project is available on GitHub:

View Code Example on GitHub
Click to browse repository

6. References

1. PIC16F17126/46 Full-Featured 14/20-Pin Microcontrollers
2. Optimizing Internal Operational Amplifiers for Analog Signal Conditioning
3. Using the Operational Amplifier on PIC16 and PIC18
4. Differential and Single-Ended ADC
5. Analog Sensor Measurement and Acquisition
6. GitHub Examples Developed Using PIC16F17146

7. Revision History

Doc. Rev.	Date	Comments
A	09/2022	Initial document release.

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