AN4873

Measurement of Total Dissolved Solids in Water Using the Integrated Operational Amplifier of PIC® Microcontrollers

Introduction

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Total Dissolved Solids (TDS) in water are described as the presence of inorganic salts and small amounts of organic matter in water. TDS can be measured by determining the conductivity of water using a conductivity probe that can detect the presence of ions in water. It is one of the most important factors that determines water quality. Ensuring acceptable values of TDS in water is important for human health, food and food processing, fish farming and other water-related industries. TDS measurement in water has applications in the medical, industrial, and residential fields.

This application note provides an overview of the concept and methods used for TDS measurement in water. It also provides a working code example that demonstrates the measurement of conductivity and TDS in water using a relaxation oscillator circuit designed with the Integrated Operational Amplifier (OPA) of the PIC16F17146 microcontroller.

The PIC16F17146 microcontroller family is equipped with advanced analog peripherals such as an OPA, 12-bit differential Analog-to-Digital converter with computation (ADCC), 8-bit buffered Digital-to-Analog converter (DAC), internal fixed voltage reference (FVR) along with core independent peripherals such as Capture Compare and PWM (CCP), 16-bit and 8-bit Timers. This application note describes the usage of integrated OPA, ADCC and CCP peripherals of the PIC16F17146 microcontroller family to measure TDS in water. The code example is available on GitHub at the link below:

View Code Example on GitHub
Click to browse repository

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1. Relevant Devices

1.1 PIC16F17146 Microcontroller Family

The PIC16F17146 microcontroller family contains an enhanced mid-range 8-bit CPU core that reaches speeds up to 32 MHz. This microcontroller family supports up to 28 KB of Flash, up to 2 KB of SRAM and up to 256 Bytes of EEPROM and is available in 8-, 14-, 20-, 28-, 40- or 44-pin packages. The PIC16F17146 microcontroller family has a suite of analog peripherals that enables 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.

Figure 1-1. Overview of the PIC16F17146 Microcontroller Family

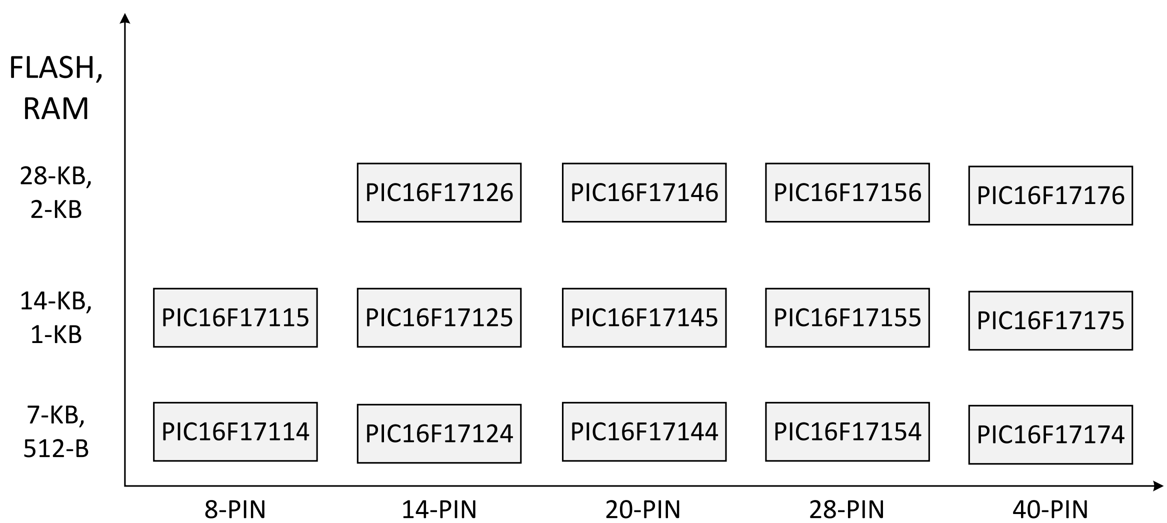


Figure 1-1 shows an overview of the PIC16F17146 microcontroller family that is available in 8-pin to 40-pin (VQFN) packages with a memory range of 7 KB to 28 KB. The parts with different Flash memory typically also have different RAM and EEPROM.

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

Notes:

1. Devices with more than 14 pins are relevant for this application note as these devices have external pins available for the OPA.
2. The PIC18-Q41 Product Family is also relevant for this application note as the devices in this family are equipped with OPA, ADCC and CCP peripherals. One exception is the ADCC peripheral available in the PIC18-Q41 microcontroller family, which supports only 12-bit single-ended conversions.

2. Overview of TDS in Water and Measurement Methodologies

2.1 Theoretical Concept

TDS in water represent the inorganic salts and small amounts of organic matter present in water. The inorganic salts are in the form of cations (usually calcium, magnesium, sodium and potassium) and anions (usually carbonate, hydrogen-carbonate, chloride, sulfate and nitrate). TDS in the water supply originate from natural sources, sewage, urban and agricultural run-off and industrial wastewater. The TDS is measured with the unit milligrams per liter (mg/L), also known as parts per million (ppm).

Higher TDS levels in water may affect its taste. When the TDS value is less than 300 mg/L, the water is considered good for drinking and when the TDS value is 300 to 600 mg/L, the water is considered acceptable for drinking. Certain components of TDS, such as chlorides, sulfates, magnesium, calcium and carbonates cause corrosion and/or scaling (layers of salts) in water distribution systems. High TDS levels (>500 mg/L) result in excessive scaling in water pipes, water heaters, boilers and household appliances, such as kettles and steam irons. Such scaling may shorten the service life of these appliances unless necessary actions are taken to limit the TDS levels in water. To ensure acceptable TDS levels and water quality, water purifiers and softeners are available. In addition, a water TDS meter may be used to determine TDS levels.

The presence of cations and anions in water makes it conductive. Therefore, TDS measurement is done by measuring conductivity in water. The conductivity of water depends upon concentration of ions present and temperature of the water. An increase in temperature increases the mobility of ions, which means TDS levels increase slightly as water temperature increases. Conductivity measurements are converted into TDS values by means of a factor, which is based on the type of salts present in water. The calibration of TDS meters is usually done using salts such as KCl (Potassium Chloride), NaCl (Sodium Chloride) or 442 (a combination of mixed salts with deionized water).

KCl - This potassium chloride solution is a stable salt and is an international calibration standard for conductivity measurements. It has a conversion factor of ~0.55. This factor may vary from 0.5048 to 0.6521.

NaCl - This sodium chloride solution best represents sea water, brackish water, or water with a high saline solution. It has a conversion factor of ~0.5.This factor may vary from 0.4755 to 0.6048.

442 - This refers to the combination of salts mixed with deionized water to comprise this standard: 40% sodium sulfate, 40% sodium bicarbonate, 20% sodium chloride. This solution best represents natural fresh water. It has a default conversion factor of ~0.7. This factor may vary from 0.6563 to 0.9961.

The conductivity equation with temperature compensation is as follows:

$$\sigma(T) = \sigma(T0)(1 + \alpha(T - T0))$$

Where σ(T) is the solution conductivity at any temperature T; σ(T0) is the solution conductivity at a reference temperature T0, usually 25°C; and α is the temperature compensation gradient in %/°C.

The temperature compensation gradient for most naturally occurring samples of water is approximately 2%/°C; however, it may range between 1% and 3%/°C.

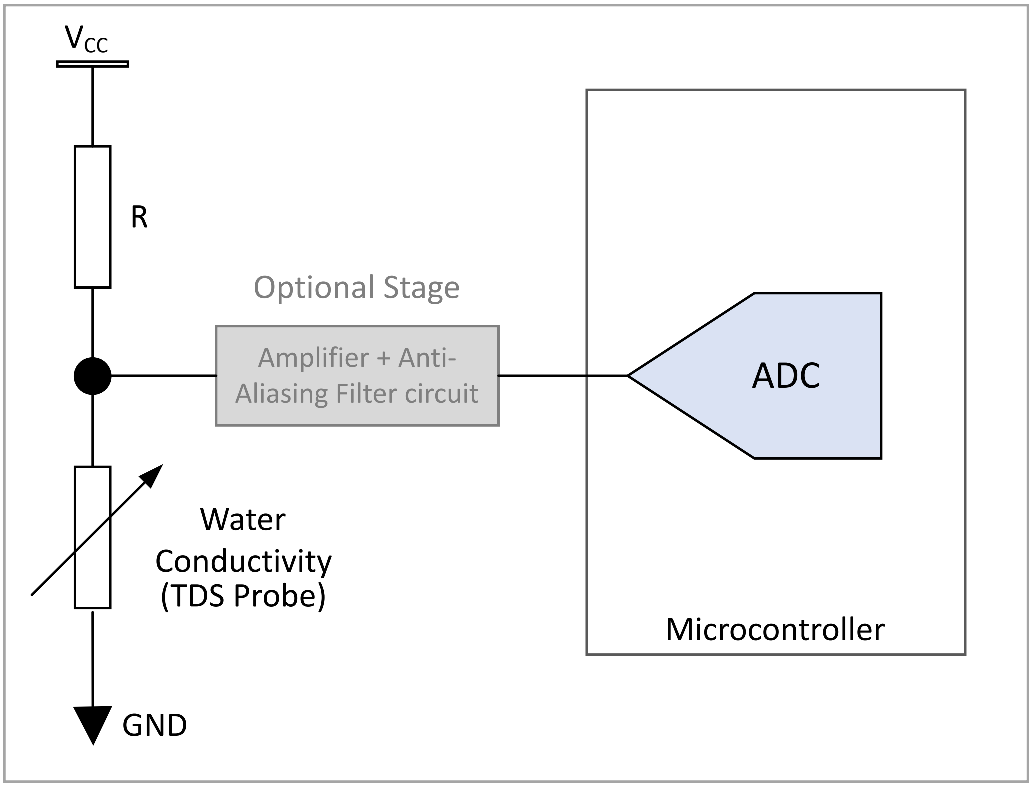
2.2 Application Measurement Methods

TDS in water may be measured using a microcontroller in two different methods – using a voltage divider circuit or using a relaxation oscillator circuit.

2.2.1 TDS Measurement Using a Voltage Divider Circuit

When using a voltage divider circuit, conductive water acts as a variable resistor and the output voltage across the variable resistor will be measured using an analog-to-digital converter (ADC). The TDS value will be calculated based on ADC results. Figure 2-1 shows the block diagram of the voltage divider circuit implemented for the measurement of TDS in water.

Figure 2-1. TDS Measurement Using a Voltage Divider Circuit



Advantages of a Voltage Divider Circuit:

- A wide range of TDS values may be measured
- Simple circuitry

Drawbacks of a Voltage Divider Circuit:

- Accuracy suffers due to deposition of anions and cations on the TDS probe pins over time, which results in frequent system calibration

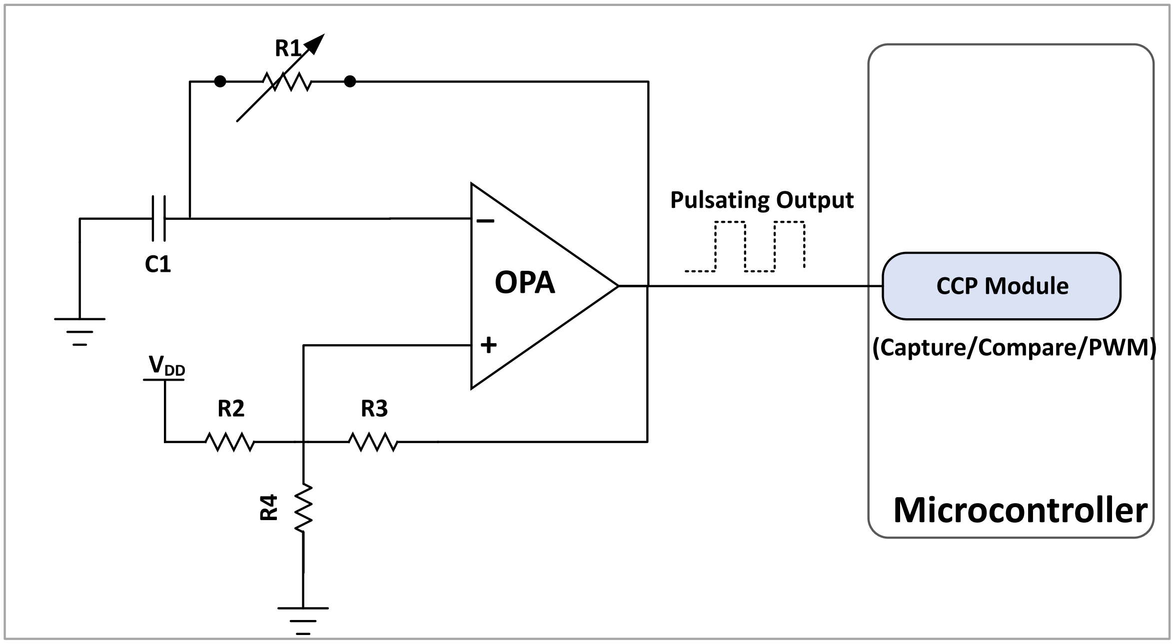
2.2.2 TDS Measurement Using a Relaxation Oscillator Circuit

When using a relaxation oscillator circuit designed with the OPA of a PIC microcontroller, the TDS probe is connected as an input to the OPA and acts as variable resistance. With this arrangement, the OPA generates pulses. The value of the input capacitor determines the frequency range of the pulse signal generated by the OPA peripheral, as the resistance of water lies between 1Ω (ocean water) and 1.5 MΩ (pure water). Figure 2-2 shows the block diagram of the relaxation oscillator circuit implemented for the measurement of TDS in water.

Time period (T) of pulses (output of op-amp):

$$T = 1.38 * R1 * C1,\ (if R2 = R3 = R4)$$

Figure 2-2. TDS Measurement Using a Relaxation Oscillator Circuit



Advantages of a Relaxation Oscillator Circuit:

- No deposition of ions at the TDS probe pins because of pulsating signal
- Better resolution than voltage divider circuit

Drawbacks of a Relaxation Oscillator Circuit:

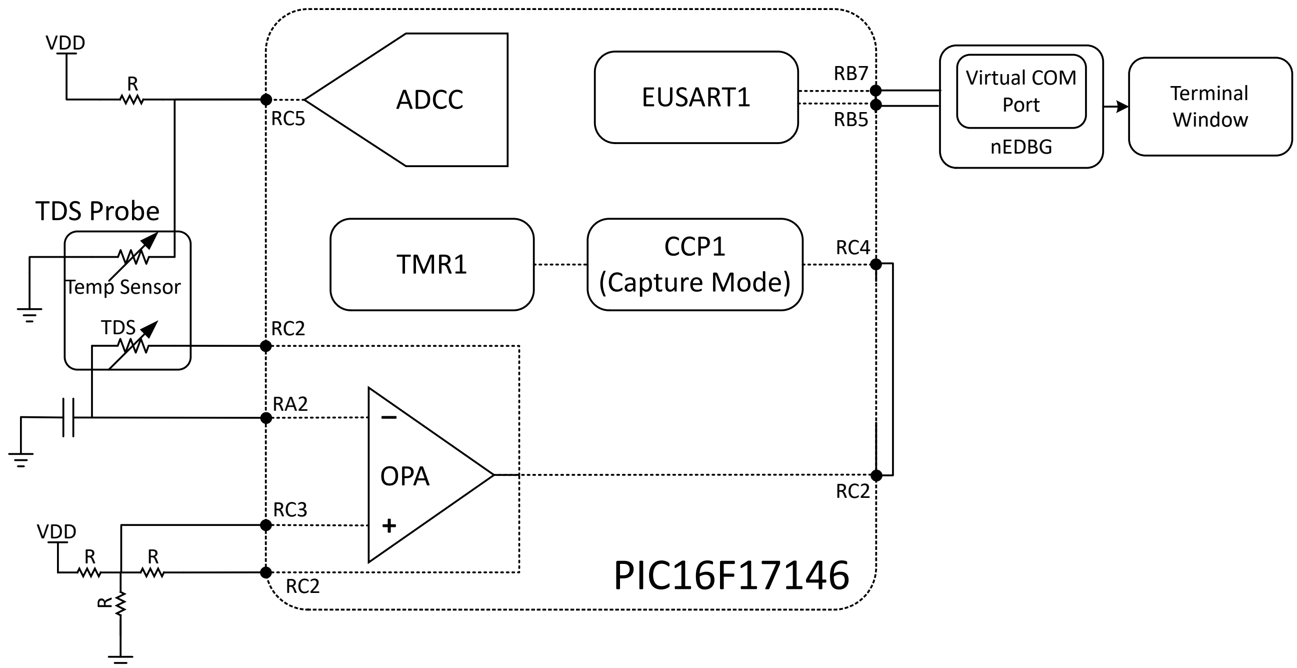
- The measurement range of the TDS value is dependent upon the frequency capturing specification of the microcontroller, whereas it is not dependent in the case of the voltage divider circuit
- Circuitry is more complex than with a voltage divider circuit and it requires more components to interface with the microcontroller

3. TDS Measurement Using a PIC16F17146 Microcontroller

3.1 Implementation

The image below shows the block diagram view of the application: the TDS measurement in water using PIC16F17146. This application is implemented using a relaxation oscillator circuit designed with the OPA of the PIC16F17146 microcontroller. The 0.1µF input capacitor is selected to measure TDS for a range of 0-2000 mg/L. The pulsating output is captured by the CCP module. Water temperature is measured using the ADCC module. The measured TDS values are shown over the terminal application using a EUSART module.

Figure 3-1. Circuit Diagram of TDS meter using PIC16F17146



3.2 Features and Peripherals of a PIC16F17146 Microcontroller used in the Application

The PIC16F17146 is a microcontroller featuring an 8-bit CPU core running at speeds up to 32 MHz, with 28 KB Flash, 2 KB SRAM and 256 Bytes of EEPROM. The microcontroller has a rich set of analog and digital peripherals that can be used in various sensor and real-time control applications.

This section covers the features of the microcontroller and the peripherals that are used to realize the TDS measurement system.

OPA

The built in OPA peripheral of the microcontroller is used for the implementation of the relaxation oscillator circuit. The OPA is configured to accept input through the inverting and non-inverting pins. Its output is fed to an appropriate peripheral through the dedicated output pin. In this application, the OPA module is responsible for generating a pulsating signal at its output. The conductivity (TDS) probe and the supported passive components are fed as inputs to the OPA while the OPA's output is fed as input to the CCP module.

ADCC

The PIC16F17146 microcontroller has a 12-bit differential ADCC peripheral that supports a computation feature. In this application, the ADCC is used to read the water temperature. It samples the output of the negative temperature coefficient (NTC) sensor that is built into the TDS probe.

CCP

The CCP module is configured in Capture mode and TMR1 is used as a clock. It is used to capture the OPA output to calculate the number of pulses over a period of time. The calculated time period is then converted into corresponding TDS values.

TMR

TMR1 is a 16-bit timer and is used as a clock source for the CCP module.

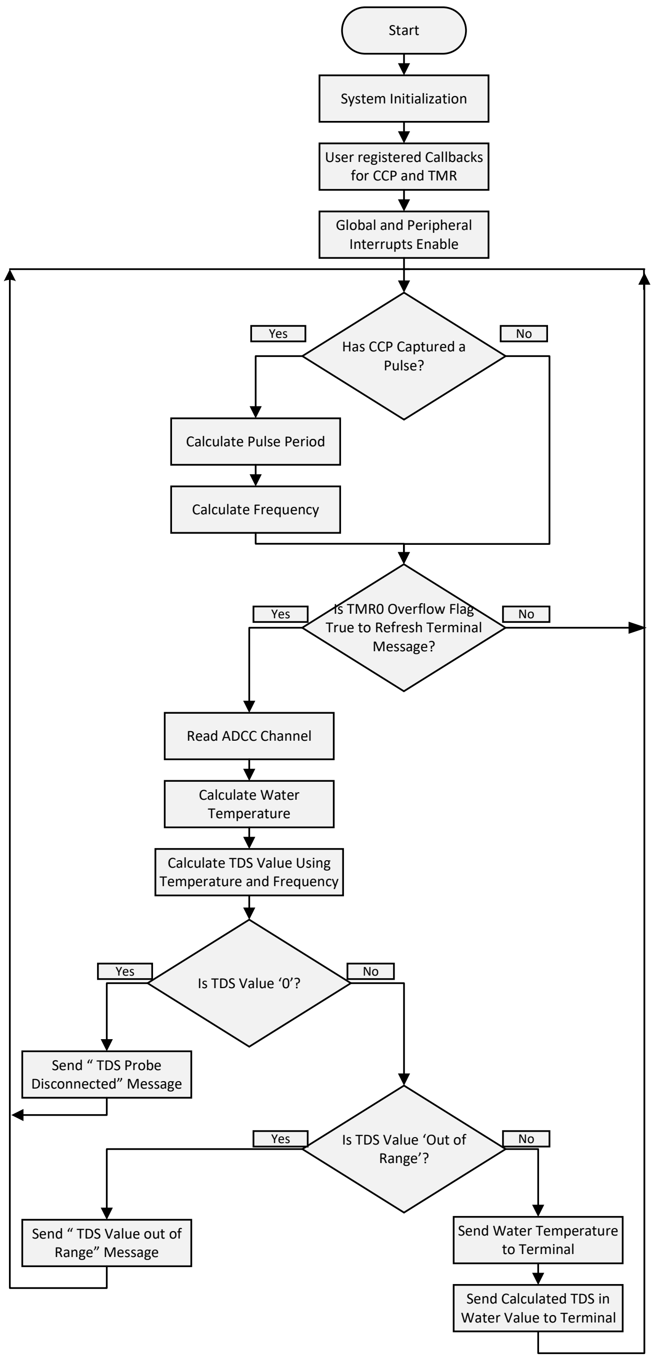
EUSART

EUSART is used to connect the PC terminal application to the microcontroller. It is also used to display TDS measurement system messages over the terminal application.

4. Firmware Overview

The firmware is available on GitHub. Refer to the link provided in the Introduction.

4.1 Application Flowchart



4.2 Firmware Operation

After the initialization of peripherals, the TDS value of water is measured every second and is displayed on the PC terminal application.

The TDS measurement and calculation sequence is as follows:

- The pulse signal generated by the relaxation oscillator circuit is monitored to observe changes in frequency, which indicate change in the TDS value of the water being tested
- The CCP peripheral is configured in Capture mode and captures every fourth rising edge of the pulse signal
- The CCP Capture register value and Timer1 overflow count values are considered. As a result, the period of pulse is determined and then frequency of the signal is calculated
  Note: Further, adjust the frequency of signal with the OPA output calibration value from the Mindi simulation model.
- The TDS value is measured by determining the conductivity of water, which is calculated from the frequency captured by the CCP module using the following equation:
  $Conductivity = \mathrm{Relaxation}\ circuit\ conversion * Captured\ frequency$

  Based on the equation mentioned earlier.
- The ADCC module reads the NTC temperature sensor output of the TDS probe and calculates the water temperature
- The value of water conductivity is then compensated for temperature
- The water conductivity is multiplied with the cell constant of TDS probe given by the manufacturer (can be modified in firmware). The value of TDS in water is measured as:
  $TDS\ value\ = Water\ conductivity * Salt\ factor$

  Note: The salt factor can be modified in the firmware based on the type of salts present in the water.
- The TDS value is sent to the PC terminal
- If the TDS probe is disconnected or removed from the water, the *hardware disconnect* error message is sent
- If the TDS value is greater than 2000, the *TDS value exceed range* error message is sent

The circuitry of this demonstrator is designed to measure the TDS values in water within a range of 0 to 2000 mg/L, using a 0.1 μF input capacitor in the relaxation oscillator circuit. By varying this capacitor value, the TDS measurement range can be modified. The designed relaxation oscillator generates pulses within a frequency range of 1Hz to 40 kHz for the TDS range of 0 to 2000 mg/L.

Note: It is recommended that the frequency of pulse signals generated by the relaxation oscillator circuit do not exceed 50 kHz. If the frequency is greater than 50 kHz, the program execution will stay within the CCP ISR for most of the time. This may affect the execution of the application.

Calibration

To accurately calibrate the device, taking frequency readings at every 20 mg/L and adjusting the frequency to the TDS value conversion equation in the firmware is recommended. While calibrating, choosing an accurate TDS meter for the reference is recommended to achieve satisfactory results.

5. Application Demo

The TDS application demo features a PIC16F17146 Curiosity Nano board, a Curiosity Nano Base for Click Boards, a TDS probe and a PROTO Click Board™. The hardware setup and operation steps of the application demo are described in detail in the code example link below:

View Code Example on GitHub
Click to browse repository

6. PIC16F17146 Microcontroller Memory Utilization

The program and data memory requirements of the application demo firmware with MPLAB® X IDE are provided in Table 6-1. Note that this data is based on firmware version 1.0.0 and may change with respect to software upgrades.

Table 6-1. Memory Utilization in the TDS Measurement Application (Optimization Disabled)

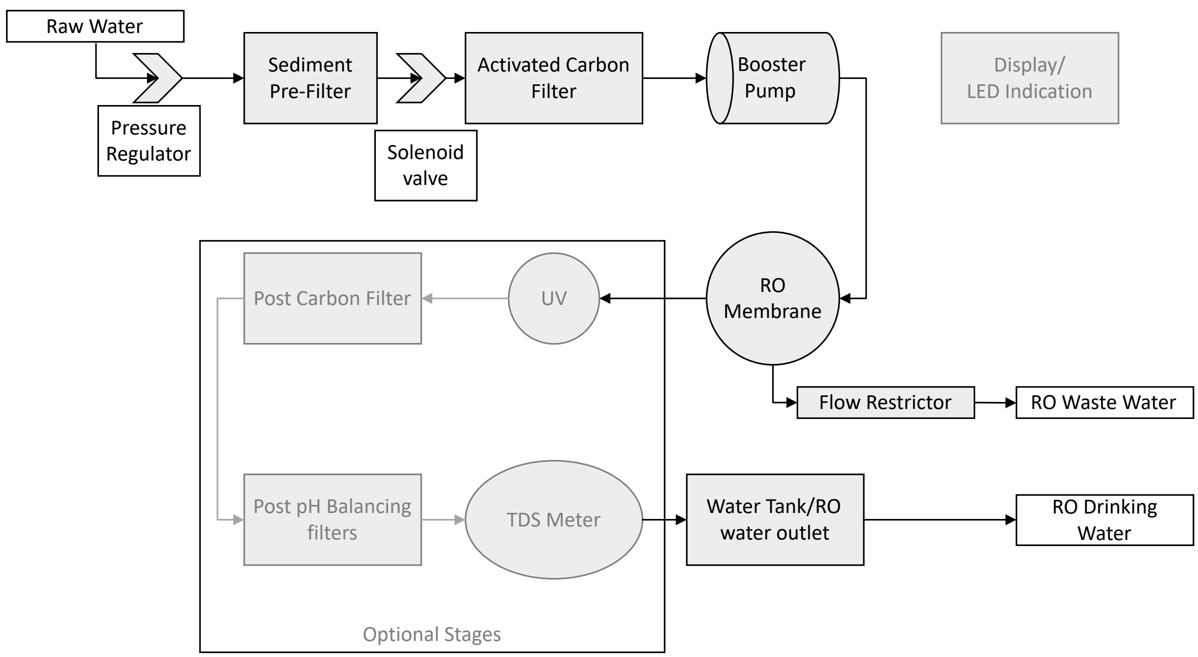
	Program Space (words)	Data Space (bytes)	EEPROM space
Used Memory	6780	289	0
Total Memory	16384	2048	256

Note: In PIC16 devices, 1 word is equal to 14 bits.

7. Extended Application: Home Reverse Osmosis (RO) System

This application note discusses how to measure the TDS in water using a PIC16F17146 microcontroller. This application may be extended to implement a simple home RO system. Figure 7-1 shows a block diagram, including the components required to design and assemble a home RO system. A basic home RO system may or may not have the optional stages as shown in Figure 7-1, but these optional stages improve the drinking water taste and quality. Additionally, a home RO system may have an optional display/LED indication to provide system information.

Figure 7-1. Block Diagram of a Home RO System



A home RO system is made up of the following components:

- Pressure Regulator and Solenoid Valve: A pressure regulator is used to detect pressure in the water inlet line that is more than 3 psi, the minimum required pressure for a home RO system. A Solenoid valve is used to cut off the inlet/outlet water flow when the RO system is not functioning.
- Sediment Pre-Filter: The sediment filter cartridge removes sand, grit, precipitated mineral particles, insoluble iron oxide and other debris that can clog the reverse osmosis membrane surface or plug the drain flow restrictor, causing reduced water production.
- Activated Carbon Filter: Most city water utilities require water leaving the plant to have a minimum chlorine level of 1.0 mg/L (1.0 ppm). The carbon filter removes chlorine and organic impurities in water while observing bad taste and odor. Additionally, it protects the membrane from choking.
- Booster Pump: The booster pump works to maintain input water pressure to the RO membrane as the membrane requires a pressure approximately 75 psi to function well.
- RO Membrane: The RO membrane does most of the work in the system. It removes over 96% of total dissolved solids (i.e., salts, minerals, metals), microorganisms and organic substances in the water. The membrane divides the water flow into two streams—filtered water from the membrane goes into the storage tank while rejected water goes into the drain.
- Post Carbon Filter: This is a granular activated carbon polishing filter that improves water taste and quality.
- Water Tank: A water tank is a RO system store for filtered water. It provides water when the drinking water faucet is turned on.

Optional RO components:

- UV: This is required to inactivate any microorganisms present in water.

- pH Balancing and Mineralizer Filter: A filter that remineralizes the RO water and raises its pH level. It also ensures taste and quality of drinking water.
- TDS Meter: This meter measures the TDS levels in water and ensures that the RO system is working properly. It can also be useful for monitoring the cartridge's life. Continuously monitoring the TDS levels in water helps to determine when a service call for the RO system is appropriate.

A home RO system has few electrically controlled components: viz. booster pump, solenoid valve, UV module, display or LEDs and TDS meters. All of the components require only ON/OFF functionality, which can be achieved using relays. In this application note, a TDS meter has been implemented. To control relays, simple GPIOs are needed, which can be achieved using a microcontroller device. This approach makes the PIC16F17146 microcontroller the best fit when implementing a home RO system.

8. Conclusion

This application note provides an overview of the measurement of TDS in water and emphasizes that the TDS in water is a function of conductivity and has a nonlinear characteristic. It discusses the two different TDS measurement methods as well as the advantages of the relaxation oscillator method for TDS measurement. It also demonstrates how PIC16F17146 can be used to implement a simple home RO system.

9. References

1. PIC16F17146 Family of Microcontrollers
2. PIC16F17146 Data Sheet
3. PIC16F17146 CNANO Evaluation Kit
4. Getting Started with Integrated Analog Peripherals of PIC® Microcontrollers
5. Using the Operational Amplifier on PIC16 and PIC18
6. PIC18-Q41 Product Family

10. Revision History

Doc. Revision	Date	Comments
A	02/2023	Initial document release.

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