

Analog Sensor Conditioning Circuits – An Overview

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INTRODUCTION

Target Audience

This application note is intended for hardware design engineers that need to condition the output of common analog sensors.

Goals

- Review sensor applications (e.g., temperature)
- Review sensor types (e.g., voltage output)
- Show various conditioning circuits
- Give technical references

Description

Analog sensors produce a change in an electrical property to indicate a change in its environment. This change in electrical property needs to be conditioned by an analog circuit before conversion to digital. Further processing occurs in the digital domain but is not addressed in this application note.

The applications mentioned are:

- Electrical
- Magnetic
- Temperature
- Humidity
- Force, Weight, Torque and Pressure
- Motion and Vibration
- Flow
- Fluid Level and Volume
- Light and Infrared (IR)
- Chemistry

For each type of electrical property, commonly used conditioning circuits are shown. Each circuit has an accompanying list of advantages and disadvantages, and a list of sensor types appropriate for that circuit. The electrical properties covered are:

- Voltage
- Current
- Resistance
- Capacitance
- Charge

In addition, circuit and firmware concerns common to many embedded designs are briefly mentioned:

- Input Protection
- Sensor Failure Detection
- Filtering
- Analog-to-Digital (A-to-D) Conversion
- Correction of Results

References to documents that treat these subjects in more depth have been included in the “References” section.

SENSOR APPLICATIONS

This section reviews a few analog sensor applications. For each application, a list of common sensor types is given for convenience. A good resource for many of these applications is OMEGA® Engineering’s handbooks [1, 2].

There are many more analog sensors than the ones discussed in this application note. For example:

- Time/frequency counters [14]
- Distance ranging sensor [25]
- Current sensing transformer [6]

Emphasis is placed on the electrical behavior of the various sensors. It is necessary to know this information when selecting an appropriate sensor conditioning circuit.

Electrical

These applications measure the state at some point in an electrical circuit. They include monitoring the condition of a crucial electrical circuit or power source.

TABLE 1: ELECTRICAL APPLICATIONS

Sensor	Electrical Parameter
Voltage	Voltage
Current	Current
Charge	Charge

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Magnetic

These sensors are used to detect magnetic field strength and/or direction. They are commonly used in compasses and motor control [6].

TABLE 2: MAGNETIC APPLICATIONS

Sensor	Electrical Parameter
Hall effect [6]	Voltage
Magneto-resistive	Resistance

Temperature

The most common sensor application is temperature measurement. Some common sensors are listed in Table 3. Overviews of temperature sensors can be found in the references [14, 15].

TABLE 3: TEMPERATURE APPLICATIONS

Sensor	Electrical Parameter
Thermocouple [19, 20]	Voltage
RTD [18]	Resistance
Thermistor [16, 17]	Resistance
IC	Voltage
IR Thermal Sensor	Current
Thermo Piles	Voltage

Humidity

Two common ways to measure humidity are listed in Table 4. It is often necessary to compensate for temperature in these applications.

TABLE 4: HUMIDITY APPLICATIONS

Sensor	Electrical Parameter
Capacitive	Capacitance
Infrared (IR)	Current

Force, Weight, Torque, and Pressure

The sensors in this section measure a mechanical force or strain. Common types are listed in Table 5.

TABLE 5: FORCE, WEIGHT, TORQUE, AND PRESSURE APPLICATIONS

Sensor	Electrical Parameter
Strain Gage [8 - 10]	Resistance
Load Cell	Resistance
Piezo-electric	Voltage or Charge
Mechanical Transducer	Resistance, Voltage, ...

Motion and Vibration

Some common analog motion and vibration sensors are listed in Table 6. In many cases, more integrated solutions are available.

TABLE 6: MOTION AND VIBRATION APPLICATIONS

Sensor	Electrical Parameter
LVDT [10]	AC Voltage
Piezo-electric	Voltage or Charge
Microphone	Voltage
Motor Sensors [6]	Voltage, Resistance, Current, ...
Ultrasonic Distance [25]	Time
IC Accelerometers	Voltage

Flow

Many different approaches are used for measuring the flow of liquids and gases. A short sample is shown in Table 7.

TABLE 7: FLOW APPLICATIONS

Sensor	Electrical Parameter
Magnetic Flow Meter	AC Voltage
Mass Flow Meter (temperature)	Resistance
Ultrasound/Doppler	Frequency
Hot-wire Anemometer [24]	Resistance
Mechanical Transducer (e.g., turbine)	Voltage, ...

Fluid Level and Volume

Table 8 gives several examples of fluid level sensors. Fluid volume in a rigid container can be calculated from the level.

TABLE 8: FLUID LEVEL AND VOLUME APPLICATIONS

Sensor	Electrical Parameter
Ultrasound	Time
Mechanical Transducer	Resistance, Voltage, ...
Capacitive	Capacitance
Switch (e.g., vibrating)	On/Off
Thermal	—

Light and Infrared (IR)

Light and IR are used to detect the presence of objects (e.g., people in a burglar alarm) and reduction in visibility (smoke and turbidity detectors).

TABLE 9: LIGHT AND IR APPLICATIONS

Sensor	Electrical Parameter
Photodiode [22, 23]	Current

Chemistry

Table 10 gives a short list of sensors that detect chemical conditions.

TABLE 10: CHEMISTRY APPLICATIONS

Sensor	Electrical Parameter
pH Electrode	Voltage (with high output impedance)
Solution Conductivity	Resistance
CO Sensor	Voltage or Charge
Turbidity (photodiode)	Current
Colorimeter (photodiode)	Current

BASIC SIGNAL CONDITIONING CIRCUITS

This section is organized by the sensor's electrical property. For each sensor electrical property listed, one or more conditioning circuits are shown. Advantages, disadvantages and sensor examples are listed for each circuit.

Voltage Sensors

The circuits in this section condition a voltage produced by a sensor.

NON-INVERTING GAIN AMPLIFIER

Figure 1 shows a non-inverting gain amplifier using an op amp. It presents a high impedance to the sensor (at V_{SEN}) and produces a positive gain from V_{SEN} to V_{OUT} .

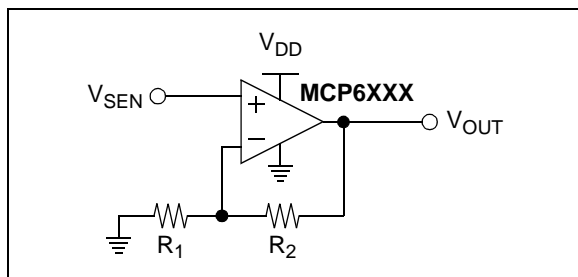


FIGURE 1: Non-inverting Gain Amplifier.

Advantages

- High input impedance
- Low bias current (CMOS op amps)
- Positive gain
- Simplicity

Disadvantages

- Limited input voltage range
- Input stage distortion
- Amplifies common mode noise

Sensor Examples

- Thermocouple
- Thermo pile
- Piezo-electric film

BUFFER FOR HIGH IMPEDANCE VOLTAGE SOURCE

This circuit requires a FET input op amp (e.g., CMOS input); see Figure 2. The FET input gives very high input impedance and very low input bias current, especially at room temperature (the ESD diodes conduct more current at higher temperatures). The operational amplifier (op amp) is used as a non-inverting amplifier.

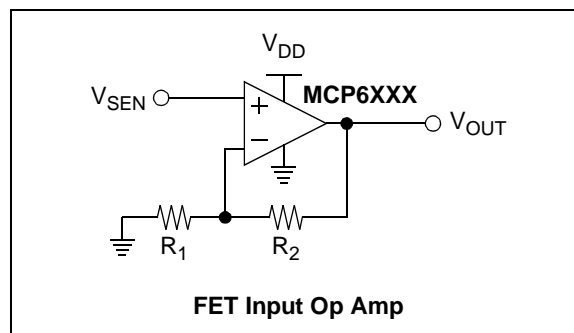


FIGURE 2: Non-inverting Gain Amplifier for High-Impedance Sensors with Voltage Output.

Advantages

- Very high input impedance
- Very low bias current (CMOS op amps)
- Positive gain
- Simplicity

Disadvantages

- Limited input voltage range
- Input stage distortion
- Amplifies common mode noise

Sensor Example

- pH electrode

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The pH electrode's impedance is a function of temperature and can be quite large. Its output voltage is proportional to absolute temperature.

INVERTING GAIN AMPLIFIER

Figure 3 shows an inverting gain amplifier using an op amp. It presents an impedance of R_1 to the sensor (at V_{SEN}) and produces a negative gain from V_{SEN} to V_{OUT} .

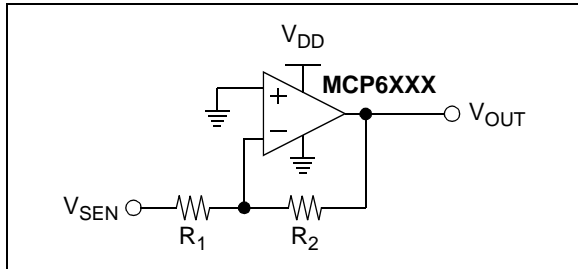


FIGURE 3: *Inverting Gain Amplifier.*

Advantages

- Resistive isolation from the source
- Large input voltage range is possible
- Virtually no input stage distortion
- Simplicity

Disadvantages

- Resistive loading of the source
- Inverting gain
- Amplifies common mode noise

Sensor Examples

- Thermo pile
- High-side (V_{DD}) voltage sensor

DIFFERENCE AMPLIFIER

Figure 4 shows a difference amplifier using an op amp. It presents an impedance of R_1 to each end of the sensor (V_{SEN+} and V_{SEN-}) and amplifies the input difference voltage ($V_{SEN+} - V_{SEN-}$).

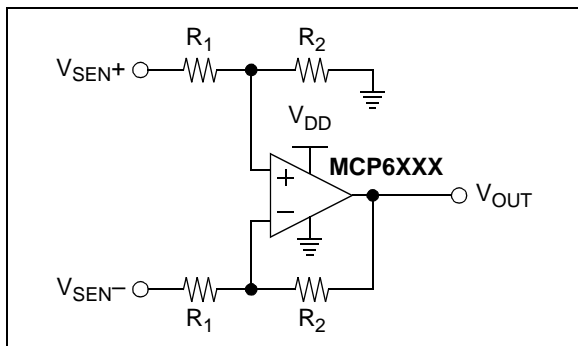


FIGURE 4: *Difference Amp.*

Advantages

- Resistive isolation from the source
- Large input voltage range is possible
- Rejects common mode noise; it is good for remote sensors
- Simplicity

Disadvantages

- Resistive loading of the source
- Input stage distortion

Sensor Examples

- Remote thermocouple
- Wheatstone bridge

INSTRUMENTATION AMPLIFIER

Figure 5 shows an instrumentation amplifier circuit that conditions a remote voltage sensor. The input resistors provide isolation and detection of sensor open-circuit failure. It amplifies the input difference voltage ($V_{SEN+} - V_{SEN-}$) and rejects common mode noise.

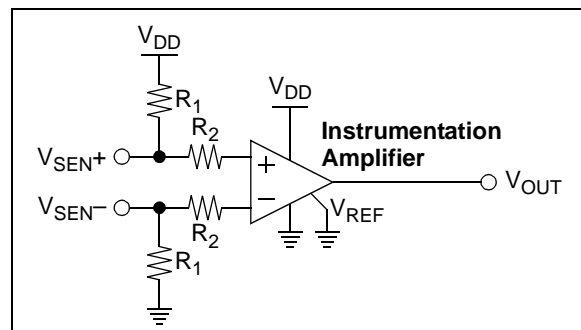


FIGURE 5: *Instrumentation Amplifier.*

Advantages

- Excellent rejection of common mode noise; it is great for remote sensors
- Resistive isolation from the source
- Detection of sensor failure

Disadvantages

- Resistive loading of the source
- Cost

Sensor Examples

- Remote thermocouple
- Remote RTD (with a current source or voltage divider to produce a voltage from the RTD)
- Wheatstone bridge
 - Strain gage
 - Pressure sensor

VARIABLE GAIN FOR WIDE DYNAMIC RANGE AND NON-LINEAR SENSORS

Figure 6 shows a Programmable Gain Amplifier (PGA) used to condition multiple sensors. These PGAs (e.g., MCP6S22) allow the user to select an input sensor and gain with the SPI™ bus. It can also help linearize non-linear sensors (e.g., a thermistor; see [16]).

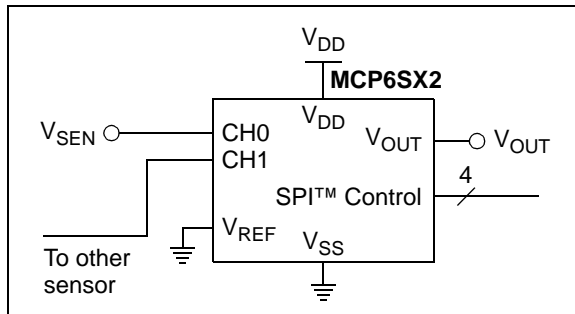


FIGURE 6: Programmable Gain Amplifier.

Advantages

- Multiple sensors (input MUX)
- CMOS input (high impedance and low bias current)
- Digital control (SPI) of input and gain
- Linearization of non-linear sources

Disadvantages

- Input stage distortion
- Amplifies common mode noise
- Needs microcontroller unit (MCU) and firmware

Sensor Examples

- Thermistor (with voltage divider to convert resistance to voltage)
- Thermo pile
- Piezo-electric film

Current Sensors

The circuits in this section condition a current produced by a sensor.

RESISTIVE DETECTOR

Figure 7 shows a resistor (R_1) that converts the sensor current (I_{SEN}) to a voltage (see [6]), as well as a difference amplifier that amplifies the voltage across the resistor while rejecting common mode noise.

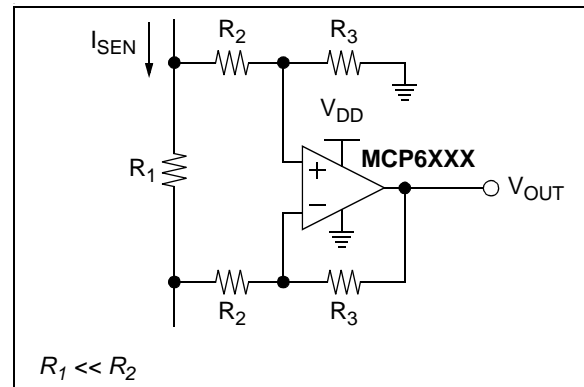


FIGURE 7: Current Sensor.

Advantages

- Good rejection of common mode noise
- Resistive isolation from the source
- Wide input voltage range

Disadvantages

- Resistive loading of the source
- Input stage distortion

Sensor Examples

- High-side (V_{DD}) current sensor
- AC mains (line) current

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TRANSIMPEDANCE AMPLIFIER

Figure 8 shows a transimpedance amplifier (R_1 and the op amp) that converts the sensor current (I_{SEN}) to a voltage. The capacitor C_1 is sometimes needed to stabilize the amplifier when the source has a large capacitance (e.g., see [5]).

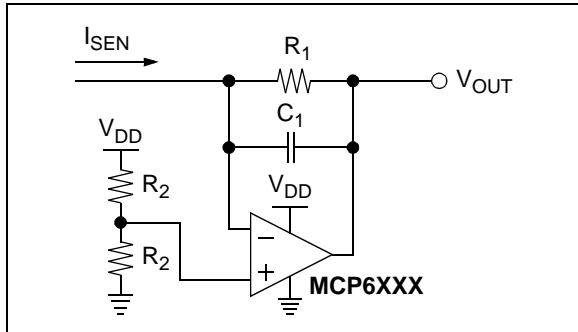


FIGURE 8: Transimpedance Amplifier.

Advantages

- Good impedance buffering of source
- Simplicity

Disadvantages

- Design may need to be stabilized

Sensor Examples

- IR smoke detector
- Photodiode
- Photodetector

LOGARITHMIC AMPLIFIER (LOG AMP)

Figure 8 shows a logarithmic amplifier (D_{1A} and the op amp) that converts the sensor current (I_{SEN}) to a voltage proportional to the logarithm of the current. R_1 maintains negative feedback when I_{SEN} is small or negative. D_{1B} is used to correct D_{1A} for temperature changes.

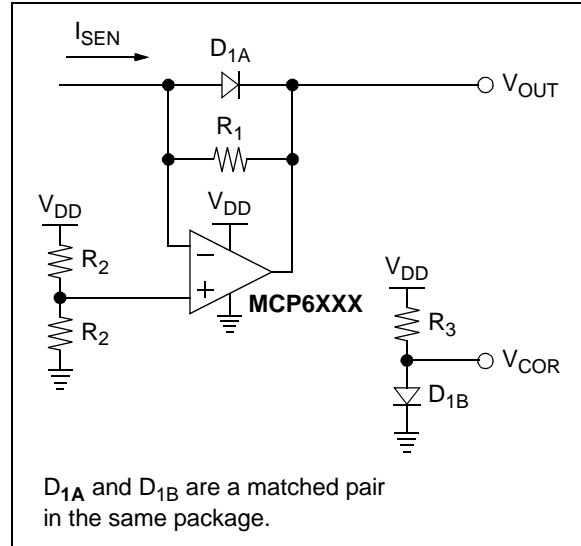


FIGURE 9: Logarithmic Amplifier.

When the source (I_{SEN}) has both polarities, add a diode in parallel with R_1 and D_{1A} , and with the opposite polarity to D_{1A} .

Advantages

- Wide dynamic range of currents
- Good impedance buffering of source
- Simplicity

Disadvantages

- Needs temperature correction

Sensor Example

- Photodiode (e.g., PWM encoded digital signal)

Resistive Sensors

The sensors in this section produce a change in resistance. There are four basic strategies shown here for converting this resistance into a measurable electrical quantity:

- Resistance-to-voltage conversion
- Resistance-to-current conversion
- RC decay
- Oscillator frequency

RESISTANCE-TO-VOLTAGE CONVERSION

The first strategy for conditioning a resistive sensor is to produce a voltage that is a function of the change in resistance.

Voltage Divider

Figure 10 shows a voltage divider (R_{SEN} and R_1) that converts the sensor resistance to a voltage. The op amp buffers the voltage divider for further signal processing. This approach has been used in AN867 and AN897 [21, 16].

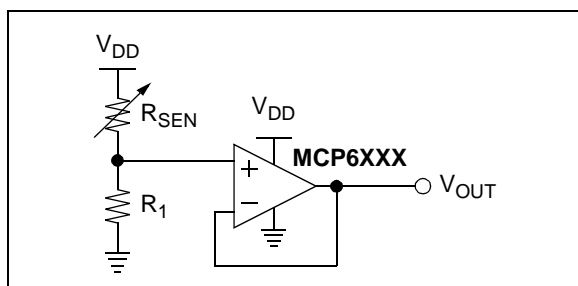


FIGURE 10: Voltage Divider with Op Amp.

Advantages

- Simplicity
- Ratiometric output (with an Analog-to-Digital Converter (ADC) using V_{DD} as its reference voltage)
- Detection of open sensor (failure)

Disadvantages

- Poor common mode noise rejection
- Voltage is a non-linear function of resistance

Sensor Examples

- Thermistor
- RTD
- Magneto-resistive compass

Voltage Divider and Variable Gain

Figure 11 shows a voltage divider (R_{SEN} and R_1) that converts the sensor resistance to a voltage. The PGA buffers the voltage divider for further signal processing and can be set to different gains when the sensor is non-linear.

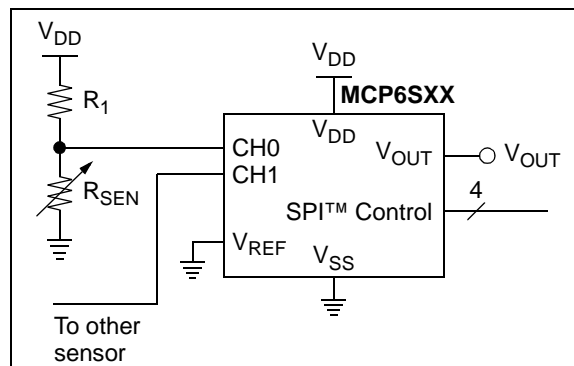


FIGURE 11: Voltage Divider with PGA.

Advantages

- Linearization of non-linear sensors
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)
- Multiplexing several sensors
- Detection of open sensor (failure)

Disadvantages

- Poor common mode noise rejection
- Needs a controller and firmware
- Voltage is a non-linear function of resistance

Sensor Example

- Thermistor

Wheatstone Bridge

Figure 12 shows a Wheatstone bridge that converts a change in resistance to a change in differential voltage. The op amp amplifies the difference voltage.

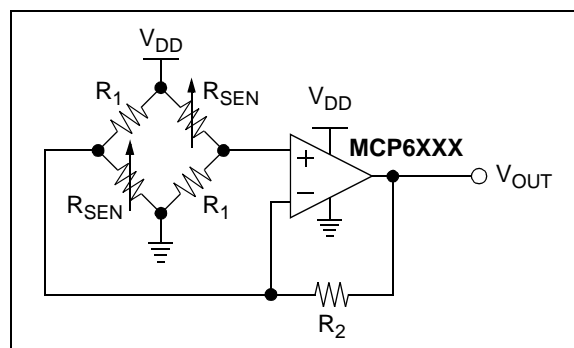


FIGURE 12: Wheatstone Bridge – Single Op Amp Circuit.

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Advantages

- Good rejection of common mode noise
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)
- Simplicity
- Detection of open sensor (failure)

Disadvantages

- Gain is a function of R_{SEN}
- Needs a controller and firmware to correct
- Voltage is a non-linear function of resistance

Sensor Examples

- Strain gage
- Pressure sensor
- Magneto-resistive compass

Figure 13 shows another Wheatstone bridge circuit. The instrumentation amplifier amplifies the bridge's difference voltage and gives excellent rejection of common mode noise.

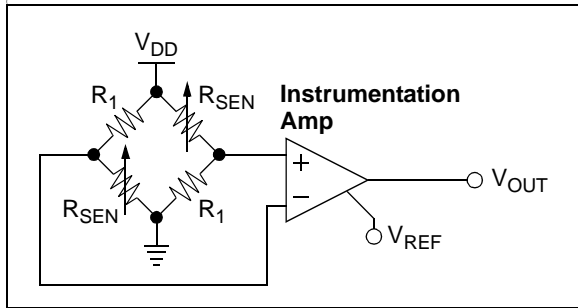


FIGURE 13: Wheatstone Bridge – Instrumentation Amplifier Circuit.

Advantages

- Excellent common mode noise rejection
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)
- Detection of open sensor (failure)

Disadvantages

- Cost
- Voltage is a non-linear function of resistance

Sensor Examples

- Strain gage
- Pressure sensor
- Magneto-resistive compass

Other implementations are shown in application notes AN251, AN717 and AN695 [8, 9, 10].

Floating Current Source

Figure 14 shows a circuit that provides a current source (I_{SEN}) that accurately converts resistance to voltage. R_{1A} , R_{1B} , R_1 , R_2 , R_3 and the op amp form a current source (Howland current pump). C_1 stabilizes this current source and reduces noise. R_4 provides isolation from ground for remote sensors. The voltage across R_{SEN} is amplified by a difference amplifier (Figure 4) which also rejects common mode noise. The voltage on top of R_4 can be used to detect an open (failed) sensor. Another current source is shown in [3, 18].

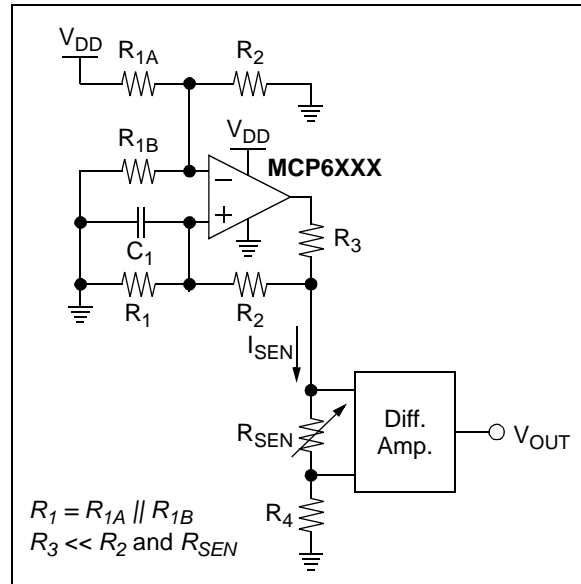


FIGURE 14: Howland Current Pump and Resistive Sensor with Difference Amplifier.

Advantages

- Linearity of resistance to voltage conversion
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)

Disadvantages

- Cost
- Requires accurate resistors

Sensor Examples

- Thermistor
- RTD
- Hot-wire anemometer

RESISTANCE-TO-CURRENT CONVERSION

The second strategy for conditioning a resistive sensor is to produce a current that is a function of the resistance. Figure 15 shows the basic strategy, where the “I-to-V Amplifier” can be a transimpedance amp (Figure 8) or a logarithmic amp (Figure 9).

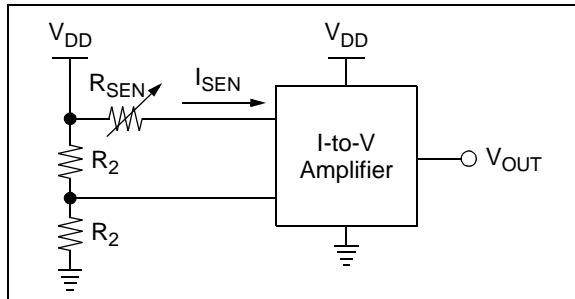


FIGURE 15: Resistance-to-Current Conversion Circuit.

Advantages

- Ratiometric output (with an ADC using V_{DD} as its reference voltage)
- Simplicity

Disadvantages

- Inverting gain

Sensor Example

- Thermistor

RC DECAY

The third strategy for conditioning a resistive sensor is to produce a voltage with a RC decay (single pole response to a step). The time it takes for the voltage to decay to a threshold is a measure of the resistance.

Figure 16 shows a circuit using a MCU circuit that sets a ratiometric threshold (proportional to V_{DD}). The time is measured for both R_1 and R_{SEN} separately in order to correct for V_{DD} , C_1 , and temperature errors. The PICmicro[®] MCU provides the switching and control needed. Application notes AN863, AN512 and AN929 [7, 11, 14] detail variations of this circuit.

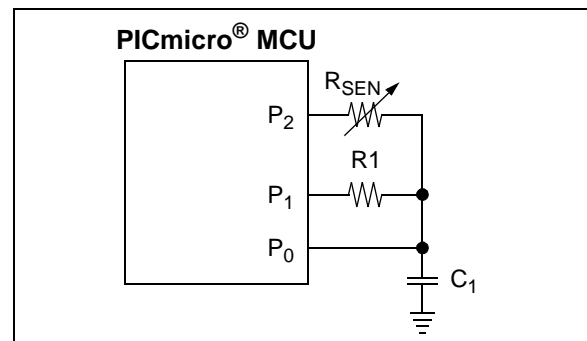


FIGURE 16: RC Decay.

Advantages

- Ratiometric correction of V_{DD} , C_1 and temperature errors
- Accurate
- Simple timing measurement

Disadvantages

- PICmicro MCU timing resolution
- Digital noise
- Threshold must be ratiometric

Sensor Example

- Thermistor

OSCILLATOR FREQUENCY

The fourth strategy for conditioning a resistive sensor is to measure a change in oscillation frequency; Figure 17 shows one implementation. It is a state variable oscillator using resistors, capacitors, op amps and a comparator. Its operation and design are detailed in application notes AN866 and AN895 [4, 12].

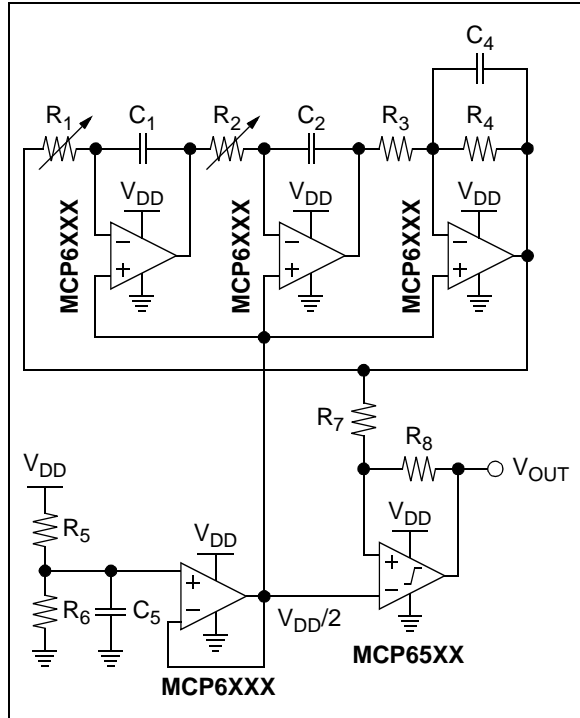


FIGURE 17: State Variable Oscillator.

Advantages

- Accuracy (with calibration)
- Good startup
- Easy processing using a PICmicro® MCU

Disadvantages

- Cost
- Design complexity

Sensor Examples

- RTD
- Hot-wire anemometer

Capacitive Sensors

The sensors in this section produce a change in capacitance. There are four basic strategies shown here for converting this capacitance into a measurable electrical quantity:

- RC decay
- Oscillator frequency
- Integration of current
- Wheatstone bridge

RC DECAY

The first strategy for conditioning a capacitive sensor is to produce a voltage with a RC decay (single pole response to a step). The time it takes for the voltage to decay to a threshold is a measure of the capacitance. Figure 18 measures this time, where the threshold is proportional to V_{DD} . R_1 has a low temperature coefficient to minimize temperature errors. The PICmicro® MCU provides the switching and control needed. AN863, AN512 and AN929 [7, 11, 14] detail a similar circuit.

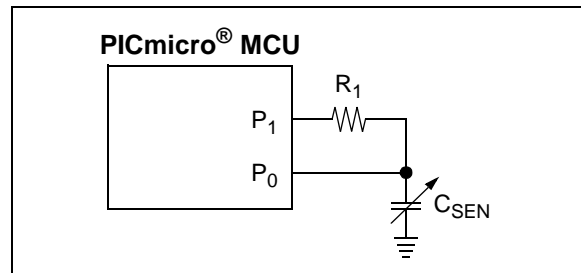


FIGURE 18: RC Decay.

Advantages

- Ratiometric correction of V_{DD} and temperature errors
- Accurate
- Simple timing measurement

Disadvantages

- PICmicro MCU timing resolution
- Digital noise
- Threshold must be ratiometric

Sensor Examples

- Capacitive humidity sensor
- Capacitive touch sensor
- Capacitive tank level sensor

OSCILLATOR FREQUENCY

The second strategy for conditioning a capacitive sensor is to measure a change in oscillation frequency. The multi-vibrator (oscillator) in Figure 19 produces a change in oscillation frequency as a function of capacitance. Its operation and design is detailed in AN866 and AN895 [4, 12].

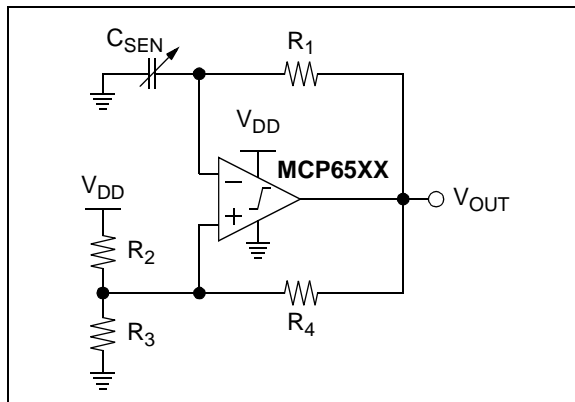


FIGURE 19: Multi-vibrator (oscillator).

Advantages

- Cost
- Ratiometric operation
- Easy processing using a PICmicro® MCU

Disadvantages

- Reduced accuracy

Sensor Examples

- Capacitive humidity sensor
- Capacitive touch sensor
- Capacitive tank level sensor

SINGLE SLOPE INTEGRATING DETECTOR

The third strategy for conditioning a capacitive sensor is to integrate a current and measure the elapsed time to reach a voltage threshold. Figure 20 shows a single-slope integrating detector. Switch SW₁, controlled by the PICmicro® MCU, zeros the voltage across C_{SEN} at the start of the integration period. The voltage at the output of the op amp linearly increases with time; the rate of increase is set by V_{REF} and R₁. The comparator at the output, which can be on the PICmicro MCU, trips at a time proportional to C_{SEN}. AN611 [13] discusses a similar circuit.

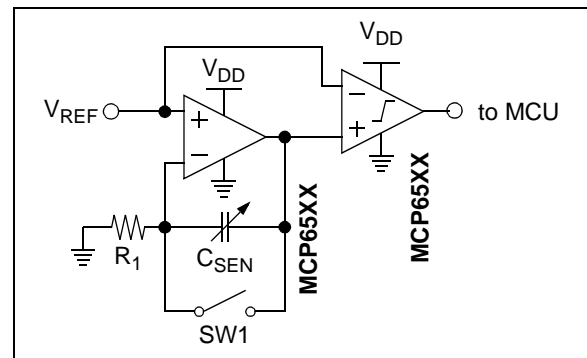


FIGURE 20: Single-slope Integrating Detector.

Advantages

- Easy processing using a PICmicro® MCU
- Accuracy depends on V_{REF} and R₁

Disadvantages

- Cost

Sensor Examples

- Capacitive humidity sensor
- Capacitive touch sensor
- Capacitive tank level sensor

CAPACITIVE WHEATSTONE BRIDGE

The fourth strategy for conditioning a capacitive sensor is to convert its impedance, at a specific frequency, to a voltage using a Wheatstone bridge. Figure 21 produces a change in differential voltage as a function of change in capacitance. An AC voltage source must drive the bridge; its frequency needs to be stable and accurate. R_1 can be a digital potentiometer (digi-pot) that is controlled to zero-out the differential voltage, or it can be a regular resistor. R_3 provides a means to bias the instrumentation amp correctly, and to keep the node between the capacitors from drifting over time. It needs to be much larger than C_2 's impedance ($1/j\omega C_2$); the divider equation can be corrected for this resistance, if necessary.

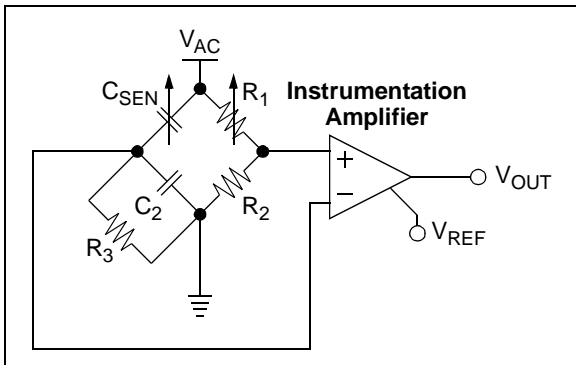


FIGURE 21: Capacitive Wheatstone Bridge.

Advantages

- Excellent common mode noise rejection
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)
- Detection of open or shorted sensor (failure)

Disadvantages

- Needs AC stimulus
- Power dissipation

Sensor Examples

- Remote capacitive sensors
 - Humidity sensor
 - Touch sensor
 - Tank level sensor

Charge Sensors

Figure 22 shows a simplified model of a “charge sensor.” It is a capacitive source that produces AC energy as a function of a change in the environment.

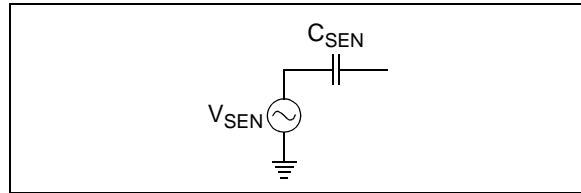


FIGURE 22: Simplified Charge Sensor Model.

Figure 23 shows a charge amplifier (C_1 and the op amp) that converts the sensor energy (charge) to an output voltage. R_1 provides a bias path for the inverting input of the op amp, and creates a high-pass filter pole (keeps the inverting input of the op amp from drifting over time). The change in charge of P_{SEN} appears almost exclusively across C_1 , which makes this an accurate way to measure the charge produced by the sensor.

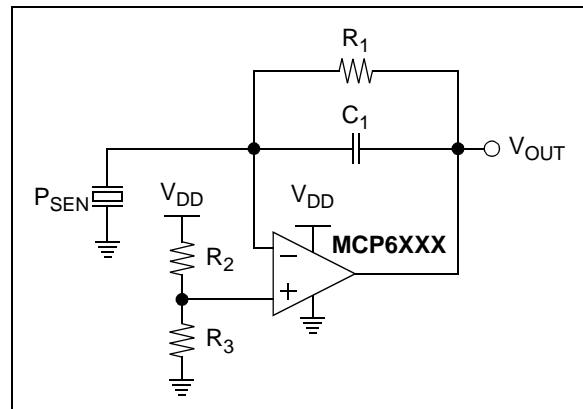


FIGURE 23: Charge Amplifier.

Advantages

- Excellent common mode noise rejection
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)
- Detection of open or shorted sensor (failure)

Disadvantages

- Needs AC stimulus
- Power dissipation

Sensor Example

- Piezo-electric film

ADDITIONAL SIGNAL CONDITIONING

Circuit and firmware concerns common to many embedded designs are mentioned here.

Input Protection

Sensor inputs need to be protected against Electrostatic Discharge (ESD), overvoltage and overcurrent events; especially if they are remote from the conditioning circuit. AN929 [14] covers these issues.

Sensor Failure Detection

Some of the circuits in this application note provide means to detect sensor failure. Other examples are given in AN929 [14].

Filtering

All of the circuits in this application note also need output filters [3]. Analog filters are used to improve ADC performance. When properly designed, they prevent interference from aliasing (even to DC) and can reduce the sample frequency requirements (saving power and MCU overhead). A simple RC filter is good enough for many applications. More difficult analog filters need to be implemented with active RC filters.

Microchip Technology Inc.'s FilterLab[®] software [26] is an innovative tool that simplifies analog active-filter (using op amps) design. It is available at no cost from our web site (www.microchip.com). The FilterLab active-filter software design tool provides full schematic diagrams of the filter circuit with component values. It also outputs the filter circuit in SPICE format.

Additional filtering can be performed digitally, if necessary. A simple averaging of results is usually good enough.

A-to-D Conversion

Many times, the conditioned sensor output is converted to digital format by an ADC. Many of the circuits in this application note are ratiometric so that variations in power supply are corrected at the ADC (e.g., Wheatstone bridges). Others circuits use an absolute reference for the ADC.

Correction of Results

Sensor errors can be corrected by calibrating each system. This can be accomplished in hardware (e.g., Digi-Pot) or firmware (e.g., calibration constants in non-volatile memory).

Correction for other environmental parameters may also be needed. For example, a capacitive humidity sensor may need correction for temperature. This is usually easiest to handle in firmware, but can also be done in hardware.

Non-linear sensors need additional correction. They may use polynomials or other mathematical functions in the MCU, to produce a best estimate of the parameter of interest. It is also possible to use a linear interpolation table in firmware; AN942 [27] gives one implementation.

SUMMARY

This application note is intended to assist circuit designers select a circuit topology for common sensor types. Common sensor applications are listed and described. Many basic signal-conditioning circuits are shown. Sensor-conditioning circuitry, and firmware common to many embedded designs, are briefly mentioned. The “References” section points to other resources that cover particular topics in detail.

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