MICROCHIP

AN1016

Detecting Small Capacitive Sensors Using the MCP6291 and PIC16F690 Devices

Author: Kumen Blake and Steven Bible
Microchip Technology Inc.

INTRODUCTION

Target Audience

This application note is intended for hardware and firmware design engineers that need to accurately detect small capacitance values.

Goals

- Detect small capacitances (e.g., 0.5 pF to 6.5 nF)
- Use minimal number of external components
- Give simple firmware solution
- Highlight design tradeoffs and alternatives

Description

This application note shows how to use a PICmicro® microcontroller and minimal external circuitry to detect small capacitances. The design is based on an operational amplifier (op amp) integrator. A capacitive humidity sensor is used to illustrate this type of application.

The design is measured to verify the theory and design choices. Alternatives and modifications to this design are briefly discussed.

References to documents that treat these subjects in more depth and breadth have been included in the **"References"** section.

The appendices give detailed information that supports the text of this application note.

Related Demo Board

The measurements for this application note were made on the Humidity Sensor PICtail™ Demo Board, which is discussed in the user's guide (DS51594) [15]. This board is further described by:

- Order Number: PIC16F690DM-PCTLHS
- Assembly Number: 102-00084R1

INTEGRATOR SOLUTION

This section describes a design that accurately measures small capacitances. It uses dual slope integration to measure the sensor's capacitance. Using an integrator for measuring small capacitive sensors has three main advantages:

- Any sensor parasitic capacitance (i.e., case-to-ground stray) is forced to the correct voltage by the op amp.
- The parasitic capacitance in parallel is much smaller than other methods.
- The measured waveform has a constant slope, which improves the timing accuracy.

Block Diagram

Figure 1 shows the block diagram of the integrator solution. The "Square Wave Source" voltage (V_{INT}) is converted to a square wave current (I_{INT}). I_{INT} is then passed to an integrator comprised of an op amp and the sensor capacitor (C_{SEN}). The "Integrator" outputs a voltage triangle wave (V_{SEN}) whose slope depends on C_{SEN}. The "Threshold Crossing Detector" tells when V_{SEN} is above or below two reference voltages: a lower voltage (V_{RL}) and a higher voltage (V_{RH}).

The "Magnitude Control" firmware routine changes the polarity of V_{INT} so that V_{SEN} goes past both V_{RL} and V_{RH} by the desired amount. The "Timing Count" firmware routine counts the time elapsed for V_{SEN} to go from V_{RL} to V_{RH} (t_1), and to go from V_{RH} to V_{RL} (t_2). The "Calculations" firmware routine calculates C_{SEN} then the relative humidity (RH) from that capacitance.

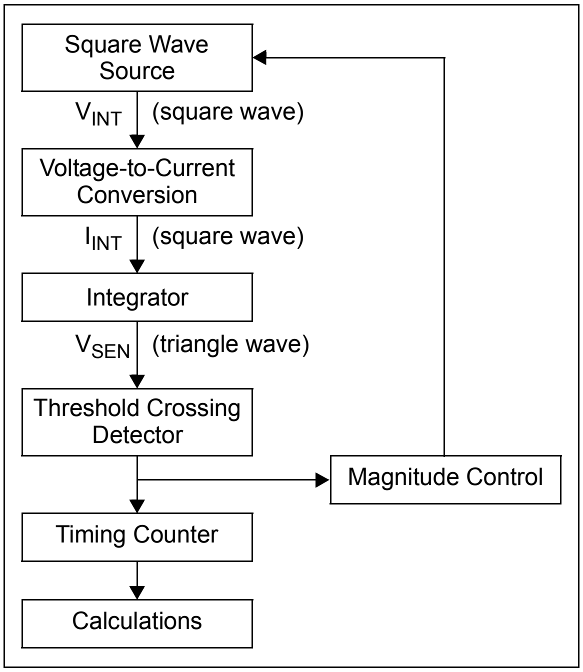

FIGURE 1: *Integrator Block Diagram.*

Figure 2 shows the timing of the main waveforms. The supply voltages are V_{DD} and ground (0V). The current I_{INT} has a positive value of I_{INTP}, and a negative value of $–I_{INTM}$ (I_{INTP} and I_{INTM} are nearly equal magnitudes).

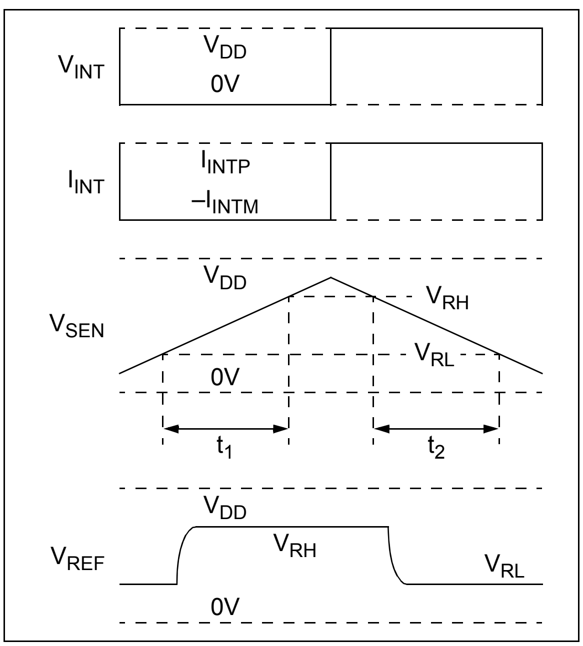

FIGURE 2: *Timing Diagram.*

Circuit

Figure 3 shows the circuit. The PICmicro® microcontroller (U_1) outputs a logic level at pin P1, making the voltage, V_{INT}, either 0V or V_{DD}. The components external to U_1 form an inverting (Miller) integrator. V_{SEN} is a triangle wave whose slope depends on C_{SEN}. The firmware, comparator and reference (V_{REF}) in U_1 control the circuit as described before.

The power supply voltages (V_{DD_DIG} and V_{DD}) were assumed to vary between 3.0V and 5.5V. This design uses 1% resistors for low cost. The SR latch and Timer1 in U_1 time the rise and fall times of the V_{SEN} triangle wave.

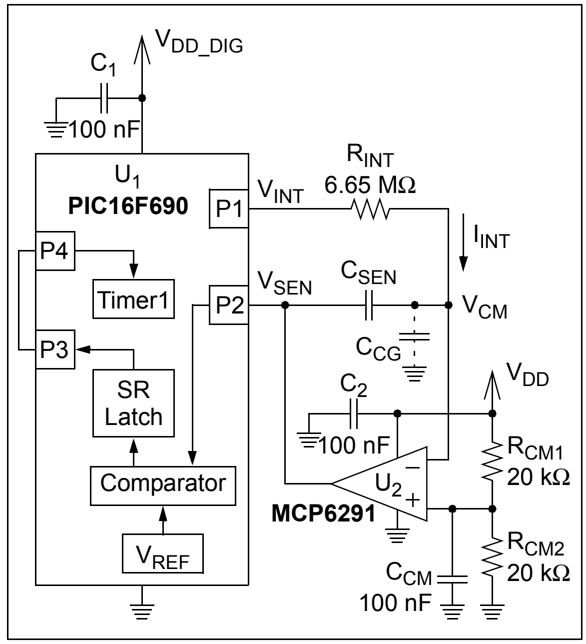

FIGURE 3: *Op Amp Integrator Circuit.*

Note 1:	C_{CG} is the sensor's case-to-ground parasitic capacitance. C_{CG} should be placed at the op amp's inverting input pin to improve the op amp's stability and eliminate any dynamic current through C_{CG}.
2:	R_{INT} is chosen to minimize the effort to calculate C_{SEN}.

The voltage V_{SEN} will have a constant positive (negative) slope when V_{INT} is 0V (V_{DD}):

EQUATION 1:

$$I_{INT} = \frac{V_{INT} - V_{CM}}{R_{INT}}$$

$$\frac{\Delta V_{SEN}}{\Delta t} = \frac{I_{INT}}{C_{SEN}}, \quad I_{INT} \text{ is constant}$$

$$I_{INT} = \frac{V_{INT} - V_{CM}}{R_{INT} C_{SEN}}, \quad V_{INT} \text{ is constant}$$

The voltage reference, V_{REF}, is set to one of two levels: a lower reference voltage, V_{RL} ($0.125V_{DD}$), and an upper reference voltage, V_{RH} ($0.500V_{DD}$). V_{RL} was selected to be within the op amp's output voltage range. V_{RH} was selected to be within the comparator's common mode input voltage range when V_{DD} goes as low as 3.0V. The comparator detects where V_{SEN} is located relative to V_{RH} and V_{RL}.

The voltage, V_{SEN}, is a triangle waveform that goes outside the levels, V_{RL} and V_{RH}; this allows the circuit to settle after changing directions, and gives time for code overhead. The firmware sets the logic level at pin P1 low (V_{INT} = 0V) when V_{SEN} needs to increase, and sets it high ($V_{INT} = V_{DD}$) when V_{SEN} needs to decrease. During measurements, the microcontroller pins are put into the states shown in Table 1.

TABLE 1: PIN STATES

Measurement Steps	Pin States	
	P1	P2
Positive Slope (measure t_1)	0	input
Negative Slope (measure t_2)	1	input

Note 1: P2 is high impedance, and is always connected to the comparator.

The I_{INT} values shown in Figure 2 (I_{INTP} and $-I_{INTM}$) have opposite signs and approximately equal magnitudes. The magnitudes are not always equal because V_{CM} is not always equal to $V_{DD\_DIG}/2$. This produces elapsed times (t_1 and t_2) that are only approximately equal as show in Equation 2.

EQUATION 2:

$$t_1 = \frac{V_{RH} - V_{RL}}{|\Delta V_{SEN}/\Delta t|} = \frac{V_{RH} - V_{RL}}{V_{CM}} \bullet C_{SEN} R_{INT}$$

$$t_2 = \frac{V_{RH} - V_{RL}}{|\Delta V_{SEN}/\Delta t|} = \frac{V_{RH} - V_{RL}}{V_{DD} - V_{CM}} \bullet C_{SEN} R_{INT}$$

Ensuring Op Amp Stability and Accuracy

The op amp (U_2) can behave poorly, or even oscillate, if C_{SEN} is not properly constrained. The parasitic capacitance from the op amp's inverting input to ground (the sensor's C_{CG} and the op amp's C_{CM}) also affects its stability. It is recommended that a unity gain stable op amp (such as the MCP6291) be used and that C_{SEN} be set as follows:

EQUATION 3:

$$C_{SEN} \geq \frac{2}{2\pi R_{INT} f_{GBWP}}$$

Where:

f_{GBWP} = op amp's Gain Bandwidth Product

To maintain accuracy, the op amp feedback loop needs sufficient loop-gain. This translates to the following requirement on C_{SEN}:

EQUATION 4:

$$C_{SEN} \geq \frac{1}{2\pi R_{INT} f_{GBWP} \varepsilon_{LG}}$$

Where:

f_{GBWP} = op amp's Gain Bandwidth Product

ε_{LG} = allowable error due to loop-gain

For instance, given a 0.5% accuracy requirement, and using the MCP6291 for U_2, gives:

- ε_{LG} = 0.005
- f_{GBWP} = 10 MHz
- C_{SEN} > 0.6 pF

C_{SEN} Extraction Equations

The measurements return timer counts, k_1 and k_2, which are related to the measurement times (t_1 and t_2) as follows:

EQUATION 5:

Timer Counts:

$$k_1 = \frac{t_1}{T_{CLK}} = \frac{V_{RH} - V_{RL}}{V_{CM}} \bullet \frac{C_{SEN} R_{INT}}{T_{CLK}}$$

$$k_2 = \frac{t_2}{T_{CLK}} = \frac{V_{RH} - V_{RL}}{V_{DD} - V_{CM}} \bullet \frac{C_{SEN} R_{INT}}{T_{CLK}}$$

Where:

T_{CLK} = microcontroller's instruction period

The measurement timer counts will be averaged together before calculating C_{SEN}; the reason why is illustrated in Equation 6. Since the error in V_{CM} is in the denominator of the k_1 and k_2 equations, and the nominal V_{CM} is $V_{DD}/2$, we have:

EQUATION 6:

V_{CM} Error Analysis Equations:

$$k_1 = \frac{k}{1 + \varepsilon}$$

$$k_2 = \frac{k}{1 - \varepsilon}$$

$$k_1 + k_2 = \frac{k}{1 - \varepsilon^2}$$

Where:

k = ideal count (when $V_{CM} = V_{DD}/2$ exactly)

ε = relative error (caused by V_{CM} error)

$$= \frac{V_{CM\_Error}}{V_{CM}} = \frac{V_{CM\_Error}}{V_{DD} - V_{CM}}$$

$$= \frac{V_{CM\_Error}}{V_{DD} / 2}$$

For instance, a +5% error in k_1 (a -5% error in k_2) becomes a -0.25% error in the average $((k_1 + k_2)/2)$; this is a very significant improvement in accuracy. Greater accuracy can be achieved by reducing the original error in k_1. For example, reducing the k_1 error to +2% gives a -0.04% error in $(k_1 + k_2)/2$.

The extraction equations are below in Equation 7. These equations assume C_{SEN} is constrained as described in Equation 3 and Equation 4. The constant, B_1, is the circuit's resolution in units of pF / count. R_{INT} (see Figure 3) was chosen to make it easy to convert k_1 and k_2 into C_{SEN} (making B_1 = 0.100 pF / count).

EQUATION 7:

Pre-calculated Constant:

$$B_1 = \frac{V_{DD}/2}{V_{RH} - V_{RL}} \bullet \frac{T_{CLK}}{R_{INT}}$$

Extraction Equation:

$$C_{SEN} \approx \frac{k_1 + k_2}{2} \bullet B_1$$

$$\approx (k_1 + k_2)\left(\frac{B_1}{2}\right), \quad (coded\ form)$$

The firmware actually multiplies the sum $(k_1 + k_2)$ by the pre-calculated constant $B_1/2$.

HUMIDITY SENSOR

The HS1101LF humidity sensor from Humirel is described in detail in its data sheet [1]. It has a relative humidity (RH) accuracy of about ±2%, and its nominal capacitance ranges from 162 pF to 193 pF.

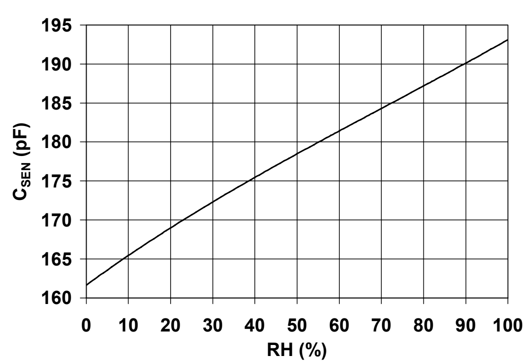

FIGURE 4: *HS1101LF Humidity Sensor's Nominal Capacitance with T_A = +25°C.*

Since C_{SEN} changes by about 31 pF across the full RH range, and has a nominal value of 180 pF, it follows that:

- A 1 pF change in C_{SEN} is a 0.56% change in its nominal value
- RH changes ≈ 3.2% for each 1 pF change in C_{SEN}
- RH changes ≈ 6% for each 1% change in C_{SEN}
- RH changes ≈ 0.32% for each increase of 1 in the count (k) for Figure 3

FIRMWARE

This algorithm is implemented in the firmware for the Humidity Sensor PICtail™ Demo Board [15]. The firmware can be downloaded from Microchip's website (www.microchip.com).

Additional Requirements

The circuit and microcontroller need to be initialized. It is necessary to drive V_{SEN} to a known point before starting the capacitance measurements; it could be either above or below V_{RL} when starting.

Averaging (8 times) is included in this algorithm. The timer counts need to be converted to C_{SEN}, then to RH.

Extra delay before starting each measurement improves the accuracy. It gives the op amp time to settle, and allows the firmware time to prepare for the next measurement.

Modular Code

The following assembly code modules (for the PIC16F690) make up the Humidity Sensor project:

- `main.inc` - contains I/O port and global defines used throughout the project
- `main.asm` - contains the main executive routine including configuration bit assignments
- `initialize_f690.asm` - initializes the PIC16F690 to known initial values
- `capacitance.asm` - reads capacitance using a dual slope integration technique; Table 2 shows the algorithm for this module
- `humidity.inc` - contains PwLI table segment values
- `humidity.asm` - contains PwLI routine to convert capacitance to %RH humidity
- `ssc.asm` - contains Synchronous Serial Communications (SSC), a synchronous serial communications protocol between a target PICmicro microcontroller unit and the PICkit™ 1 Flash Starter Kit or PICkit™ 2 Starter Kit.
- `16f690.lkr` - linker script for Humidity Sensor project

These files can be downloaded from the Microchip web site (www.microchip.com); and are contained in the `00084R1.zip` file.

Top Level Algorithm

Figure 5 shows the flow chart for the top level program. This implementation includes averaging eight C_{SEN} readings together.

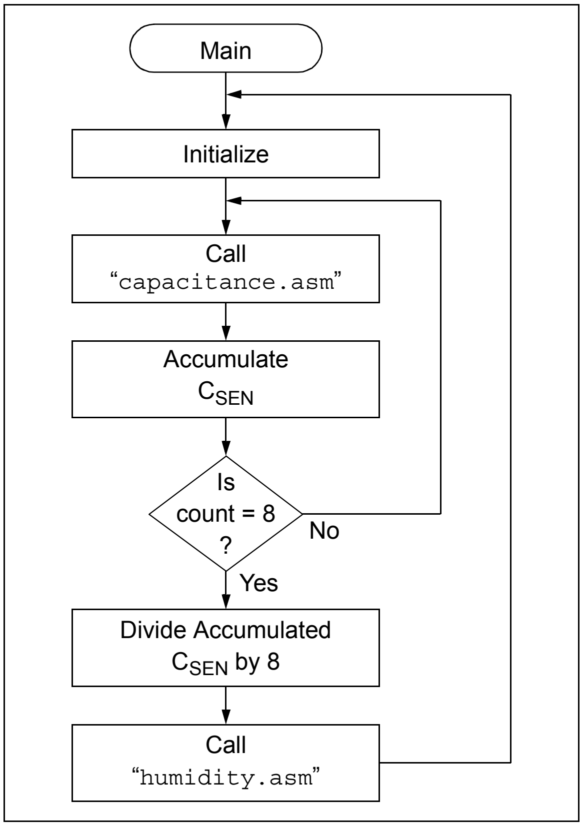

FIGURE 5: *Top Level Flow Chart.*

The algorithm shown does not include any accuracy improvements. The user can add code to either correct the reference levels (V_{RL} and V_{RH}), using the internal ADC, or calibrate the entire circuit's errors (including temperature drift).

Capacitance Module

Table 2 shows the algorithm for the capacitance module, and includes the PICmicro microcontroller's pin states.

The pin assignments on the Humidity Sensor PICtail™ Demo Board [15] used for the measurements in this application note are:

- P1 = RC2 (V_{INT})
- P2 = RC1 (V_{SEN})
- P3 = RA4/T1G
- P4 = RC4/C2OUT

Pin P2 is configured as the comparator's input during the measurements. This gives the comparator time to settle before the measurements are made.

TABLE 2: CAPACITANCE ALGORITHM

Algorithm Steps	Pin States	
	P1	**P2**
Initialize V_{SEN} (Note 1)		
(Move V_{SEN} to < V_{RL})	1	input
Set V_{REF} to V_{RL}		
Detect when V_{SEN} < V_{RL}		
Delay		
Positive V_{SEN} Slope (Note 2)		
(Move V_{SEN} from < V_{RL} to > V_{RH})	0	input
Start count k_1 when V_{SEN} = V_{RL}		
Set V_{REF} to V_{RH}		
Stop count k_1 when V_{SEN} = V_{RH}		
Delay		
Negative V_{SEN} Slope		
(Move V_{SEN} from > V_{RH} to < V_{RL})	1	input
Start count k_2 when V_{SEN} = V_{RH}		
Set V_{REF} to V_{RL}		
Stop count k_2 when V_{SEN} = V_{RL}		
Delay		

Note 1: $V_{RL} = 0.125V_{DD}$ and $V_{RH} = 0.500V_{DD}$. These are lower range levels in the PIC16F690's V_{REF} (CV_{REF}).

2: The counts k_1 and k_2 increment once for each PICmicro instruction cycle (T_{CLK} = 0.5 μs)

Relative Humidity Module

Once C_{SEN} has been calculated and averaged, the relative humidity (RH) for the HS1101LF sensor can be estimated. The conversion is accomplished using a piecewise linear interpolation table [11]. **Appendix A: "Piecewise Linear Interpolation Table"** contains details on the design of this table.

DESIGN MODIFICATIONS AND ALTERNATIVES

Possible Modifications

SIMPLE MODIFICATIONS

To produce different resolutions (pF / count), change the R_{INT} value. It makes the code simpler when the resolution is a simple multiple of 1 pF. One possible set of values is:

- R_{INT} = 6.65 MΩ for 0.1 pF / count
- R_{INT} = 665 kΩ for 1 pF / count
- R_{INT} = 66.5 kΩ for 10 pF / count

More than one resolution in the same circuit can be obtained by switching between several R_{INT} resistors on the Printed Circuit Board (PCB). It is also possible to use multiple microcontroller pins, one for each R_{INT} on the PCB. The R_{INT} values not being used would have their pins set to hi-Z.

The parasitic capacitance (C_{PAR}) in parallel with C_{SEN} is caused by board and op amp package stray capacitances. It is typically about 0.5 pF; the calculated C_{SEN} should be corrected (have C_{PAR} subtracted) by this amount. C_{PAR} can be measured by leaving having C_{SEN} open (0 pF).

Many of the errors over relative humidity, supply voltage and temperature will be consistent over time. This makes it possble to calibrate out these errors; see **"Error Analysis"**.

OP AMP INTEGRATOR WITH REDUCED CURRENT

The circuit in Figure 6 achieves greater resolution by attenuating the square wave (V_A). The components R_{A1}, R_{A2} and R_{A3} form an attenuator with a DC bias point at $V_{DD}/2$ and a gain of 0.0100 V/V. Thus, the current magnitudes I_{INTP} and I_{INTM} will be 100 times smaller than those produced by the circuit in Figure 3. This, in turn, produces longer integration times.

This circuit has the following key performance numbers:

- C_{SEN} needs to be larger than 0.6 pF for a 0.5% accuracy and for stability
- Resolution ≈ 0.001 pF / count

The attenuator increases the equivalent error at V_{CM}. This can be handled by using resistors with tighter tolerances for R_{A1}, R_{A2} and R_{A3}; Figure 6 uses 1% resistors for low cost.

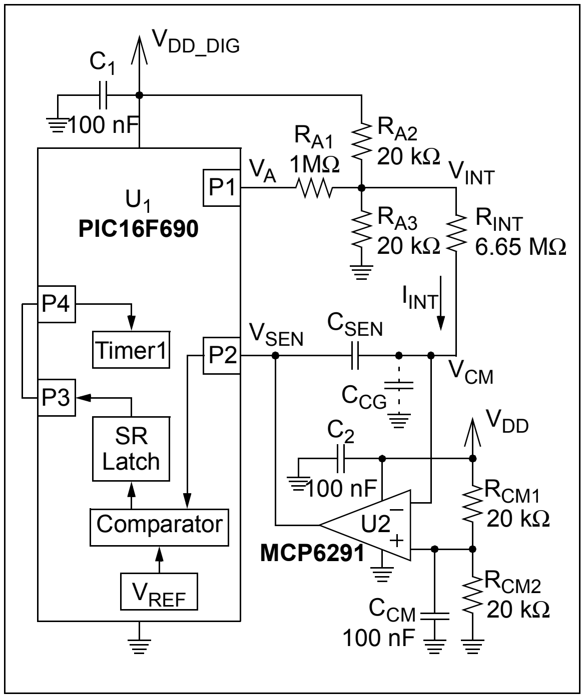

FIGURE 6: Op Amp Integrator Circuit with Reduced Current.

Note 1:	C_{CG} is the sensor's case-to-ground parasitic capacitance. C_{CG} should be placed at the op amp's inverting input pin to improve the op amp's stability and eliminate any dynamic current through C_{CG}.
2:	R_{INT} is chosen to minimize the effort to calculate C_{SEN}.

Other Ciruits

A quick overview of different methods to measure capacitance is found in AN990, "Analog Sensor Conditioning Circuits - An Overview" (AN990) [5]. Those designs include an R-C decay and an oscillator.

The R-C decay method [6, 8] is very low cost and easy to implement. It is difficult to use this method for small capacitive sensors because of the microcontroller's parasitic pin capacitance and leakage currents.

It is quite popular to use a 555 timer and the capacitive sensor to form an oscillator circuit, which works well for larger capacitors. Smaller capacitors see greater inaccuracies due to the 555 timer's parasitic pin capacitance and leakage currents. Also, 555 timers from different vendors behave quite differently.

It is also possible to create other oscillator circuits [7]. They can be quite accurate with proper calibration, and they can be either simple or complicated.

ERROR ANALYSIS

The design in this application note is accurate enough to make a detailed error analysis worth the effort. The dominant error sources are covered in this section. They will be covered in the same sequence they propagate through the circuit and algorithm. Their impact on RH accuracy, and possible improvements, will be sumarized at the end.

Ratiometric Design

The circuit was designed to be ratiometric. This is accomplished by making I_{INT}, V_{CM}, V_{RL} and V_{RL} proportional to V_{DD}.

Using a ratiometric design makes the measurement times independent of power supply voltage (V_{DD}), eliminating one source of measurement error.

Current (I_{INT}) Imbalance

When I_{INTP} and I_{INTM} are not equal, the timer counts, k_1 and k_2, are not equal. This causes an error (ε) in the calculated counts k_1 and k_2. **"CSEN Extraction Equations"** discusses this phenomenon in detail.

Errors in V_{CM} (V_{CM_Error} in Equation 6) contribute to the current imbalance. The common mode voltage setting resistors (R_{CM1} and R_{CM2}) and the op amp (U_1) dominate the V_{CM} errors. If R_{CM1} is 1% low and R_{CM2} is 1% high, then the relative error (ε) would would be +2%. If op amp U_1's input offset voltage (V_{OS_OA}) is +4.5 mV and V_{DD} is 5.0V, then ε would be +0.2%.

The current I_{INT} is also imbalanced by the op amp input bias current (I_{B_OA}). This produces a relative error $\varepsilon = I_{B\_OA} / I_{INT}$. This error is largest, for CMOS input op amps, at high temperatures.

The attenuator in Figure 6 also causes a current (I_{INT}) imbalance. A mismatch between R_{A2} and R_{A3} produces this current mismatch.

Errors in Average Count (k)

The relative error (ε) in k_1 and k_2 causes a smaller error of ε^2 in the average count, $k = (k_1 + k_2)/2$; see **"CSEN Extraction Equations"**.

Errors in the average count, k, are produced by the relative error in the following:

- V_{REF} levels ($V_{RH} – V_{RL}$)
- R_{INT}
- Comparator CMRR (change in offset vs. V_{SEN})
- Oscillator frequency

Note that when we subtract V_{RL} from V_{RH}, the comparator's offset voltage is cancelled (because it is constant).

The op amp's gain-bandwidth product can have a significant effect on the errors for small C_{SEN} values; see Equation 4. The smaller C_{SEN} is, the larger this error is.

Errors in Calculating C_{SEN}

The parasitic capacitance C_{PAR} will cause an error of about 0.5 pF if no correction is made, and about ±0.1 pF if the correction is made.

The nominal value of B_1 is not exactly 0.1 pF / count; it is approximately 0.10025 pF / count. This error (+0.25%) has been designed to smaller than most errors.

The designed circuit's measurement resolution is 0.1 pF / count. The quantization error cannot be better than 1/2 this value (0.05 pF / count).

Errors in Calculating RH

"Humidity Sensor" gives basic information on the Humirel's HS1101LF capacitive RH sensor. As explained there, the circuit in Figure 3 has a RH resolution of about 0.32% / count (3.2% / pF). Also, a 1% error in measuring C_{SEN} produces a 6% RH error.

In addition, there is a ±2% error in the nominal RH value, and a ±6% error due to temperature variations (at -40°C and +85°C).

RH is calculated from C_{SEN} using a piece-wise linear (PWL) lookup table [11]. This table has been designed to make the firmware simple and quick by using 64 lookup table rows. This has the added benefit of producing a very accurate estimate of RH (better than ±0.01% error).

Overview of Errors

Table 3 includes all of the errors mentioned in this section. These errors are at room temperature (+25°C). It also shows how the errors propagate through the circuit and the algorithm.

The dominant errors are:

- V_{REF} accuracy: $(V_{RH} – V_{RL}) / (V_{DD}/2)$
- R_{INT}
- The internal oscillator frequency
- The op amp Gain-Bandwidth Product (f_{GBWP}) for very small C_{SEN} values
- The nominal sensor (HS1101LF) error

TABLE 3: ERROR ANALYSIS AT ROOM TEMPERATURE

Error Sources			Effects			
Cause	**Special Conditions**	**Worst Case Error (Note 1)**	**Imbalance ε (Note 2)**	**Error in k (Note 3)**	**Error in C_{SEN}**	**Error in RH**
Current (I_{INT}) Imbalance						
R_{CM1} and R_{CM2}	—	±1%	±2.0%	±0.05%	±0.05%	±0.3%
V_{OS_OA}	—	±3 mV	±0.2%			
I_{B_OA} **(Note 4)**	—	≈ 20 pA	±0.004%			
Average Count (k)						
$V_{RH} – V_{RL}$ **(Note 5)**	—	±4%	—	±4%	±4%	±24%
R_{INT}	—	±1%	—	±1%	±1%	±6%
Comparator CMRR	—	±0.18%	—	±0.18%	±0.18%	±1.1%
Comparator V_{OS}	—	±10 mV	—	0%	0%	0%
Oscillator	internal	±1%	—	±1%	±1%	±6%
	external	±0.01%	—	±0.01%	±0.01%	±0.1%
f_{GBWP}	for HS1101LF	–0.002%	—	–0.002%	–0.002%	–0.01%
	at C_{SEN} = 0.6 pF	–0.5%	—	–0.5%	–0.5%	N/A
Calculating C_{SEN}						
C_{PAR}	not corrected	0.5 pF	—	—	0.5 pF	1.6%
	corrected	±0.1 pF	—	—	±0.1 pF	±0.3%
B_1	—	0.25%	—	—	0.25%	1.5%
Quantization Error	—	±0.05 pF	—	—	±0.05 pF	±0.3%
Calculating RH						
HS1101LF, Nominal Error	—	±3%	—	—	—	±3%
HS1101LF, Drift per Year	—	±1%	—	—	—	±1%
PWL Lookup Table	—	±0.01%	—	—	—	±0.01%

Note 1: It is assumed that V_{DD} is at its lowest value (3.0V for this design) when converting errors in mV to percentage errors.

2: The error in V_{CM} is given as a percentage of $V_{DD}/2$, which is the same as the relative error ε.

3: The error magnitudes are calculated one at a time, except when converting from ε to $ε^2$ (“Error in k” column) for the current imbalance. In the latter case, the relative errors are added together before squaring.

4: This error becomes bigger as the ambient temperature increases. At +125°C, I_{B_OA}’s contribution to the imbalance ε is ±5 nA or ±1.1%, causing the RH error to be ±0.6%.

5: Both V_{RL} and V_{RH} have a maximum specified error of ±0.0104V_{DD}. Since ($V_{RH} – V_{RL}$) has a nominal value of 0.375V_{DD}, each error becomes ±0.0278($V_{RH} – V_{RL}$). The two errors were added in the RMS sense to obtain the ±4% value shown above.

Possible Improvements

The V_{REF} levels (V_{RH} and V_{RL}) can be corrected, in some microcontrollers, by internally connecting an ADC to the V_{REF} output. Since the ADC has better accuracy than the V_{REF} ladder, the measurement can be improved.

Components with tighter tolerance will directly improve the RH accuracy. The resistor, $R_{INT,}$ and the oscillator are two important examples.

Most of the remaining errors can be corrected with appropriate calibration procedures and calculations. The calculated RH can be corrected for errors across temperature; both the sensor and the circuit can be calibrated at the same time. Once the decision is made to calibrate the errors, there is no need to correct the V_{REF} levels using the internal ADC.

MEASURED RESULTS

The basic circuits in Figure 3 and Figure 6 were measured with different R_{INT} values. First, known capacitors were measured to validate the accuracy of these designs. Then the HS1101LF relative humidity sensor was measured and compared to another, calibrated humidity sensor.

The measurements were made on the Humidity Sensor PICtail™ Demo Board, which is discussed in the user's guide (DS51594) [15]. This board is further described by:

- Order Number: PIC16F690DM-PCTLHS
- Assembly Number: 102-00084R1

Fine Resolution Measurements

The circuit in Figure 6 was measured first; it has the 40 dB attenuation of the square wave. This made it possible to measure the parasitic capacitance, C_{PAR}, and other small capacitances. The C_{SEN} resolution is 0.001 pF / count.

Figure 7 shows the V_{SEN} waveform across time. T1G is the Timer 1 Gate waveform; it shows when the comparator decides that V_{SEN} has reached either V_{RL} or V_{RH}. C_{SEN} was 166.0 pF and R_{INT} was 6.65 MΩ.

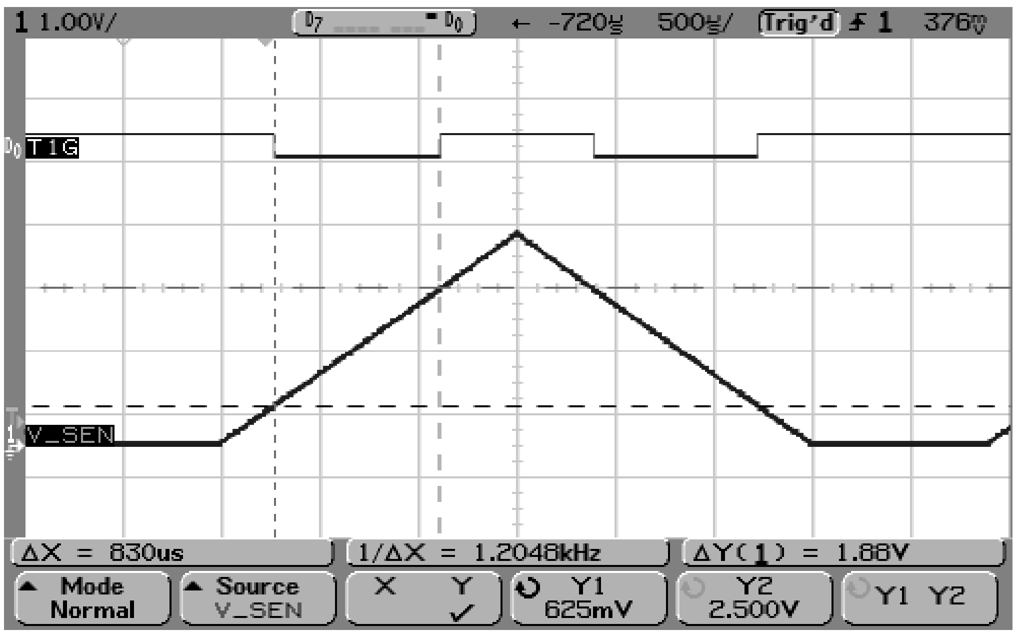

FIGURE 7: V_{INT} and V_{SEN} Waveforms with C_{SEN} = 166 pF.

Figure 8 shows the measurement discrepancy between the values read from an HP4285A LCR meter and the circuit in Figure 6. These measurements were taken across a range of allowed C_{SEN} values. The parasitic capacitance C_{PAR} was measured by leaving C_{SEN} open; the value for the Humidity Sensor PICtail™ Demo Board [15] turned out to be approximately 0.27 pF.

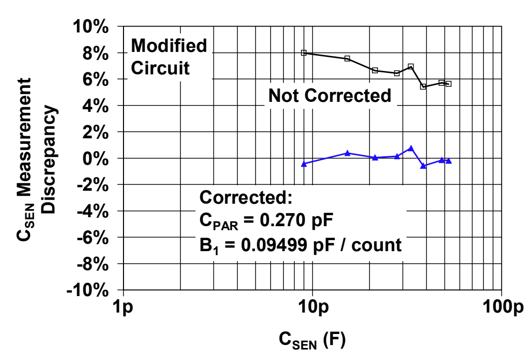

FIGURE 8: C_{SEN} Measurement Discrepancy.

Normal Resolution Measurements

The circuit in Figure 3 does not attenuate the square wave, making it possible to measure larger capacitors. The C_{SEN} resolution is 0.1 pF / count.

Figure 9 shows the measurement discrepancy between the values read from an HP4285A LCR meter and the circuit in Figure 3. These measurements were taken across a range of allowed C_{SEN} values.

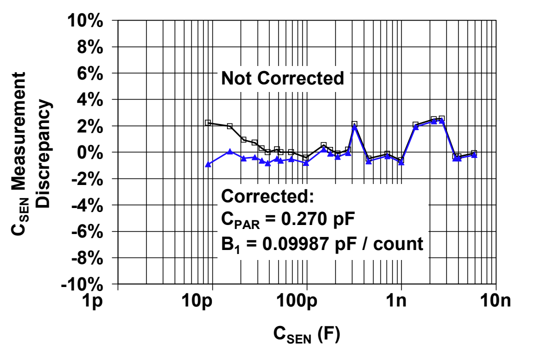

FIGURE 9: C_{SEN} Measurement Discrepancy.

HS1101LF Sensor Measurements

The circuit in Figure 3 was used to measure the HS1101LF relative humidity sensor. The measurement resolution is 0.1 pF / count (0.6% RH change per count) and R_{INT} is 6.65 MΩ. The curves in Figure 10 show how the sensor reacted when it was breathed on for about half second; the result is the impulse response of the sensor.

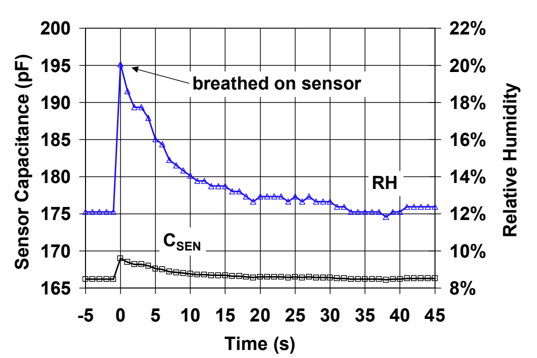

FIGURE 10: HS1101LF Impulse Response.

LESSONS LEARNED

Several important lessons were learned in the process of building, measuring and debugging this design.

Ratiometric Design

This design assumes V_{DD} ranges from 3.0V to 5.5V (e.g., two lithium batteries). To avoid supply rejection errors, and to make the design simpler to implement, a ratiometric approach was very helpful. The implementation is as follows:

- The square wave V_{INT} is ratiometric
- V_{CM} is ratiometric
- V_{CM} and R_{INT} make the current I_{INT} ratiometric, so the voltage V_{SEN} is ratiometric
- CV_{REF} reference (used for V_{RH} and V_{RL}) is ratiometric (the other internal reference is not)

Reference Voltages Chosen

The reference voltages (V_{RH} and V_{RL}) need to be selected carefully. The analog components need to stay within their allowed ranges, but V_{RH} and V_{RL} need to be as far apart as possible for accuracy reasons:

- The lower CVREF range is more accurate than the upper range (±1.04% vs. ±1.56%).
- The comparator's V_{CMR} range is V_{DD} – 1.5V, which is at its worst case value ($V_{DD}/2$) when V_{DD} = 3.0V (it is not ratiometric).
- The op amp's output should stay above 0.2V to 0.3V to maintain accuracy and avoid overdrive recovery problems (about $0.1V_{DD}$ when V_{DD} = 3.0V).

For these reasons, the design uses $V_{RL} = 0.125V_{DD}$ and $V_{RH} = 0.500V_{DD}$ in the lower CVREF range.

Choosing the Microcontroller

The PIC16F690 has several key features that help this design:

- Comparator latch makes the firmware simpler and avoids delay in a firmware loop.
- The comparator can be connected internally to the reference (CV_{REF}) and to the board.
- It has an accurate internal oscillator.
- It operates over the required supply range.

Calibration

Capacitive relative humidity sensors are quite sensitive to capacitive measurement errors. It can be costly to use components with tighter tolerances. The designs in this application note are a big help because they have low parasitic capacitance in parallel with the sensor, and they are immune to sensor case to ground capacitances.

The most effective way to overcome the sensitivity problem is to calibrate the errors in production. All of the errors can be corrected in the same step.

Miscellaneous

Using dual slope integration minimizes errors due to the V_{CM} error (I_{INT} imbalance).

The op amp's gain-bandwidth product affects the relative error for small C_{SEN} values. Select an op amp that gives an acceptable error at the smallest C_{SEN} value that will be measured.

R_{INT} is selected last to make the code simpler to implement. It is chosen so that B_1 becomes a convenient number (e.g., 0.1 pF / count).

It is important to use a greater number of bits for the averaging (accumulation) of C_{SEN}. The counter in this design is a 16-bit value, and the accumulator is a 24-bit value. This avoids truncation errors, and can prevent counter results being interpreted as negative values.

SUMMARY

This application note shows hardware and firmware design engineers how to use a PICmicro® microcontroller and an op amp integrator to accurately measure small capacitances. Simple firmware is included that produces capacitance and relative humidity values for the HS1101LF relative humidity sensor.

Measurements verify the theory and design choices. An error analysis points to possible improvements in the design. Other alternatives and modifications to this design are also covered. Key lessons learned help the user focus on the important aspects of the given design.

The references and appendices give detailed information that supports the text of this application note.

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APPENDIX A: PIECEWISE LINEAR INTERPOLATION TABLE

In order to convert C_{SEN} to RH, the firmware uses a piecewise linear interpolation table [11]. This table is designed specifically for Humirel's HS1101LF relative humidity sensor [1]. First, the calculated C_{SEN} value is limited in range and converted to a 10-bit integer:

EQUATION A-1:

$$\begin{aligned} CSN &= 0, \quad C_{SEN} < 130.0\ pF \\ &= 1023, \quad C_{SEN} > 232.3\ pF \\ &= \frac{C_{SEN} - 130.0\ pF}{0.1\ pF}, \ otherwise \end{aligned}$$

The top 6 bits of CSN are used as a pointer (INTRVL) to the correct row of the table. The bottom 4 bits of CSN (CSN – ACSN, interpreted as integers between 0 and 15) are the input to the linear interpolation formula using the coefficients for the current row. The entries in the table give errors less than ±0.01%.

EQUATION A-2:

$$\begin{aligned} X &= A_{RHO} + A_{RH1}(CSN - ACSN) \\ RH &= max\{min\{X,\ 100\%\},\ 0\%\} \end{aligned}$$

TABLE A-1: HS1101LF COEFFICIENT LOOKUP TABLE

INTRVL	ACSN	A_{RH0} (%)	A_{RH1} (% / LSb)
0	0	0	0
1	16	0	0
...	...	...	...
17	272	0	0
18	288	0	0
19	304	-3.08	0.250
20	320	0.92	0.259
21	336	5.06	0.267
22	352	9.33	0.276
23	368	13.75	0.285
24	384	18.31	0.294
25	400	23.00	0.302
26	416	27.84	0.310
27	432	32.80	0.318
28	448	37.89	0.325
29	464	43.09	0.332
30	480	48.40	0.337
31	496	53.79	0.341
32	512	59.26	0.345
33	528	64.77	0.347
34	544	70.32	0.347
35	560	75.88	0.346
36	576	81.41	0.344
37	592	86.91	0.339
38	608	92.33	0.332
39	624	97.64	0.325
40	640	100	0
41	656	100	0
...	...	...	...
62	992	100	0
63	1008	100	0

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