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.
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.

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

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**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. \( V_{SEN} \)
range. VRH was selected to be within the comparator’s common mode input voltage range when VDD goes as low as 3.0V. The comparator detects where VSEN is located relative to VRH and VRL.

The voltage, VSEN, is a triangle waveform that goes outside the levels, VRL and VRH; 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 (VIN = 0V) when VSEN needs to increase, and sets it high (VIN = VDD) when VSEN needs to decrease. During measurements, the microcontroller pins are put into the states shown in Table 1.

### TABLE 1: PIN STATES

<table>
<thead>
<tr>
<th>Measurement Steps</th>
<th>Pin States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Slope (measure t1)</td>
<td>P1</td>
</tr>
<tr>
<td>Negative Slope (measure t2)</td>
<td>1</td>
</tr>
</tbody>
</table>

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

The INT values shown in Figure 2 (INTP and INTM) have opposite signs and approximately equal magnitudes. The magnitudes are not always equal because VCM is not always equal to VDD/2. This produces elapsed times (t1 and t2) that are only approximately equal as show in Equation 2.

**EQUATION 2:**

\[
t_1 = \frac{VRH - VRL}{\Delta VSEN/\Delta t} = \frac{VRH - VRL}{VCM} \cdot CSEN \cdot RINT
\]

\[
t_2 = \frac{VRH - VRL}{\Delta VSEN/\Delta t} = \frac{VRH - VRL}{VDD - VCM} \cdot CSEN \cdot RINT
\]

Ensuring Op Amp Stability and Accuracy

The op amp (U2) can behave poorly, or even oscillate, if CSEN is not properly constrained. The parasitic capacitance from the op amp’s inverting input to ground (the sensor’s CCG and the op amp’s CCM) also affects its stability. It is recommended that a unity gain stable op amp such as the MCP6291 be used and that CSEN be set as follows:

**EQUATION 3:**

\[
CSEN \geq \frac{2}{2\pi RINTfGBWP^2} \cdot \frac{1}{\varepsilon_{LG}}
\]

Where:

- \(f_{GBWP}\) = op amp’s Gain Bandwidth Product
- \(\varepsilon_{LG}\) = allowable error due to loop-gain

For instance, given a 0.5% accuracy requirement, and using the MCP6291 for U2, gives:

- \(\varepsilon_{LG} = 0.005\)
- \(f_{GBWP} = 10\) MHz
- \(CSEN > 0.6\) pF

CSEN Extraction Equations

The measurements return timer counts, k1 and k2, which are related to the measurement times (t1 and t2) as follows:

**EQUATION 5:**

\[
k_1 = \frac{t_1}{T_{CLK}} = \frac{VRH - VRL}{VCM} \cdot CSEN \cdot RINT \cdot T_{CLK}
\]

\[
k_2 = \frac{t_2}{T_{CLK}} = \frac{VRH - VRL}{VDD - VCM} \cdot CSEN \cdot RINT \cdot T_{CLK}
\]

Where:

- \(T_{CLK}\) = microcontroller’s instruction period

The measurement timer counts will be averaged together before calculating CSEN; the reason why is illustrated in Equation 6. Since the error in VCM is in the denominator of the k1 and k2 equations, and the nominal VCM is VDD/2, we have:

**EQUATION 6:**

\[
VCM = \frac{k}{l + \varepsilon}
\]

\[
k_1 + k_2 = \frac{k}{l - \varepsilon^2}
\]

Where:

- \(k\) = ideal count (when VCM = VDD/2 exactly)
- \(\varepsilon\) = relative error (caused by VCM error)

\[
\varepsilon = \frac{V_{CM, Error}}{V_{CM}} = \frac{V_{DD} - V_{CM}}{V_{DD} - V_{CM}}
\]

\[
\varepsilon = \frac{V_{CM, Error}}{V_{DD}/2}
\]
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:**

\[
B_1 = \frac{VDD/2}{V_{RH} - V_{RL}} \cdot \frac{T_{CLK}}{R_{INT}}
\]

Extraction Equation:

\[
C_{SEN} = \frac{k_1 + k_2}{2} \cdot B_1
\]

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

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.

![HS1101LF Humidity Sensor's Nominal Capacitance with TA = +25°C](image)

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 \( \approx 3.2\% \) for each 1 pF change in \( C_{SEN} \)
- RH changes \( \approx 6\% \) for each 1% change in \( C_{SEN} \)
- RH changes \( \approx 0.32\% \) 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 CSEN readings together.

![Top Level Flow Chart](image)

The algorithm shown does not include any accuracy improvements. The user can add code to either correct the reference levels (VRL and VRH), 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 (VINT)
- P2 = RC1 (VSEN)
- 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**

<table>
<thead>
<tr>
<th>Algorithm Steps</th>
<th>Pin States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initialize VSEN (Note 1)</td>
<td>P1</td>
</tr>
<tr>
<td>(Move VSEN to &lt; VRL)</td>
<td>1</td>
</tr>
<tr>
<td>Set VREF to VRL</td>
<td></td>
</tr>
<tr>
<td>Detect when VSEN &lt; VRL</td>
<td></td>
</tr>
<tr>
<td>Delay</td>
<td></td>
</tr>
<tr>
<td>Positive VSEN Slope (Note 2) (Move VSEN from &lt; VRL to &gt; VRH)</td>
<td>0</td>
</tr>
<tr>
<td>Start count k1 when VSEN = VRH</td>
<td></td>
</tr>
<tr>
<td>Set VREF to VRH</td>
<td></td>
</tr>
<tr>
<td>Stop count k1 when VSEN = VRH</td>
<td></td>
</tr>
<tr>
<td>Delay</td>
<td></td>
</tr>
<tr>
<td>Negative VSEN Slope (Move VSEN from &gt; VRH to &lt; VRL)</td>
<td>1</td>
</tr>
<tr>
<td>Start count k2 when VSEN = VRH</td>
<td></td>
</tr>
<tr>
<td>Set VREF to VRH</td>
<td></td>
</tr>
<tr>
<td>Stop count k2 when VSEN = VRL</td>
<td></td>
</tr>
<tr>
<td>Delay</td>
<td></td>
</tr>
</tbody>
</table>

**Note 1:** VRL = 0.125VDD and VRH = 0.500VDD. These are lower range levels in the PIC16F690's VREF (CVREF).

**Note 2:** The counts k1 and k2 increment once for each PICmicro instruction cycle (TCLK = 0.5 μs)

Relative Humidity Module

Once CSEN 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 \( R_{\text{INT}} \) value. It makes the code simpler when the resolution is a simple multiple of 1 pF. One possible set of values is:

- \( R_{\text{INT}} = 6.65 \, \text{M} \Omega \) for 0.1 pF / count
- \( R_{\text{INT}} = 665 \, \text{k} \Omega \) for 1 pF / count
- \( R_{\text{INT}} = 66.5 \, \text{k} \Omega \) for 10 pF / count

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

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

Many of the errors over relative humidity, supply voltage and temperature will be consistent over time. This makes it possible 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 \( V_{\text{DD}}/2 \) and a gain of 0.0100 V/V. Thus, the current magnitudes \( I_{\text{INTP}} \) and \( I_{\text{INTM}} \) 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:

- \( C_{\text{SEN}} \) needs to be larger than 0.6 pF for a 0.5% accuracy and for stability
- Resolution \( \approx 0.001 \) pF / count

The attenuator increases the equivalent error at \( V_{\text{CM}} \). 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: \( C_{\text{CG}} \) is the sensor’s case-to-ground parasitic capacitance. \( C_{\text{CG}} \) should be placed at the op amp’s inverting input pin to improve the op amp’s stability and eliminate any dynamic current through \( C_{\text{CG}} \).

Note 2: \( R_{\text{INT}} \) is chosen to minimize the effort to calculate \( C_{\text{SEN}} \).

Other Circuits

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 summarized 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 ($\varepsilon$) 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 ($\varepsilon$) would be $+2\%$. If op amp $U_1$’s input offset voltage ($V_{OS\_OA}$) is $+4.5\,mV$ and $V_{DD}$ is $5.0\,V$, then $\varepsilon$ 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 ($\varepsilon$) in $k_1$ and $k_2$ causes a smaller error of $\varepsilon^2$ 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 $\pm0.1\,pF$ 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 $\pm2\%$ error in the nominal RH value, and a $\pm6\%$ 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 $\pm0.01\%$ 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
### Possible Improvements

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

Components with tighter tolerance will directly improve the RH accuracy. The resistor, $R_{\text{INT}}$, 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 $V_{\text{REF}}$ levels using the internal ADC.

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### TABLE 3: ERROR ANALYSIS AT ROOM TEMPERATURE

<table>
<thead>
<tr>
<th>Error Sources</th>
<th>Cause</th>
<th>Special Conditions</th>
<th>Worst Case Error (Note 1)</th>
<th>Imbalance $\epsilon$ (Note 2)</th>
<th>Error in $k$ (Note 3)</th>
<th>Error in CSEN</th>
<th>Error in RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current ($i_{\text{INT}}$) Imbalance</td>
<td>$R_{\text{CM1}}$ and $R_{\text{CM2}}$</td>
<td>—</td>
<td>±1%</td>
<td>±2.0%</td>
<td>±0.05%</td>
<td>±0.05%</td>
<td>±0.3%</td>
</tr>
<tr>
<td></td>
<td>$V_{\text{OS}_{\text{OA}}}$</td>
<td>—</td>
<td>±3 mV</td>
<td>±0.2%</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$I_{\text{B}_{\text{OA}}}$ (Note 4)</td>
<td>—</td>
<td>≈20 pA</td>
<td>±0.004%</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Average Count ($k$)</td>
<td>$V_{\text{RH}} - V_{\text{RL}}$ (Note 5)</td>
<td>—</td>
<td>±4%</td>
<td>±4%</td>
<td>±4%</td>
<td>±24%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{\text{INT}}$</td>
<td>—</td>
<td>±1%</td>
<td>±1%</td>
<td>±6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Comparator CMRR</td>
<td></td>
<td>±0.18%</td>
<td>±0.18%</td>
<td>±0.18%</td>
<td>±1.1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Comparator $V_{\text{OS}}$</td>
<td></td>
<td>±10 mV</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oscillator</td>
<td>internal</td>
<td>±1%</td>
<td>±1%</td>
<td>±6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>external</td>
<td>±0.01%</td>
<td>±0.01%</td>
<td>±0.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$f_{\text{GBWP}}$</td>
<td>for HS1101LF</td>
<td>−0.002%</td>
<td>−0.002%</td>
<td>−0.002%</td>
<td>−0.01%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>at $C_{\text{SEN}} = 0.6$ pF</td>
<td>−0.5%</td>
<td>−0.5%</td>
<td>−0.5%</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculating $C_{\text{SEN}}$</td>
<td>$C_{\text{PAR}}$</td>
<td>not corrected</td>
<td>0.5 pF</td>
<td>—</td>
<td>—</td>
<td>0.5 pF</td>
<td>1.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>corrected</td>
<td>±0.1 pF</td>
<td>—</td>
<td>—</td>
<td>±0.1 pF</td>
<td>±0.3%</td>
</tr>
<tr>
<td></td>
<td>$B_{1}$</td>
<td>—</td>
<td>0.25%</td>
<td>—</td>
<td>—</td>
<td>0.25%</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>Quantization Error</td>
<td>—</td>
<td>±0.05 pF</td>
<td>—</td>
<td>—</td>
<td>±0.05 pF</td>
<td>±0.3%</td>
</tr>
<tr>
<td>Calculating RH</td>
<td>HS1101LF, Nominal Error</td>
<td>—</td>
<td>±3%</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>±3%</td>
</tr>
<tr>
<td></td>
<td>HS1101LF, Drift per Year</td>
<td>—</td>
<td>±1%</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>±1%</td>
</tr>
<tr>
<td></td>
<td>PWL Lookup Table</td>
<td>—</td>
<td>±0.01%</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>±0.01%</td>
</tr>
</tbody>
</table>

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

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

3: The error magnitudes are calculated one at a time, except when converting from $\epsilon$ to $\epsilon^2$ (“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, $I_{\text{B}_{\text{OA}}}$'s contribution to the imbalance $\epsilon$ is ±5 nA or ±1.1%, causing the RH error to be ±6%.

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

The basic circuits in Figure 3 and Figure 6 were measured with different $R_{\text{INT}}$ 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, $C_{\text{PAR}}$, and other small capacitances. The $C_{\text{SEN}}$ resolution is 0.001 pF / count.

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

![FIGURE 7: $V_{\text{INT}}$ and $V_{\text{SEN}}$ Waveforms with $C_{\text{SEN}}$ = 166 pF.](image)

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 $C_{\text{SEN}}$ values. The parasitic capacitance $C_{\text{PAR}}$ was measured by leaving $C_{\text{SEN}}$ open; the value for the Humidity Sensor PICtail™ Demo Board [15] turned out to be approximately 0.27 pF.

![FIGURE 8: $C_{\text{SEN}}$ Measurement Discrepancy.](image)
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 $CV_{REF}$ range is more accurate than the upper range ($\pm1.04\%$ vs. $\pm1.56\%$).
- 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 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 $CV_{REF}$ 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 (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 $B_3$ 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.

REFERENCES

Humidity Sensors


General Sensors


Capacitive Sensors


Related Literature

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:**

$$CSN = 0, \quad C_{SEN} < 130.0 \text{pF}$$
$$= 1023, \quad C_{SEN} > 232.3 \text{pF}$$
$$= C_{SEN} - 130.0 \text{pF, otherwise}$$

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:**

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

### TABLE A-1: HS1101LF COEFFICIENT LOOKUP TABLE

<table>
<thead>
<tr>
<th>INTRVL</th>
<th>ACSN</th>
<th>$A_{RHO}$ (%)</th>
<th>$A_{RH1}$ (% / LSb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>0</td>
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<td>17</td>
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<td>0</td>
</tr>
<tr>
<td>18</td>
<td>288</td>
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<td>0</td>
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<tr>
<td>19</td>
<td>304</td>
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<td>0.250</td>
</tr>
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<td>0.259</td>
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<tr>
<td>21</td>
<td>336</td>
<td>5.06</td>
<td>0.267</td>
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<tr>
<td>22</td>
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<td>24</td>
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<tr>
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<td>400</td>
<td>23.00</td>
<td>0.302</td>
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<tr>
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