AN1014

Measuring Small Changes in Capacitive Sensors

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 detect small changes in capacitance.

Goals

- Detect small capacitance changes (e.g., 0.001 pF)
- Estimate capacitances (i.e., 10 pF to 1 nF)
- Use minimal number of external components
- Create simple firmware solution
- Show design trade-offs and alternative circuits

Description

This application note shows a switched capacitor circuit that uses a PICmicro® microcontroller, and minimal external passive components, to measure small changes in capacitance. The values are very repeatable under constant environmental conditions.

The design is measured to verify the theory and design choices. Some design alternatives and modifications are explored. Information on the circuit board and firmware used in the measurements is included.

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

SWITCHED CAPACITOR SOLUTION

This section describes a circuit that is appropriate for measuring small changes in capacitance (e.g., 0.001 pF) for relatively small capacitors (i.e., 10 pF to 10 nF).

Switched Capacitor Preliminaries

Figure 1 shows the general situation when a grounded, switched (sensing) capacitor (C_{SEN}) transfers energy from a voltage source (V_S) to an output integrating (storage) capacitor (C_{INT}). Each time one of the switches closes, charge is transferred to, or from, C_{SEN} to equalize the voltages. The period of a complete switching cycle is T_{SW}.

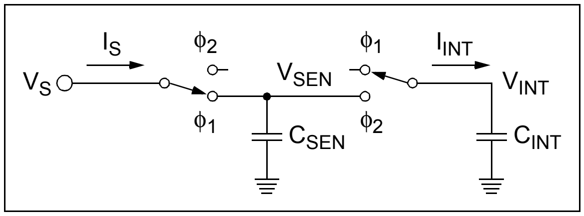

FIGURE 1: *Diagram of a Grounded, Switched Capacitor.*

C_{INT} is chosen to be much larger than C_{SEN}, so V_{INT} can be considered to be approximately constant during any one switching cycle. The charges transferred per time (Q_S/T_{SW} and Q_{INT}/T_{SW}) can be approximated, on the average, as currents flowing between two voltages (V_S and V_{INT}). Thus, the switches and C_{SEN} can be modeled as a series resistance (R_{SEN} in Equation 1 and Figure 2):

EQUATION 1:

$$R_{SEN} \approx \frac{T_{SW}}{C_{SEN}}$$

Since:

$$I_S = Q_S / T_{SW}$$
$$\approx (V_S - V_{SEN})\, C_{SEN} / T_{SW}$$
$$I_{INT} = Q_{INT} / T_{SW}$$
$$\approx (V_{SEN} - V_{INT})\, C_{SEN} / T_{SW}$$

When switches close:

$$(V_S - V_{SEN}) \approx (V_{SEN} - V_{INT})$$

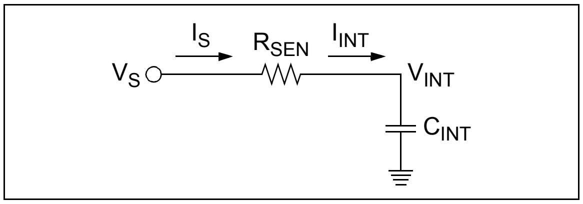

FIGURE 2: *Equivalent Model for the Grounded, Switched Capacitor.*

Hardware

CIRCUIT

Figure 3 shows the circuit used to measure a capacitive sensor. The PICmicro® microcontroller provides the timing, internal voltage reference and comparator to measure R-C step response times.

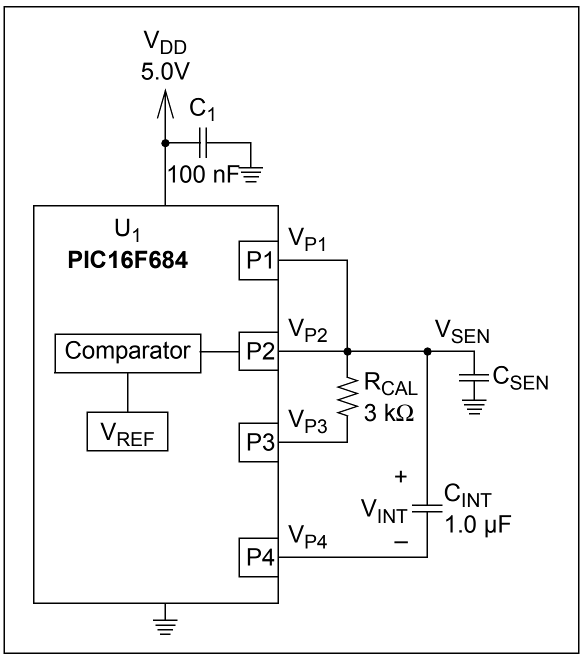

FIGURE 3: *Capacitor Sensor Circuit.*

The voltages in the diagram are related as follows:

EQUATION 2:

$$V_{SEN} = V_{P1} = V_{P2}$$
$$V_{INT} = V_{SEN} - V_{P4}$$

The pin assignments used on the PCB in **Appendix B: "Circuit Board"** are as follows:

- P1 = RC4
- P2 = RC1
- P3 = RC3
- P4 = RC2

The circuit has two measurement steps:

- First Measurement Step (Switching)
  - C_{SEN} is used as a switched capacitor resistor, which causes the voltage, $V_{INT,}$ to exponentially approach V_{DD} (starting at 0V)
- Second Measurement Step (Calibration)
  - R_{CAL} is grounded, causing $V_{INT} = V_{SEN}$ to exponentially approach 0V

FIRST MEASUREMENT STEP (SWITCHING)

The simplified model of the first measurement step is described in Equation 3 and Figure 4. C_{SEN} is used as a switched capacitor resistor, and C_{INT} is the integrating capacitor. Pin P3 is put in a high-impedance state so that R_{CAL} doesn't affect the measurements. The voltage across C_{INT} (V_{INT}) starts at 0V (after a preliminary discharge time) and exponentially approaches V_{DD}. The comparator detects when V_{INT} reaches an upper reference voltage (V_{RH}), and the microcontroller measures the number of switching periods (k_1 periods of length T_{SW}) needed to reach that point.

EQUATION 3:

$$V_{INT} = 0V, \quad t < 0$$
$$\approx V_{DD}(1 - e^{-t/\tau 1}), \quad t \geq 0$$
$$k_1 \approx \frac{\ln(V_{DD}/(V_{DD} - V_{RH}))}{C_{SEN}/C_{INT}}$$

Where:

C_{SEN}	<<	C_{INT}
R_{SEN}	=	T_{SW} / C_{SEN}
τ_1	=	$R_{SEN}C_{INT}$
T_{SW}	=	Switching Period

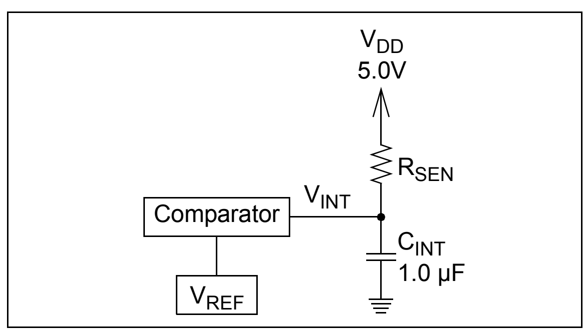

FIGURE 4: *Equivalent Model for V_{INT}.*

The PICmicro® microcontroller produces a switch clock (CKSW) with period T_{SW}. This clock signal alternately selects between two cycles: the charging cycle and the sharing cycle. The resistor, $R_{CAL,}$ is left floating, so it doesn't affect this measurement. Table 1 gives the pin states for the two cycles during a typical switching period (T_{SW}). Figure 5 shows typical waveforms for the first measurement cycle (see Figure 3 for the voltages shown). V_{P4} shows an R-C step response because R_{CAL} interacts with the I/O port pin capacitance at P4.

TABLE 1: PIN STATES

Cycles	Pin States			
	P1	**P2**	**P3**	**P4**
Charging Cycle	1	input	hi-Z	hi-Z
Sharing Cycle	hi-Z	input	hi-Z	0

Note 1: The Charge Cycle charges C_{SEN} to the voltage V_{DD}.
2: The Share Cycle shares the charge between C_{SEN} and C_{INT}, which slowly increases V_{INT}.
3: P2 is high impedance, and is always connected to the comparator.
4: Not shown are transition states between the cycles; see Table 3.

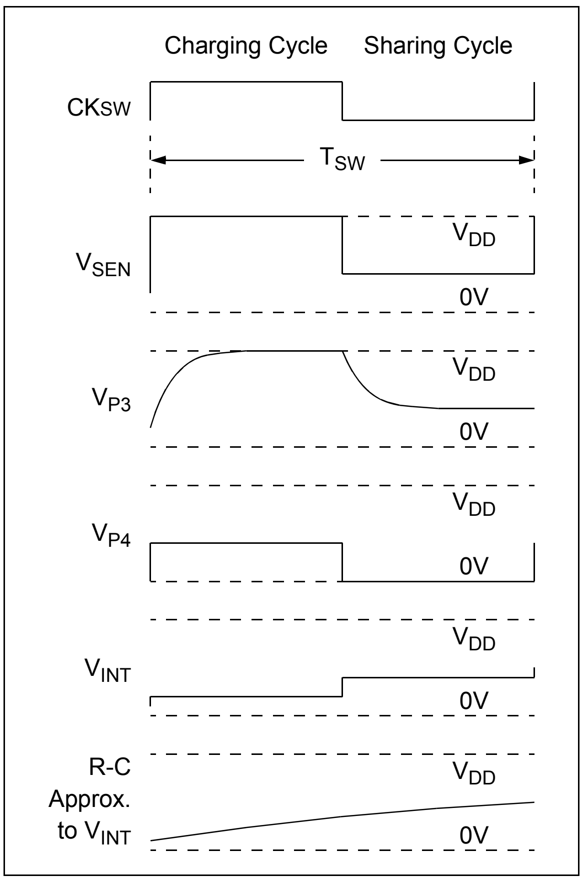

FIGURE 5: First Measurement Step Timing.

Many switching periods (T_{SW}) are needed to increase V_{INT} until it reaches the higher reference voltage (V_{RH}). The microcontroller counts the number of switching periods (T_{SW}) needed for V_{INT} to increase from V_{RL} to V_{RH}; the result is placed in the counter k_1 (the "switching count"). The time needed for V_{INT} to reach V_{RH} is k_1T_{SW}. As will be shown later, k_1 is a measure of the ratio C_{SEN} / C_{INT}.

Figure 6 and Figure 7 illustrate the sequence discussed above. Notice how the integrator voltage (V_{INT}) looks like a series of stair steps due to the digital control provided by the microcontroller. When C_{INT} is very large (compared to C_{SEN}), these steps are very small, and the waveform is well approximated by an R-C step response. V_{SEN} = V_{DD} during the first part of the switching cycle (charging C_{SEN}), and V_{SEN} = V_{INT} during the second part of switching cycle (sharing charge with C_{INT}).

C_{INT} is set much lower in these figures than it would be for a practical circuit in order to make the switch response easier to see. The parameters used to produce these figures are:

- C_{INT} = 1.0 nF
- C_{SEN} = 100 pF
- T_{SW} = 5.0 µs
- V_{DD} = 5.0V

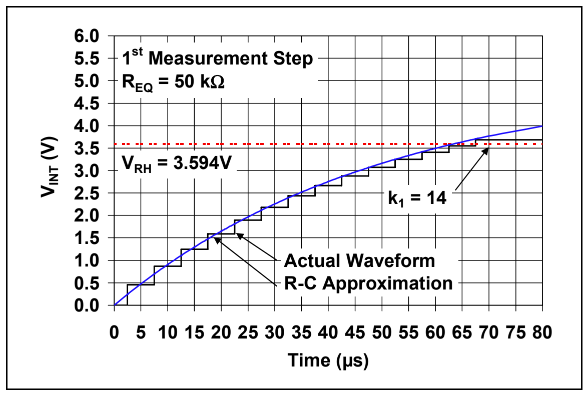

FIGURE 6: First Measurement Step Example – V_{INT} Voltage.

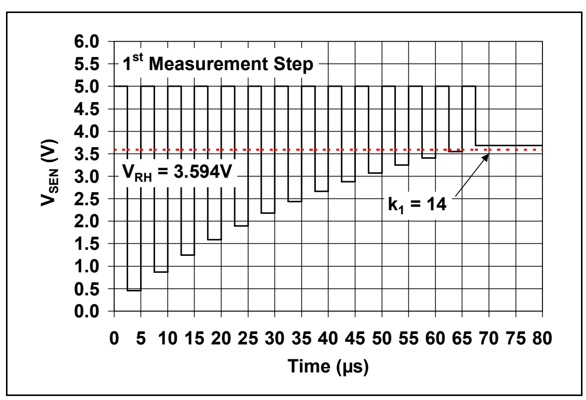

FIGURE 7: First Measurement Step Example – V_{SEN} Voltage.

The parasitic input capacitances (C_{PAR}) at each of the microcontroller input pins, P1–P3, are in parallel with C_{SEN}. The parasitic capacitance at pin P4 (also C_{PAR}) produces a current in the same direction as C_{SEN}, and sees the same voltage change during switching as the other parasitic capacitances, so it can also be considered to be in parallel with C_{SEN}. Thus, for greater accuracy for small C_{SEN}, it can be replaced by the sum ($C_{SEN} + 4C_{PAR}$) in all of the equations for the first measurement step. R_{CAL} is chosen so that the time constant, $R_{CAL}C_{PAR}$, is much shorter than the switching period, T_{SW}. The equation for k_1 becomes:

EQUATION 4:

$$k_1 \approx \frac{ln(V_{DD}/(V_{DD} - V_{RH}))}{(C_{SEN} + 4C_{PAR})/C_{INT}}$$

SECOND MEASUREMENT STEP (CALIBRATION)

The model of the second measurement step is described in Equation 5 and Figure 8. R_{CAL}, C_{INT} and C_{SEN} are all grounded (connected in parallel), and no energy is transferred to these parts. The voltage, V_{INT}, starts at a high value (V_{RH}) and decays exponentially towards ground. The comparator detects when V_{INT} has reached a low value (V_{RL}). The microcontroller measures the time elapsed (k_2 instruction periods of length, T_{CLK}).

EQUATION 5:

$$V_{INT} = V_{SEN} = V_{RH}, \quad t < 0$$

$$= V_{RH}e^{-t/\tau 2}, \quad t \geq 0$$

$$k_2 \approx \frac{R_{CAL}(C_{INT} + C_{SEN}) ln(V_{RH}/V_{RL})}{T_{CLK}}$$

Where:

$\tau_2 = R_{CAL}(C_{INT} + C_{SEN})$

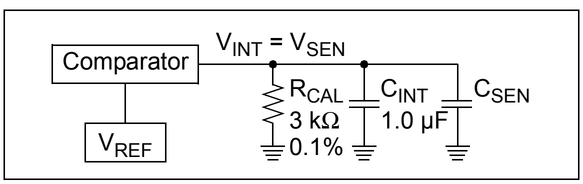

FIGURE 8: Model for V_{INT}.

The PICmicro microcontroller counts the number of its internal instruction cycles (CLK, with period, T_{CLK}) needed for V_{INT} to decrease from V_{RH} to V_{RL}. This result is placed in the counter, k_2 (the "calibration count"). The time needed is k_2T_{CLK}. As will be shown later, k_2 is a measure of the sum $C_{INT} + C_{SEN}$; it is used to correct for errors in C_{INT} (process variation, temperature drift, aging, etc.). Table 2 gives the pin states for this measurement step.

TABLE 2: PIN STATES

Cycles	Pin States			
	P1	P2	P3	P4
Calibration Cycle	hi-Z	input	0	0

Note 1: The Calibration Cycle discharges C_{INT} and C_{SEN}, through R_{CAL} to ground, until it reaches the voltage V_{RL}.

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

Figure 9 illustrates the measurement step discussed above. C_{INT} is set much lower in this figure than it would be for a practical circuit in order to make the waveform easier to interpret. The parameters used to produce this figure are:

- C_{INT} = 1.0 nF
- C_{SEN} = 100 pF
- T_{CLK} = 0.5 µs
- V_{DD} = 5.0V

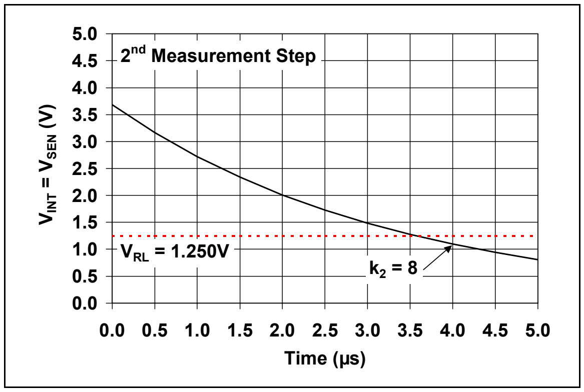

FIGURE 9: Second Measurement Step Example – $V_{INT} = V_{SEN}$ Voltage.

The parasitic input capacitances (C_{PAR}) at each of the microcontroller input pins, P1–P3, are in parallel with C_{SEN}. The parasitic capacitance at pin P4 is shorted to ground. Thus, for greater accuracy for small C_{SEN}, it can be replaced in all of the equations for the second measurement step by the sum ($C_{SEN} + 3C_{PAR}$). The equation for k_2 becomes:

EQUATION 6:

$$k_2 \approx \frac{R_{CAL}(C_{INT} + C_{SEN} + 3C_{PAR}) ln(V_{RH}/V_{RL})}{T_{CLK}}$$

Measurement Resolution

As a general rule, the higher the counts k_1 and k_2 are, the greater the resolution of the measured C_{INT} and C_{SEN}. Larger C_{INT} produces larger k_2 counts and better resolution. Smaller C_{SEN} produces larger k_1 counts and greater resolution; this is opposite the behavior of R-C decay timing methods [7], and is a significant advantage for this method. When C_{SEN} becomes smaller than $4C_{PAR}$, however, its resolution becomes worse.

The resolution for C_{SEN} and C_{INT} can be made higher by increasing C_{INT} and R_{CAL}. R_{CAL} needs to be small enough so that the parasitic capacitance at pin P3 of U_1 can settle in time, (i.e., $10R_{CAL}C_{PAR} < T_{SW}/2$).

Equation 7 shows approximations to the normalized resolution for these capacitances ($\Delta C_{INT}/C_{INT}$ and $\Delta C_{SEN}/C_{SEN}$) as a function of a change in the number of counts (Δk_1 and Δk_2). Figure 10 and Figure 11 show the same results in graphic form for a design optimized for C_{SEN} near 180 pF (and $C_{PAR} \approx 7.7$ pF). Notice that the Δk_1 increment is -1 in Figure 10; this means C_{SEN} decreases when k_1 increases.

EQUATION 7:

$$\frac{\Delta C_{INT}}{C_{INT}} \approx \frac{\Delta k_1}{k_1} \bullet \frac{C_{SEN} + 4C_{PAR}}{C_{INT}}, \qquad \Delta k_2 = 0$$

$$\frac{\Delta C_{INT}}{C_{INT}} \approx \frac{\Delta k_2}{k_2}, \qquad \Delta k_1 = 0$$

$$\frac{\Delta C_{SEN}}{C_{SEN}} \approx \frac{\Delta k_1}{k_1} \bullet \frac{C_{SEN} + 4C_{PAR}}{C_{SEN}}, \qquad \Delta k_2 = 0$$

$$\frac{\Delta C_{SEN}}{C_{SEN}} \approx \frac{\Delta k_2}{k_2} \bullet \frac{C_{SEN} + 4C_{PAR}}{C_{SEN}}, \qquad \Delta k_1 = 0$$

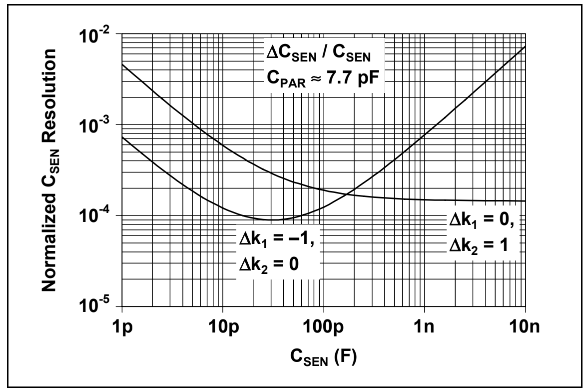

FIGURE 10: Example – Normalized C_{SEN} Resolution ($\Delta C_{SEN}/C_{SEN}$) vs. Δk_1 and Δk_2.

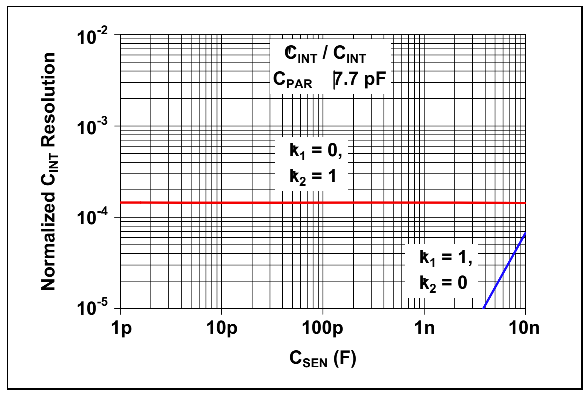

FIGURE 11: Example – Normalized C_{INT} Resolution ($\Delta C_{INT}/C_{INT}$) vs. Δk_1 and Δk_2.

FIRMWARE

The firmware discussed in this section is designed for the circuit in **Appendix B: "Circuit Board"**, and is implemented with the code shown in **Appendix C: "Firmware"**.

Detailed Algorithm

Table 3 shows the algorithm in detail, including the microcontroller's pin states. State 3 and State 4 are the first measurement step (the two parts to the switching cycle), and State 5 is the second measurement step. The initialization, calculation, output and sleep states are needed for complete functionality.

The microcontroller pin assignments in **Appendix B: "Circuit Board"** are:

- P1 = RC4
- P2 = RC1
- P3 = RC3
- P4 = RC2

TABLE 3: ALGORITHM

Circuit State	Pin States				Action
	P1	P2	P3	P4	
1. Initialize	—	—	—	—	Initialize PICmicro® microcontroller
					Configure hardware settings
					Initialize counts (k_1 and k_2) to zero **(Note 3)**, **(Note 4)**
2. Discharge	0	input	0	0	Discharge C_{INT} and C_{SEN} to 0V
					Allow time for capacitors to discharge to 0V
3. Charge	hi-Z	input	hi-Z	hi-Z	Quick Transition (avoid crowbar current)
	1	input	hi-Z	hi-Z	Charge C_{SEN} to V_{DD}
					Allow time for C_{SEN} to charge
					Increment k_1
4. Share Charge	hi-Z	input	hi-Z	hi-Z	Quick Transition (avoid crowbar current)
	hi-Z	input	hi-Z	0	Share charge between C_{SEN} and C_{INT}
					Allow time for C_{INT} and C_{SEN} to share charges
					IF ($V_{P2} < V_{RH}$) THEN (GOTO State 3) **(Note 1)**
5. Calibrate	hi-Z	input	0	0	Calibrate (C_{INT} + C_{SEN}) value using R_{CAL}
					(increment k_2 at each T_{CLK} period) UNTIL ($V_{P2} < V_{RL}$) **(Note 2)**
6. Calculate **(Note 5)**	0	input	0	0	Calculate capacitances
					(discharge C_{INT} and C_{SEN} to 0V)
					Calculate $A_R = C_{SEN}/C_{INT}$ from k_1 and circuit values
					Calculate $A_S = C_{INT} + C_{SEN}$ from k_2 and circuit values
					Calculate C_{INT} and C_{SEN}
7. Output	0	input	0	0	Output results (k_1, k_2, C_{INT} and C_{SEN})
					(discharge C_{INT} and C_{SEN} to 0V)
8. Sleep	0	input	0	0	Put circuit into Sleep mode
					(continue to discharge C_{INT} and C_{SEN} to 0V)
					Power Down
					Stay in sleep for fixed amount of time (e.g., 1 minute)
					Power Up
					GOTO State 1

Note 1: V_{RH} is the upper V_{REF} value used by the comparator ($0.6875V_{DD}$ = 3.438V).

2: V_{RL} is the lower V_{REF} value used by the comparator ($0.25V_{DD}$ = 1.25V).

3: k_1 is the "share charge cycles" counter; it increments once for each time states 3 and 4 are executed (T_{SW} = 6.5).

4: k_2 is the "calibrate cycles" counter; it increments once for each PICmicro instruction cycle (T_{CLK} = 0.5 µs).

5: The firmware in **Appendix C: "Firmware"** does not include the calculation of C_{INT} and C_{SEN}. It outputs k_1 and k_2 via the SPI bus, and leaves the conversion to capacitance to another routine written by the user.

Flow Chart

Figure 12 shows the flow chart for the firmware in **Appendix C: "Firmware"**, which is an abbreviated version of the algorithm in Table 3.

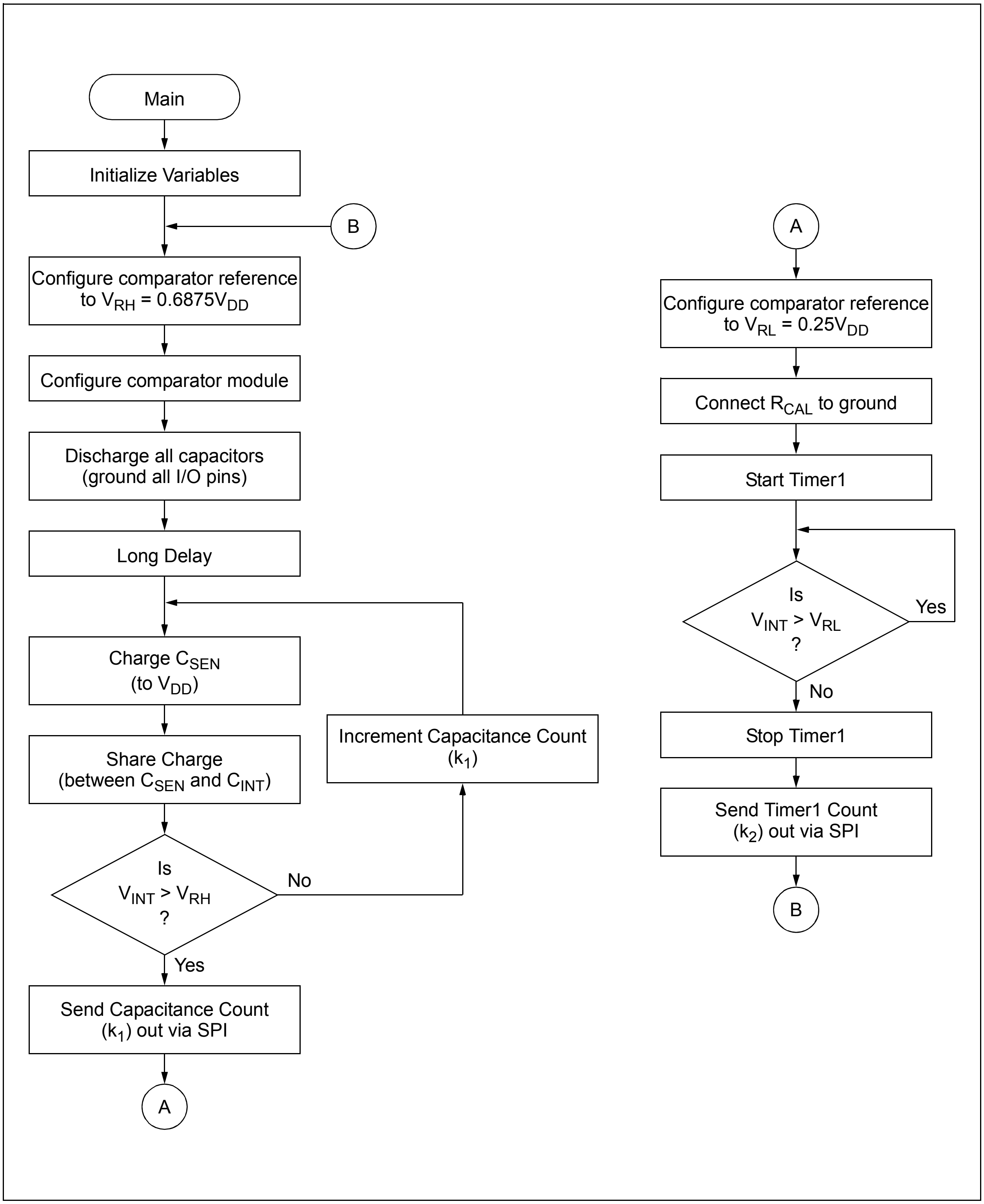

FIGURE 12: *Flow Chart.*

Capacitance Extraction Equations

The extraction equations in this section are not implemented in the firmware shown in **Appendix C: "Firmware"**. It is up to the user to write a routine that accepts k_1 and k_2, then calculates C_{INT} and C_{SEN}.

The extraction equations for C_{INT} and C_{SEN} are:

EQUATION 8:

Assumption:

$$C_{INT} >> C_{SEN} + 4C_{PAR}$$

Pre-calculated Constants:

$$B_1 = \ln\left(\frac{V_{DD}}{V_{DD} - V_{RH}}\right)$$

$$B_2 = \frac{T_{CLK}}{R_{CAL}\ \ln(V_{RH}/V_{RL})}$$

Extraction Equations:

$$A_R = B_1 / k_1$$

$$A_S = B_2\, k_2$$

$$C_{INT} \approx \frac{A_S + C_{PAR}}{1 + A_R}$$

$$\approx A_S, \quad \textit{(Simplified formula)}$$

$$C_{SEN} \approx A_R C_{INT} - 4C_{PAR}$$

The accuracy of these extractions depend on:

- The measurement resolution (k_1 and k_2)
- Estimating the correct value for C_{PAR}
- Keeping C_{SEN} in the recommended range of values

The main difficulty in implementing this algorithm is caused by the division needed to calculate A_R. The references [9-12] discuss general division routines. Reference [13] discusses one approach to using piece-wise linear approximation tables in microcontrollers.

MEASURED RESULTS

Setup

Measurements were made with the following nominal circuit design parameters:

- C_{INT} = 1.0 µF
- C_{SEN} = 10 pF to 10 nF
- R_{CAL} = 3.01 kΩ
- T_{SW} = 5.0 µs
- T_{CLK} = 0.5 µs
- V_{DD} = 5.0V
- V_{RL} = 1.250V
- V_{RH} = 3.438V

These measurements were made with the board discussed in **Appendix B: "Circuit Board"**.

Measured Circuit Parameters

The measured circuit parameters are:

- C_{INT} = 1.082 µF
- C_{PAR} = 7.7 pF
- R_{CAL} = 3.013 kΩ (by the HP3457A)

Appendix A: "Measured Results" gives a complete list of measured k_1, k_2 and C_{SEN} values.

Oscilloscope Plots

V_{SEN} was measured with an oscilloscope; the results are plotted in Figure 13. A closer look at the calibration step (R-C decay) is shown in Figure 14.

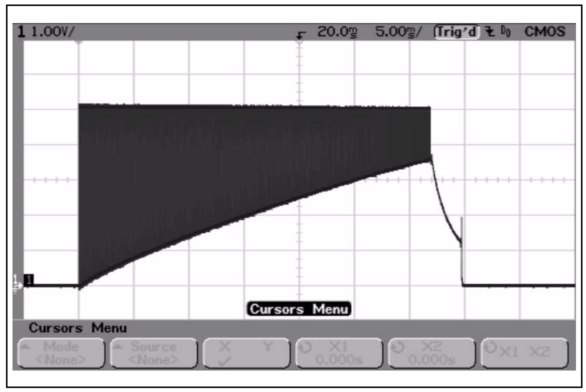

FIGURE 13: V_{SEN} Time Response with C_{SEN} = 220 pF.

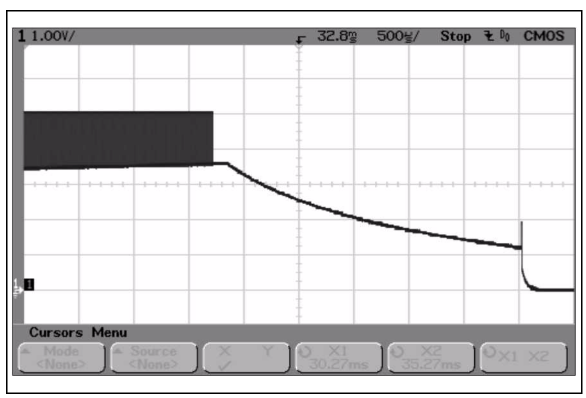

FIGURE 14: V_{SEN} Time Response Detail with C_{SEN} = 220 pF.

Measurement Resolution

Figure 15 shows how well the extracted values of C_{SEN} (including the correction for C_{PAR}) match the values produced by the HP4285A Precision LCR Meter. C_{PAR} was estimated to be 7.6 pF.

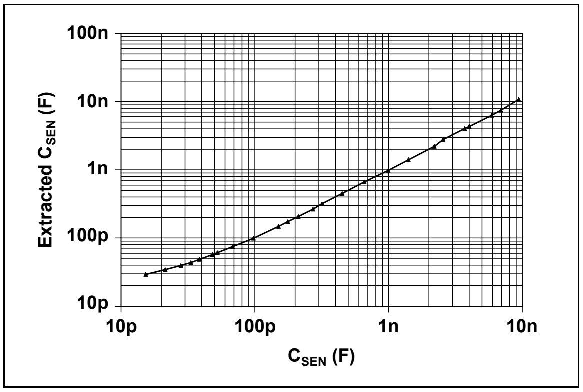

FIGURE 15: Extracted Sensor Capacitances.

Tests on the bench verified the excellent resolution of this method. The results were very consistent over a short period of time.

Comparing measurements over a long period of time gave results that were not as consistent. It appears that drift with temperature and capacitor dielectric absorption may cause the inconsistencies.

Measurement Accuracy

The measurement accuracy is not as good as that produced by other circuits. The errors seen on the bench were on the order of ±10 pF and ±10%.

The parasitic capacitance value (about 7.7 pF) significantly affected extracted C_{SEN} values when the latter was smaller (more than 10% error below 300 pF).

The remaining error, at low C_{SEN} values, that can be seen in Figure 15 are caused by leakage currents at the microcontroller pins. The smaller C_{SEN} is, the greater this effect is.

Because the physical mechanisms that degrade the measurement accuracy vary significantly with process, temperature, time and other environmental variables, it is difficult to correct these errors.

DESIGN ALTERNATIVES

Possible Modifications

A list of modifications to the design follows:

- Increase resolution (increase k_1 and k_2)
  - Decrease T_{CLK}
  - Increase C_{INT}
  - Increase R_{CAL}
- Simplify the circuit and firmware
  - Use simpler extraction equations (e.g., ignore C_{PAR})
  - Remove R_{CAL} and the second measurement step (use the nominal value of C_{INT} in the extractions)
- Increase accuracy
  - Increase T_{SW} for better settling of V_{SEN} and V_{P3}
  - Improve V_{REF} accuracy by measuring the levels, V_{RL} and $V_{RH,}$ with an ADC internal to the microcontroller

Other Circuits

One common approach using a microcontroller is to measure the R-C step response time [7]. Its resolution is roughly constant, so it works well for larger capacitances. Its resolution for small capacitances is poor.

Another common approach is to use the capacitor to set an oscillator's frequency. 555 timer oscillators are quite common [8]. They suffer from parasitic capacitance to ground, and the fact that 555 timers from different manufacturers can be quite different. State variable oscillators using op amps are also used for applications demanding higher precision [3, 6]. They are more parasitic insensitive, but use many more external components.

The application note, AN990 [4], gives an overview of analog sensor conditioning circuits. It includes additional circuits for capacitive sensors.

SUMMARY

This application note gives hardware and firmware design engineers a circuit that detects small changes in capacitance (small values). This circuit gives consistent results over a short time frame, especially when the environment is not rapidly changing.

The design is simple and low cost; it only needs a PICmicro microcontroller and very few passive components. It uses the microcontroller to implement a switched capacitor circuit that gives more resolution to small capacitances.

Measurements of an actual circuit illustrate the operation of this circuit, and its resolution.

A discussion of alternate circuits help the designer select the best circuit for an application. Suggested design modifications help the designer choose a more appropriate design point.

Information on the circuit board and firmware used in the measurements is included in the appendicies.

REFERENCES

General Sensors

[1] "The OMEGA® Made in the USA Handbook™", Vol. 1, OMEGA Engineering, Inc., 2002.

[2] "The OMEGA® Made in the USA Handbook™", Vol. 2, OMEGA Engineering, Inc., 2002.

[3] AN866, "Designing Operational Amplifier Oscillator Circuits For Sensor Applications", Jim Lepkowski; Microchip Technology Inc., DS00866, 2003.

[4] AN990, "Analog Sensor Conditioning Circuits – An Overview", Kumen Blake, Microchip Technology Inc., DS00990, 2005.

[5] AN512, "Implementing Ohmmeter/Temperature Sensor", Doug Cox; Microchip Technology Inc., DS00512, 1997.

[6] AN895 "Oscillator Circuits For RTD Temperature Sensors", Ezana Haile and Jim Lepkowski; Microchip Technology Inc., DS00895, 2004.

Capacitive Sensors

[7] AN611, "Resistance and Capacitance Meter Using a PIC16C622", Rodger Richey; Microchip Technology Inc., DS00611, 1997.

[8] "Measure Relative Humidity With a PIC® MCU", Ricardo Jimenez and Claudia Angulo, Design Briefs, Electronic Design, p. 79-80, March 17, 2005.

Math Routines

[9] AN526, "PIC16C5X / PIC16CXXX Math Utility Routines", Amar Palacherla, Microchip Technology Inc., 1997.

[10] AN544, "Math Utility Routines", Frank J. Testa, Microchip Technology Inc., 1997.

[11] AN575, "IEEE 754 Compliant Floating Point Routines", Frank J. Testa, Microchip Technology Inc., 1997.

[12] AN617, "Fixed Point Routines", Frank J. Testa, Microchip Technology Inc., 1996.

[13] AN942, "Piecewise Linear Interpolation on PIC12/14/16 Series Microcontrollers", John Day and Steven Bible; Microchip Technology Inc., 2004.

Data Sheets

[14] MCP6001/2/4 Data Sheet, "1 MHz, Low-Power Op Amp", Microchip Technology Inc., DS21733, 2005.

[15] PIC16F684 Data Sheet, "14-Pin Flash-Based, 8-Bit CMOS Microcontrollers with nanoWatt Technology", Microchip Technology Inc., DS41202, 2004.

[16] PIC16C745/765 Data Sheet, "8-Bit CMOS Microcontrollers with USB", Microchip Technology Inc., DS41124, 2000.

APPENDIX A: MEASURED RESULTS

Table A-1 shows the results of measuring discrete capacitors with this method. The table shows the nominal values chosen, the capacitance values measured by a HP4285A LCR meter and the resulting counts produced by the circuit described in **Appendix B: "Circuit Board"**. This data is shown in Figure 15.

TABLE A-1: LISTING OF MEASURED RESULTS

C_{SEN} (F)		Counts (Note 1)	Extracted C_{SEN} (F) (Note 2)	
Nominal	Measured	k_1	with	without
0p (open)	—	28,688	47.9p	17.1p
15p	15.3p	22,880	60.0p	29.3p
22p	21.4p	21,111	65.0p	34.3p
27p	28.0p	19,492	70.4p	39.7p
33p	33.2p	18,425	74.5p	43.8p
39p	38.5p	17,306	79.3p	48.6p
47p	48.2p	15,592	88.1p	57.3p
56p	52.5p	14,944	91.9p	61.2p
68p	68.2p	13,024	105.4p	74.7p
100p	97.6p	10,547	130.2p	99.5p
150p	150.4p	7,644	179.6p	148.9p
180p	176.6p	6,716	204.4p	173.7p
220	211.0p	5,792	237.0p	206.3p
270p	271.6p	4,632	296.4p	265.7p
330p	318.0p	3,920	350.2p	319.5p
470p	448.4p	2,863	479.4p	448.7p
680p	656.0p	1,976	694.5p	663.8p
1.0n	0.991n	1,351	1.015n	0.985n
1.5n	1.406n	952	1.441n	1.410n
2.2n	2.202n	609	2.250n	2.219n
2.7n	2.550n	488	2.807n	2.776n
3.3n	3.715n	338	4.048n	4.017n
3.9n	4.013n	313	4.370n	4.339n
5.6n	5.874n	215	6.350n	6.319n
6.8n	6.915n	182	7.493n	7.462n
10n	9.42n	126	10.79n	10.76n

Note 1: For simplicity, the value of k_2 was assumed to be constant and equal to the value measured at 100 pF (k_2 = 6,890).

2: The extracted C_{SEN} is shown with (ignoring $4C_{PAR}$) and without (including $4C_{PAR}$) subtracting $4C_{PAR}$ = 30.7 pF.

APPENDIX B: CIRCUIT BOARD

The PCB described in this appendix was used for the measurements in **“Measured Results”**. PCB design files are available for downloading from Microchip’s web site (www.microchip.com):

- AN1014.zip (Contains all of the following files)
  - AN1014_SCH.dxf (schematic)
  - AN1014_PL1.bmp (top silk-screen plot)
  - AN1014_PL2.bmp (top metal plot)
  - AN1014_PL3.bmp (bottom metal plot)
  - AN1014_GER.zip (zipped Gerber files)

B.1 Schematic

The components have reasonable tolerances since this circuit is not accurate. R_CAL is 3.01 kΩ so that the RCALCSEN time constant is about 23 ns, which is much less than T_{CLK} = 500 ns.

The microcontroller pin assignments are:

- P1 = RC4
- P2 = RC1
- P3 = RC3
- P4 = RC2

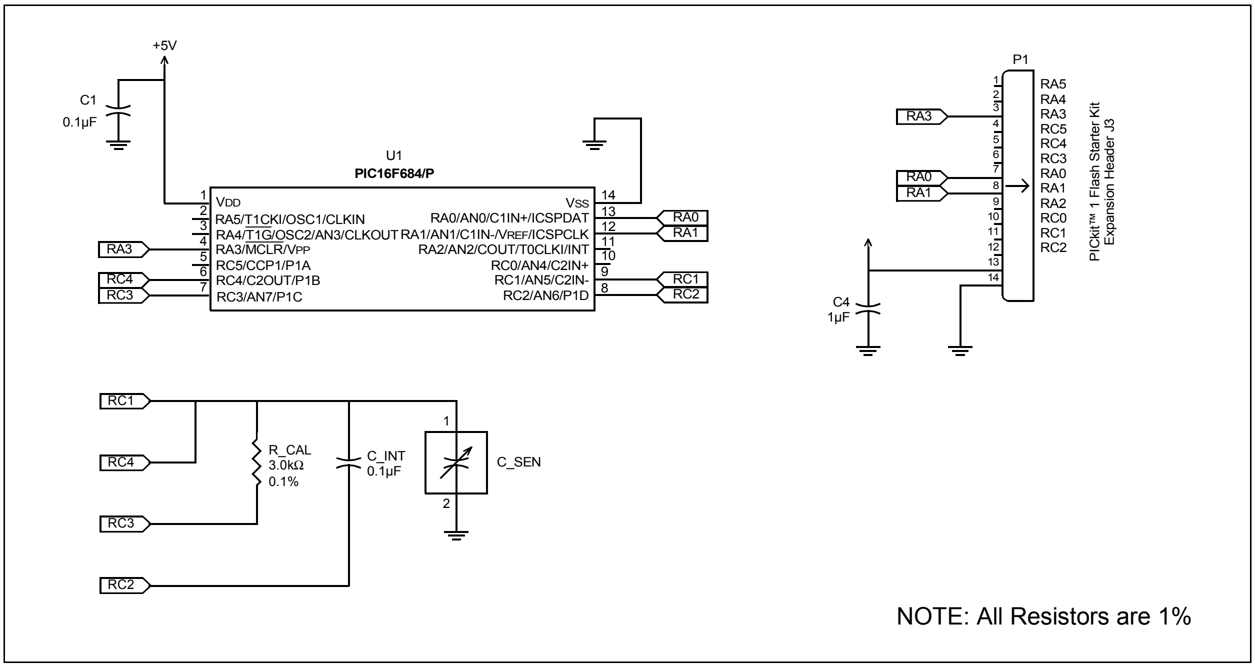

FIGURE B-1: *Schematic.*

B.2 Layout Plots

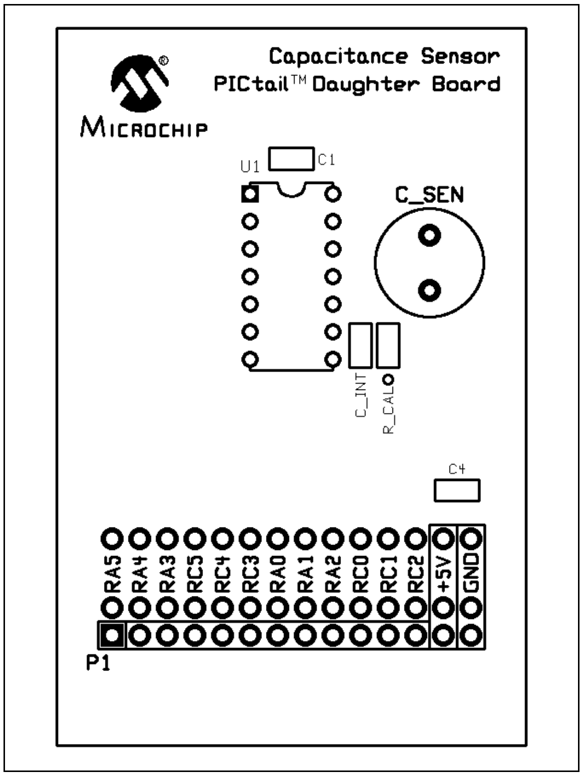

FIGURE B-2: *Top Silk-screen Layer.*

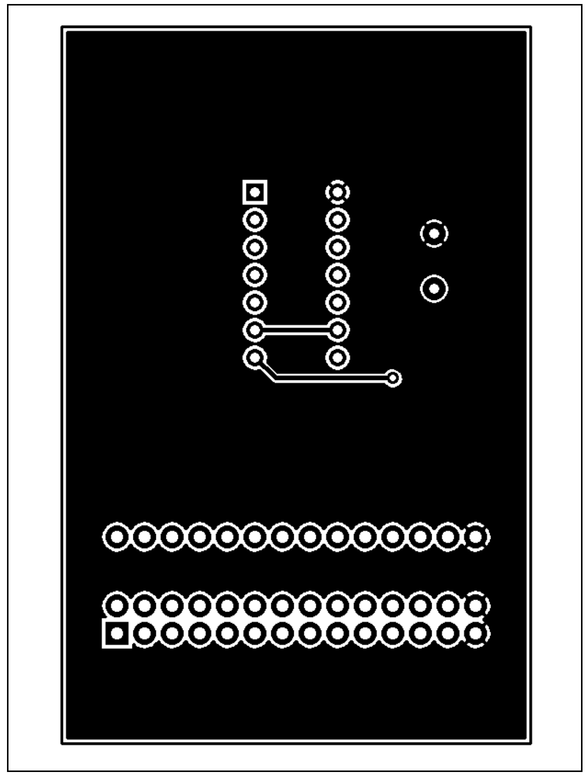

FIGURE B-4: *Bottom Metal Layer.*

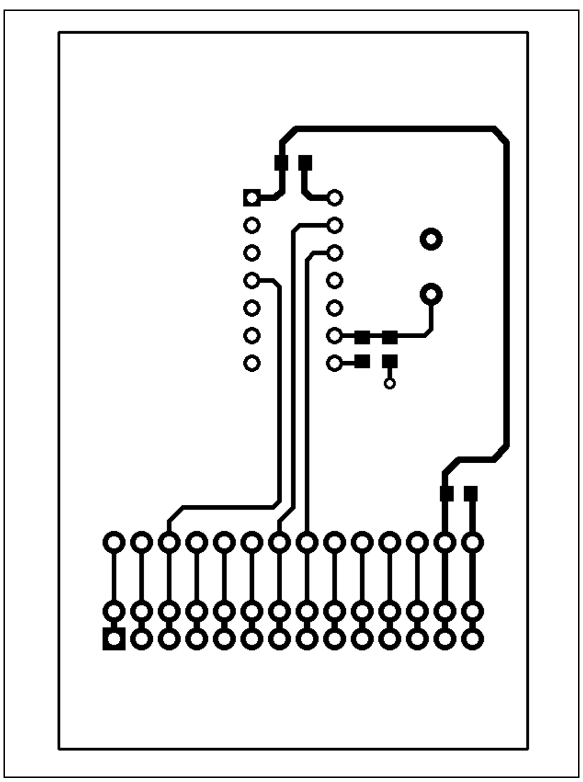

FIGURE B-3: *Top Metal Layer.*

B.3 Bill of Materials (BOM)

TABLE B-1: BILL OF MATERIALS

Qty	Reference	Description	Manufacturer	Part Number
1	C_SEN	Ceramic Disk or Monolithic Capacitor, Leaded, 0.200” spacing, 10 pF to 1 nF	—	—
1	C1	Ceramic Capacitor, 100 nF, 50V, 10%, X7R, 0805 SMD	Kemet	C0805C104K5RACTU
2	C_INT, C4	Ceramic Capacitor, 1.0 μF, 16V, 10%, X7R, 0805 SMD	Kemet	C0805C105K5RACTU
1	P1	Header, 1 × 14, 0.100" Pitch, Vertical, Gold	Molex/Waldom Electronics	22-28-4143
1	R_CAL	Chip Resistor, 3.01 kΩ, 1/8W, 1%, 0805 SMD	Yageo America	9C08052A3011FKHFT
1	U1	PIC16F684, PICmicro® microcontroller, 14-pin, 20 MHz, PDIP-14	Microchip Technology Inc.	PIC16F684-I/P
2	(for C_SEN)	Pin Receptacle, 0.015” to 0.025” dia., 0.060” Hole dia.	Mill-Max®	0669-0-15-15-30-27-10-0
1	(for U1)	IC Socket, 14-pin DIP, Gold Plated, 0.300", Low Profile	Mill-Max®	115-93-314-41-003000
1	—	Bare Printed Circuit Board	—	—

Note 1: The capacitor, C_SEN, is an arbitrary value inserted into the C_SEN socket pins by the user. The user may try values between 0 pF (open) to 1 μF to observe the circuit’s operation, if so desired.

APPENDIX C: FIRMWARE

The firmware file (AN1014.asm) is available for downloading from Microchip's web site at www.microchip.com.

TABLE C-1: MAIN ROUTINE

```
;----------------------------------------------------------------------
;----------------------------------------------------------------------
; Main Program
;----------------------------------------------------------------------
;----------------------------------------------------------------------

MAIN

;----------------------------------------
; Initialize PICmicro
;----------------------------------------

        call    INITIALIZE

;----------------------------------------
; Initialize Variables
;----------------------------------------

        bcf     FLAG, TRIP          ; clear tick counter trip flag.

        bsf     INTCON, GIE         ; enable global interrupts


MAINLOOP

        ; configure comparator module and voltage reference

        bsf     STATUS, RP0         ; ---- Select Bank 1 -----
        ;         76543210
        movlw   b'10001110'         ; configure comparator reference
        movwf   VRCON               ;   CVref Enabled; VRR High Range; VR=0x14

        bcf     STATUS, RP0         ; ---- Select Bank 0 -----
        ;         76543210
        movlw   b'00000010'         ; configure comparator module
        movwf   CMCON0

        clrf    C_COUNT_L           ; clear C_SEN / C_INT ratio count
        clrf    C_COUNT_H
        clrf    C_COUNT_U
```

TABLE C-1: MAIN ROUTINE (CONTINUED)

```
        ; remove all electrical charges (ground all I/O pins)

        bsf     STATUS, RP0         ; ---- Select Bank 1 -----

        ;            /------------ COM (RC4) digital output
        ;            |/----------- R_CAL (RC3) digital output
        ;            ||/---------- C_INT (RC2) digital output
        ;            |||
        ;          xx543210
        movlw   b'00000011'
        movwf   TRISC

        bcf     STATUS, RP0         ; ---- Select Bank 0 -----

        ;            /------------ COM (RC4) ground
        ;            |/----------- R_CAL (RC3) ground
        ;            ||/---------- C_INT (RC2) ground
        ;            |||
        ;          xx543210
        movlw   b'00000000'
        movwf   PORTC

        ; long delay to ensure all charges are removed

DELAY_LOOP
        btfss   FLAG, TRIP
         goto   DELAY_LOOP          ; no, loop
        bcf     FLAG, TRIP          ; clear tick counter trip flag.

        ; charge C_SEN
CHARGE
        bsf     STATUS, RP0         ; ---- Select Bank 1 -----

        ;            /------------ COM (RC4) digital output
        ;            |/----------- R_CAL (RC3) digital input (high impedance)
        ;            ||/---------- C_INT (RC2) digital input (high impedance)
        ;            |||
        ;          xx543210
        movlw   b'00001111'
        movwf   TRISC

        bcf     STATUS, RP0         ; ---- Select Bank 0 -----

        ;            /------------ COM (RC4) Vdd (digital output)
        ;            |/----------- R_CAL (RC3) (high impedance)
        ;            ||/---------- C_INT (RC2) (high impedance)
        ;            |||
        ;          xx543210
        movlw   b'00010000'
        movwf   PORTC

        ; share charges between C_SEN and C_INT

        bsf     STATUS, RP0         ; ---- Select Bank 1 -----

        ;            /------------ COM (RC4) digital input (high impedance)
        ;            |/----------- R_CAL (RC3) digital input (high impedance)
        ;            ||/---------- C_INT (RC2) digital output
        ;            |||
        ;          xx543210
        movlw   b'00011011'
        movwf   TRISC
```

TABLE C-1: MAIN ROUTINE (CONTINUED)

```
        ; compare voltage across C_INT to CVref ( 0.6875 * Vdd )

        bcf     STATUS, RP0         ; ---- Select Bank 0 -----

        btfss   CMCON0, 7           ; is C_SEN > CVref?
         goto   AHEAD               ;   yes, we are done, jump ahead
                                    ;   no, charge C_SEN again and
                                    ;       keep count how many loops

        incf    C_COUNT_L, F        ; save count
        btfsc   STATUS, Z
         incf   C_COUNT_H, F
        btfsc   STATUS, Z
         incf   C_COUNT_U, F

        goto    CHARGE

AHEAD

        ; send capacitance count out via SPI

        movfw   C_COUNT_U
        call    SPI_PutByte
        movfw   C_COUNT_H
        call    SPI_PutByte
        movfw   C_COUNT_L
        call    SPI_PutByte

        ; discharge ( C_INT + C_SEN ) through R_CAL and time

        clrf    TMR1L               ; clear Timer1
        clrf    TMR1H

        bsf     STATUS, RP0         ; ---- Select Bank 1 -----

        ;         76543210
        movlw   b'10100110'         ; configure comparator reference
        movwf   VRCON               ;   CVref Enabled; VRR Low Range; VR=0x06

        ;            /------------- COM (RC4) digital input (high impedance)
        ;            |/------------ R_CAL (RC3) digital output
        ;            ||/----------- C_INT (RC2) digital output
        ;            |||
        ;         xx543210
        movlw   b'00010011'
        movwf   TRISC

        bcf     STATUS, RP0         ; ---- Select Bank 0 -----

        ;            /------------- COM (RC4) (high impedance)
        ;            |/------------ R_CAL (RC3) ground
        ;            ||/----------- C_INT (RC2) ground
        ;            |||
        ;         xx543210
        movlw   b'00010000'
        movwf   PORTC

        bsf     T1CON, TMR1ON       ; turn on Timer1, begin counting
```

TABLE C-1: MAIN ROUTINE (CONTINUED)

```
        ; compare voltage across C_INT to CVref ( 0.25 * Vdd )

        btfss   CMCON0, 7           ; is C_INT > CVref?
         goto   $ - 1               ;   yes, loop

        bcf     T1CON, TMR1ON       ;   no, turn off (stop) Timer1

        ; send R_CAL discharge counts (time) out via SPI

        movfw   TMR1H               ; report Timer1 contents
        call    SPI_PutByte
        movfw   TMR1L
        call    SPI_PutByte


        goto    MAINLOOP
```

Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
- There are dishonest and possibly illegal methods used to breach the code protection feature. All of these methods, to our knowledge, require using the Microchip products in a manner outside the operating specifications contained in Microchip's Data Sheets. Most likely, the person doing so is engaged in theft of intellectual property.
- Microchip is willing to work with the customer who is concerned about the integrity of their code.
- Neither Microchip nor any other semiconductor manufacturer can guarantee the security of their code. Code protection does not mean that we are guaranteeing the product as "unbreakable."

Code protection is constantly evolving. We at Microchip are committed to continuously improving the code protection features of our products. Attempts to break Microchip's code protection feature may be a violation of the Digital Millennium Copyright Act. If such acts allow unauthorized access to your software or other copyrighted work, you may have a right to sue for relief under that Act.

QUALITY MANAGEMENT SYSTEM
CERTIFIED BY DNV
ISO/TS 16949:2002

Microchip received ISO/TS-16949:2002 quality system certification for its worldwide headquarters, design and wafer fabrication facilities in Chandler and Tempe, Arizona and Mountain View, California in October 2003. The Company's quality system processes and procedures are for its PICmicro® 8-bit MCUs, KEELOQ® code hopping devices, Serial EEPROMs, microperipherals, nonvolatile memory and analog products. In addition, Microchip's quality system for the design and manufacture of development systems is ISO 9001:2000 certified.

WORLDWIDE SALES AND SERVICE

AMERICAS

Corporate Office
2355 West Chandler Blvd.
Chandler, AZ 85224-6199
Tel: 480-792-7200
Fax: 480-792-7277
Technical Support:
http://support.microchip.com
Web Address:
www.microchip.com

Atlanta
Alpharetta, GA
Tel: 770-640-0034
Fax: 770-640-0307

Boston
Westborough, MA
Tel: 774-760-0087
Fax: 774-760-0088

Chicago
Itasca, IL
Tel: 630-285-0071
Fax: 630-285-0075

Dallas
Addison, TX
Tel: 972-818-7423
Fax: 972-818-2924

Detroit
Farmington Hills, MI
Tel: 248-538-2250
Fax: 248-538-2260

Kokomo
Kokomo, IN
Tel: 765-864-8360
Fax: 765-864-8387

Los Angeles
Mission Viejo, CA
Tel: 949-462-9523
Fax: 949-462-9608

San Jose
Mountain View, CA
Tel: 650-215-1444
Fax: 650-961-0286

Toronto
Mississauga, Ontario,
Canada
Tel: 905-673-0699
Fax: 905-673-6509

ASIA/PACIFIC

Australia - Sydney
Tel: 61-2-9868-6733
Fax: 61-2-9868-6755

China - Beijing
Tel: 86-10-8528-2100
Fax: 86-10-8528-2104

China - Chengdu
Tel: 86-28-8676-6200
Fax: 86-28-8676-6599

China - Fuzhou
Tel: 86-591-8750-3506
Fax: 86-591-8750-3521

China - Hong Kong SAR
Tel: 852-2401-1200
Fax: 852-2401-3431

China - Qingdao
Tel: 86-532-8502-7355
Fax: 86-532-8502-7205

China - Shanghai
Tel: 86-21-5407-5533
Fax: 86-21-5407-5066

China - Shenyang
Tel: 86-24-2334-2829
Fax: 86-24-2334-2393

China - Shenzhen
Tel: 86-755-8203-2660
Fax: 86-755-8203-1760

China - Shunde
Tel: 86-757-2839-5507
Fax: 86-757-2839-5571

China - Wuhan
Tel: 86-27-5980-5300
Fax: 86-27-5980-5118

China - Xian
Tel: 86-29-8833-7250
Fax: 86-29-8833-7256

ASIA/PACIFIC

India - Bangalore
Tel: 91-80-2229-0061
Fax: 91-80-2229-0062

India - New Delhi
Tel: 91-11-5160-8631
Fax: 91-11-5160-8632

India - Pune
Tel: 91-20-2566-1512
Fax: 91-20-2566-1513

Japan - Yokohama
Tel: 81-45-471- 6166
Fax: 81-45-471-6122

Korea - Gumi
Tel: 82-54-473-4301
Fax: 82-54-473-4302

Korea - Seoul
Tel: 82-2-554-7200
Fax: 82-2-558-5932 or
82-2-558-5934

Malaysia - Penang
Tel: 60-4-646-8870
Fax: 60-4-646-5086

Philippines - Manila
Tel: 63-2-634-9065
Fax: 63-2-634-9069

Singapore
Tel: 65-6334-8870
Fax: 65-6334-8850

Taiwan - Hsin Chu
Tel: 886-3-572-9526
Fax: 886-3-572-6459

Taiwan - Kaohsiung
Tel: 886-7-536-4818
Fax: 886-7-536-4803

Taiwan - Taipei
Tel: 886-2-2500-6610
Fax: 886-2-2508-0102

Thailand - Bangkok
Tel: 66-2-694-1351
Fax: 66-2-694-1350

EUROPE

Austria - Wels
Tel: 43-7242-2244-399
Fax: 43-7242-2244-393

Denmark - Copenhagen
Tel: 45-4450-2828
Fax: 45-4485-2829

France - Paris
Tel: 33-1-69-53-63-20
Fax: 33-1-69-30-90-79

Germany - Munich
Tel: 49-89-627-144-0
Fax: 49-89-627-144-44

Italy - Milan
Tel: 39-0331-742611
Fax: 39-0331-466781

Netherlands - Drunen
Tel: 31-416-690399
Fax: 31-416-690340

Spain - Madrid
Tel: 34-91-708-08-90
Fax: 34-91-708-08-91

UK - Wokingham
Tel: 44-118-921-5869
Fax: 44-118-921-5820

10/31/05