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AN58829

Infrared Thermometer using PSoC®

Author: Sanjeev Kumar K.
Associated Project: Yes
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To get the latest version of this application note, or the associated project file, please visit http://www.cypress.com/go/AN58829

This application note describes how to build an infrared thermometer using PSoC® 1. This application note also discusses the theory of Infrared thermometers in brief. This design uses no external active components to buffer, amplify, and detect the signal source.

Contents

Introduction

Infrared thermometers are widely used in medical and industrial applications.

- They measure temperature without any contact with the object for measurement.
- They measure a wide range of temperature.
- Their accuracy is comparable with other types of thermometers.

Infrared Thermometer Principle

Infrared thermometer uses thermopile sensor to measure temperature. Thermopile sensor has an IR absorber connected with a series of thermocouples. The cold contacts of the thermocouples are connected to a known reference. These thermocouples measure the object temperature. The ambient temperature of the sensor is measured using a thermistor.

Figure 1. Thermopile

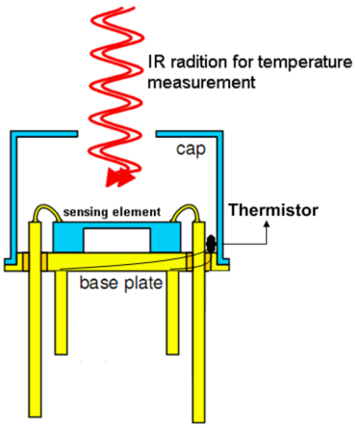
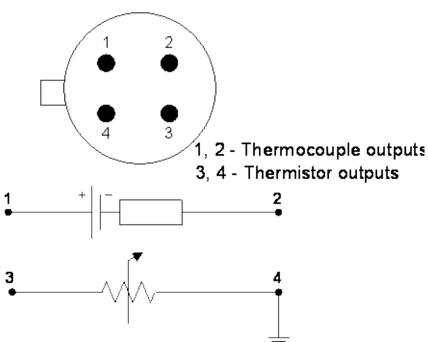


Figure 2. Thermopile Pin Details



A thermopile sensor has four pins, two of them give the voltage across the series of thermocouples and the other two pins are used to measure thermistor resistance. The thermopile sensor generates a voltage, which is proportional to the incident infrared (IR) radiation power. You can deduct the object's temperature from the thermopile signal because every object emits IR radiation with a power, which is a strict function of its temperature.

The total radiation power P_{obj} emitted by an object of temperature T_{obj} can be expressed as Equation 1

Equation 1 $$P_{obj} = \sigma .\varepsilon .T_{obj}$$

with σ being the Stefan-Boltzmann constant and ε the so-called emission factor (or emissivity) of the object. In an ideal case ε has the values '1' and '0'. For most substances, the emission factor lies in the range 0.85 to 0.95. Equation 1 is called the Stefan-Boltzmann law.

The heat-balance equation relates the net power P_{rad} received by the thermopile to two temperatures: T_{obj} and T_{amb}. In most cases the instrument's temperature T_{obj} equals (or is near to) the temperature of the ambient T_{amb}. Therefore, refer to this value as Ta, the ambient temperature. The total heat power P_{rad} received from the object at temperature T_{obj} is given to

Equation 2 $$P_{rad} = k.\varepsilon.(T_{obj}^4 - T_a^4)$$

Thermopile generates a voltage V_{tp} which is proportional to the incident radiation.

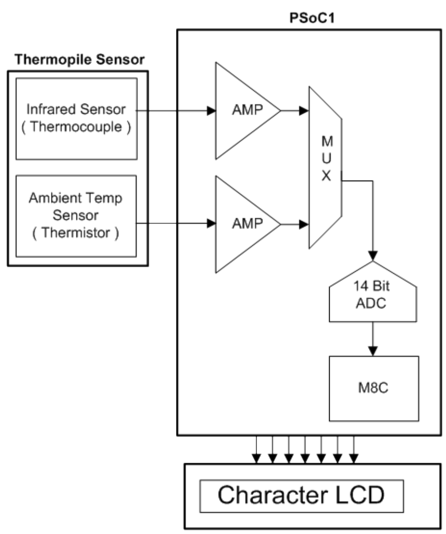
Equation 3 $$V_{TP} = S \cdot k \cdot \varepsilon \cdot (T_{obj}^4 - T_a^4)$$

Equation 4 $$V_{TP} = K(T_{obj}^4 - T_a^4)$$

Where S is sensitivity is calibration constant and ε is emissivity.

Usually, sensitivity of the thermocouple is in the range of microvolts if the ambient temperature is fixed. An empirical relation between V_{tp} and T_{obj} or a look up table gives the object temperature. From Equation 2 it is evident that V_{tp} changes according to changes in ambient temperature. This ambient temperature needs to be compensated to get the correct object temperature.

Figure 3. Block Diagram



Steps to Calculate Object Temperature

1. Measure thermopile voltage (V_{tp})
2. Measure thermistor resistance (R_a) and calculate ambient temperature (T_a)
3. Calculate ambient temperature compensation and object temperature

Measure Thermopile Voltage

Usually the output of thermopile is in the order of a few µV, so take care for offset and SNR.

As an example, a sensor from Perkin Elmer TPS23B is used. The average sensitivity ($\Delta V_{TP}/\Delta T$) of the thermopile is 50 µV/K or 1.845 mV at 309.9K, which is the typical human body temperature.

Thermopile voltage can be amplified using correlated double sampling method (CDS). CDS is followed to reduce offset and low frequency noise cancellation. For more details on CDS, refer Application Note AN2226, *Correlated Double Sampling*. A brief about this method is reproduced here for reference. Consider the two ends of a voltage source (thermopile) connected as the inputs to the programmable gain amplifier (PGA). This is then connected to the analog to digital convertor (ADC) that has offsets. The block diagram of the connections is shown in Figure 4.

When the MUX selection is input 1, the Vout would be as shown in Equation 3.

Equation 5 $$Vout1 = Vsource + Voffset1 + Vnoise1$$

When the MUX selection is changed to input 2, the Vout would be changed to Equation 4.

Equation 6 $$Vout2 = Voffset2 + Vnoise2$$

Voffset1 and Voffset2 are equal as the offset is constant over time. So when you subtract Vout2 from Vout1, the offset is cancelled and the result is:

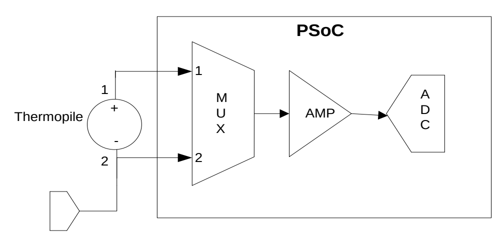
Equation 7 $$Vtp = Vsource + Vnoise1 - Vnoise2$$

The noise subtraction in time gives a result of low frequency noise cancelation response for the system .This response affects only the noise and not the actual signal, thus cancelling the low frequency noise. The details about the math for this waveform are given in AN2226.

IIR Filter

IIR low pass filter is implemented in software to reduce the high frequency noise. In other words, the implementation essentially takes a part of the old value and adds it to a part of the new value. The theory and implementation behind the IIR filter in software are provided in the Application Note AN2099, *Single-Pole IIR Filters*. The voltage measurement for temperature sensor is well filtered by the CDS and IIR filter. The value is then used for both thermopile voltage and ambient temperature compensation.

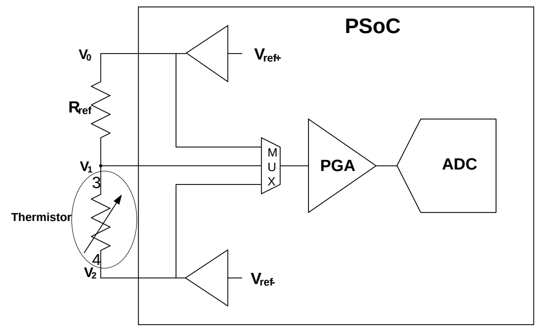
Figure 4. Thermopile Connections Block Diagram



Measure Thermistor Resistance (Ra) and Calculate Ambient Temperature

Thermistor resistance can be measured by 'PSoC Style' as described in detail in the application note, AN2017.

Figure 5. Thermistor Connection Block Diagram



A voltage divider is constructed using a reference Rref and thermistor inside the sensor. V0 and V2 are voltage references RefHi and RefLo from PSoC. A mux is switched between V0, V1, and V2. The signal from the mux is fed to a PGA of gain 'G', which is read by an ADC.

Equation 8 $$R_{thermistor} = R_{ref} * \left(\frac{V_1 - V_2}{V_0 - V_1} \right)$$

Find the thermistor value either in the thermistor lookup table provided by the sensor manufacturer or using Stein Harts equation to locate the ambient temperature T_a.

Object temperature calculation

To calculate the object temperature, follow these steps:

1. Locate the equivalent temperature T_a in the lookup table provided by the sensor manufacturer.
2. Locate the equivalent temperature of V_{tp} (from Equation 5) to T_{tp}.
3. The object temperature is calculated by adding T_{tp} to T_a.

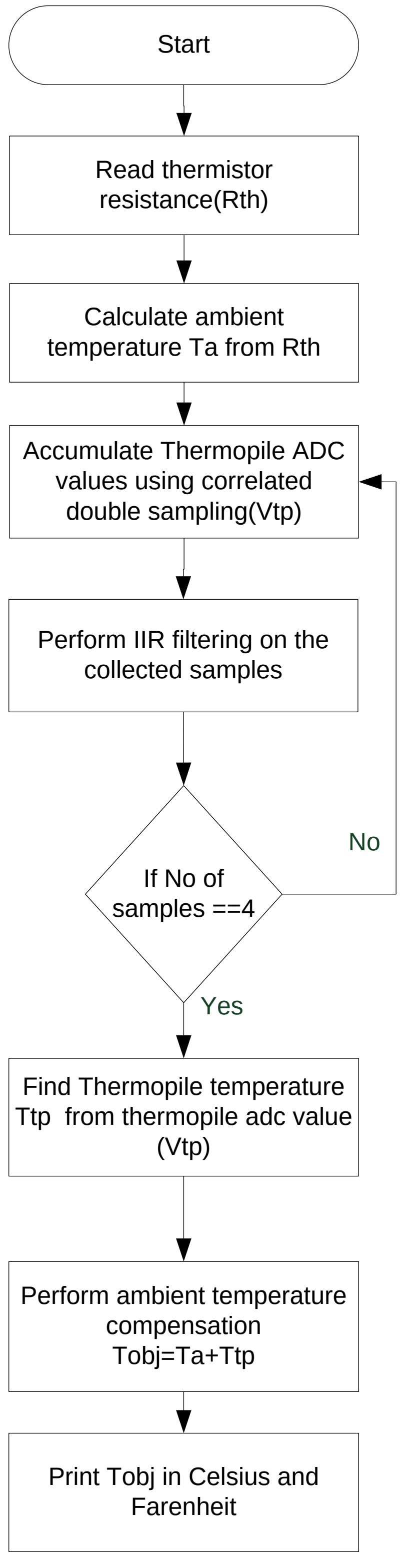
Equation 9 $$T_{obj} = T_{tp} + T_a$$

Software

The software flow is as follows:

- Create lookup table
- Read ADC values for thermistor and thermo couple
- Process ADC values for temperature

Figure 6. Software Flow



Create Lookup Table

The lookup table for a thermistor is created using the table from Perkin-Elmer data sheet, which describes the thermistor's voltage against temperature characteristics.

Table 1. Thermistor Data

Temperature	Rnom	Temperature	Rnom
°C	Ω	°C	Ω
-20	915479	45	44175
-15	694575	50	36497
-10	531349	55	30303
-5	409715	60	25280
0	318336	65	21187
5	249149	70	17836
10	196369	75	15079
15	155815	80	12800
20	124439	85	10910
25	100000	90	9334
30	80843	95	8016
35	65732	100	6908
40	53743		

Table 1 has temperature mapped against resistance value. Consider Rnom (Rth) as the nominal resistance. Thermistor can be calculated from Equation 8.

Table 2. Thermocouple Data

Temperature	Typ	Temperature	Typ
°C	mV	°C	mV
-20	-1.55	40	0.71
-10	-1.29	50	1.25
0	-0.98	60	1.84
10	-0.61	70	2.48
20	-0.21	80	3.16
25	0	90	3.9
30	0.23	100	4.7

Table 2 represents the variation in thermopile voltage with temperature difference between the hot and cold ends of the thermopile. The reference temperature is taken as 25 degrees Celsius; by subtracting 25 from the left column, you get the correlation between the temperature difference and the milli volt output.

Because the temperature scale moves in steps of 5 near 25 degrees and steps of 10 farther away, it is difficult to index in an array. Therefore, it is beneficial to linearly interpolate between the temperature values so that the entire array is in steps of 5 degrees.

The thermopile voltage is amplified and then fed to the ADC. Therefore, you can construct a table that maps ADC voltages directly to a temperature difference.

Read ADC Values

This function captures and accumulates 32 thermopile and thermistor values into variables tp_avg and tr_avg respectively. It then calculates the average of those values and stores the average in variables called tp and tr. Correlated doubling and IIR filtering is performed in this part of code.

Process ADC Values for Temperature

The temperature is calculated from the thermistor resistance R_{th} and thermopile voltage V_{tp} values using the following algorithm:

- Check for overflow and underflow; if condition exists, exit with an error.
- Find the closest value in the appropriate table for the ADC value.
- Perform linear interpolation between the closest two values.
  - For the thermopile, the interpolation formula is as follows:

$$T_{tp} = -45 + 5i + 5 * \left(\frac{V_{tp} - U_{tp}Cal[i]}{U_{tp}Cal[i+1] - U_{tp}Cal[i]} \right)$$

  - For the thermistor, the interpolation formula is follows:

$$T_a = -20 + 5i + 5 * \left(\frac{R_{th} - U_{th}Cal[i]}{U_{th}Cal[i+1] - U_{th}Cal[i]} \right)$$

Where

$\mathbf{U_{th}}$ and $\mathbf{U_{tp}}$ are lookup table entries for thermistor and thermocouple respectively.

i is the index of lookup table, or temperature

Ambient temperature can also be calculated from Stein Hart's equation:

$$T_C = \frac{1}{A + B \cdot \ln(R) + C \cdot \ln(R)^3} - 273.15$$

Where:

A, **B**, and **C** are empirical constants that are determined from thermistor characteristics

R is the thermistor’s resistance in ohms.

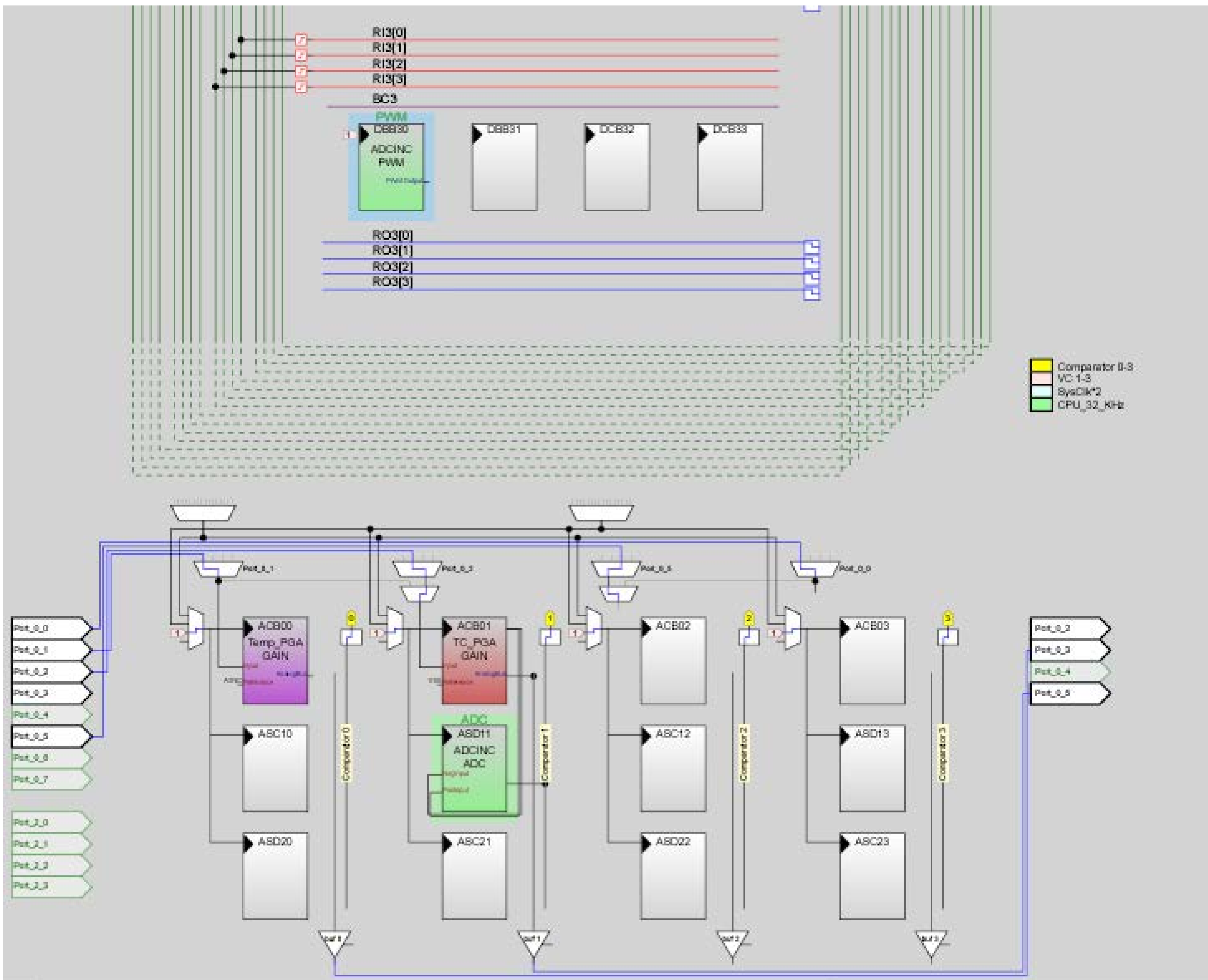
T_C is the temperature in Celsius.

To increase accuracy, temperature is calculated from ADC values using the polynomial provided by the sensor manufacturer or from a bigger lookup table, which has much closer values of temperature.

Ambient temperature compensation is performed using Equation 10

Equation 10 $$T_{obj} = T_{tp} + T_a$$

Figure 7. PSoC Internal Routing Diagram



Schematic

Figure 8 shows the schematic of infrared and Table 3 provides details of each net.

Figure 8. Schematic

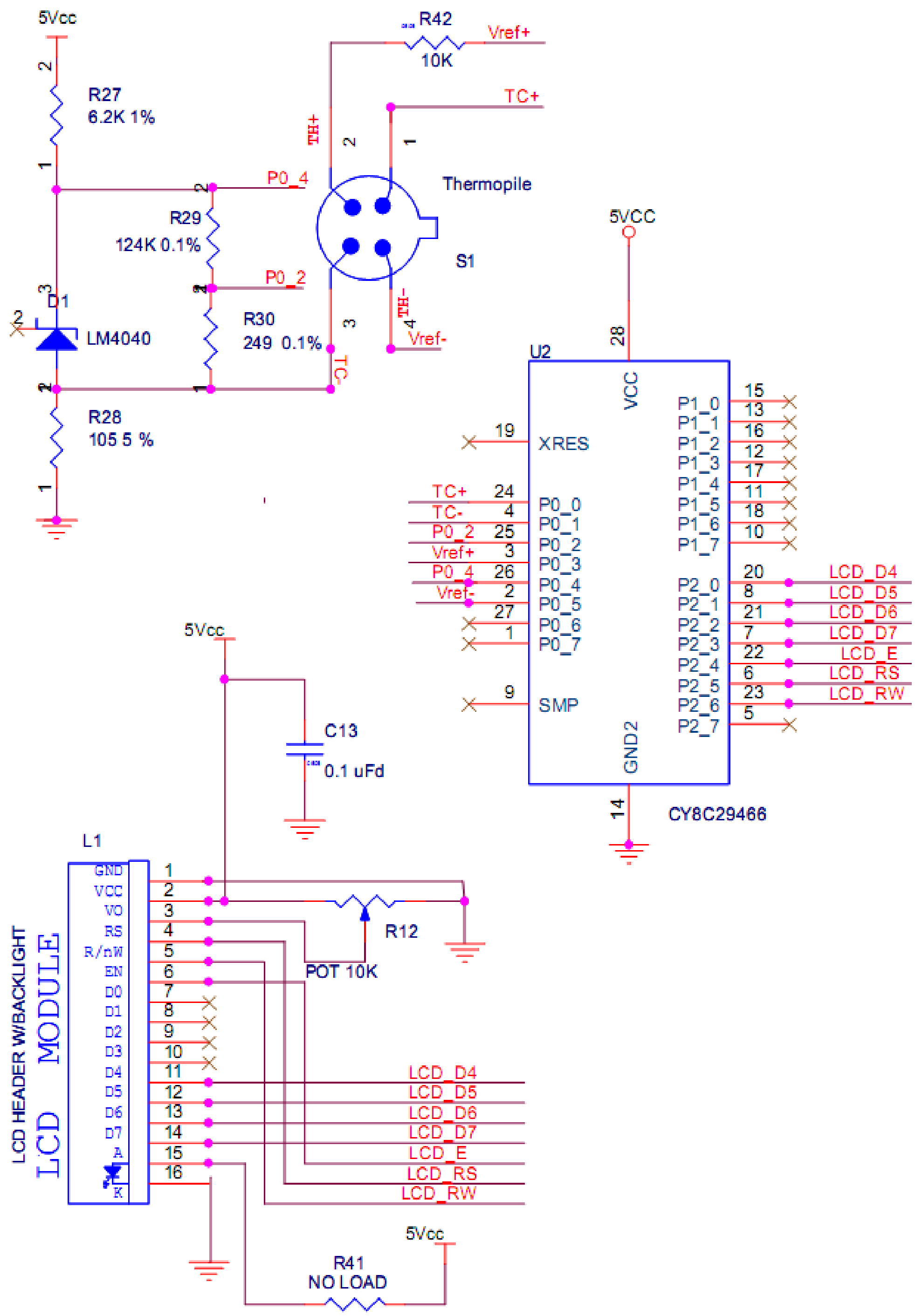


Table 3. Net Details

Net Name	Details
TH+ and TH-	Thermistor output of thermopile sensor
TC+ and TC-	Thermocouple output of thermopile sensor
AGND	Analog ground
LCD_xx	LCD data and control lines
Vref- and Vref+	Reference voltages from PSoC

Accuracy of Object Temperature

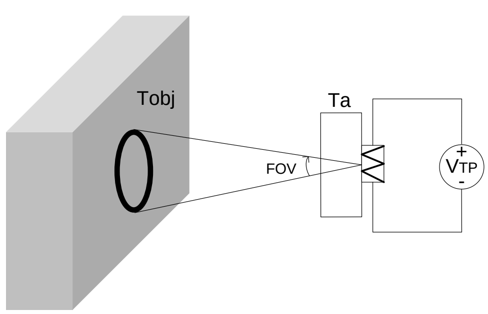
The accuracy of object temperature depends on the following parameters. These parameters help to increase accuracy from 98 to 99 percent:

- Field of view angle (FOV) of IR radiation from object to sensor
- Type of casing and optics used in sensor
- Distance between sensor and object
- Calibration of the device

Field of View Angle

FOV angle is the angular measure of the cone opening from which the sensor receives radiation as Figure 9 shows.

Figure 9. FOV Angle



V_{tp} varies with $\sin^2$ (FOV) and accuracy can be increased by keeping FOV nearer to 90 degrees.

Casing and Optics in the Sensor

The type of casing used around the sensor affects its accuracy. Therefore, take special care when enclosing the sensor. More details of the case designing can be got from the sensor manufacturer. Figure 10 shows the casing built for Perkin Elmer TPS23B sensor. Sensor manufacturers can be contacted for more details about the design of casing.

Figure 10. Casing

Distance between Sensor and Object

The distance between the sensor and object produces a variation in readings. Therefore, the typical distance provided by the sensor manufacturer should be maintained. For sensor TPS23B, the distance is 2 to 3 cm. Proximity sense in PSoC can be used to maintain correct distance between sensor and object (human body) thereby reducing the error due to incorrect positioning.

Calibration

Follow these steps for calibration:

1. Measure the offset of your device: The thermopile sensor is exposed to a complete thermal equilibrium in a closed environment. In front of the window, the same temperature is presented as the equilibrium temperature. Now the sensor gives 0 V, which is used to calibrate the offset of the electronics. Alternatively, a precise voltmeter is used for the thermopile output to measure how good the thermal equilibrium is.
2. The voltage V_T_{Obj} (exp) is used to scale the sensors output in future and get a calibration constant *k*. From the table or from the polynomial, you get a voltage of a typical sensor V_T_Obj (theor) by calculating:

$$V_{Tobj}(theor) := V_{Tobj}(Radiation\_source) - V_{Tobj}(Sensor)$$

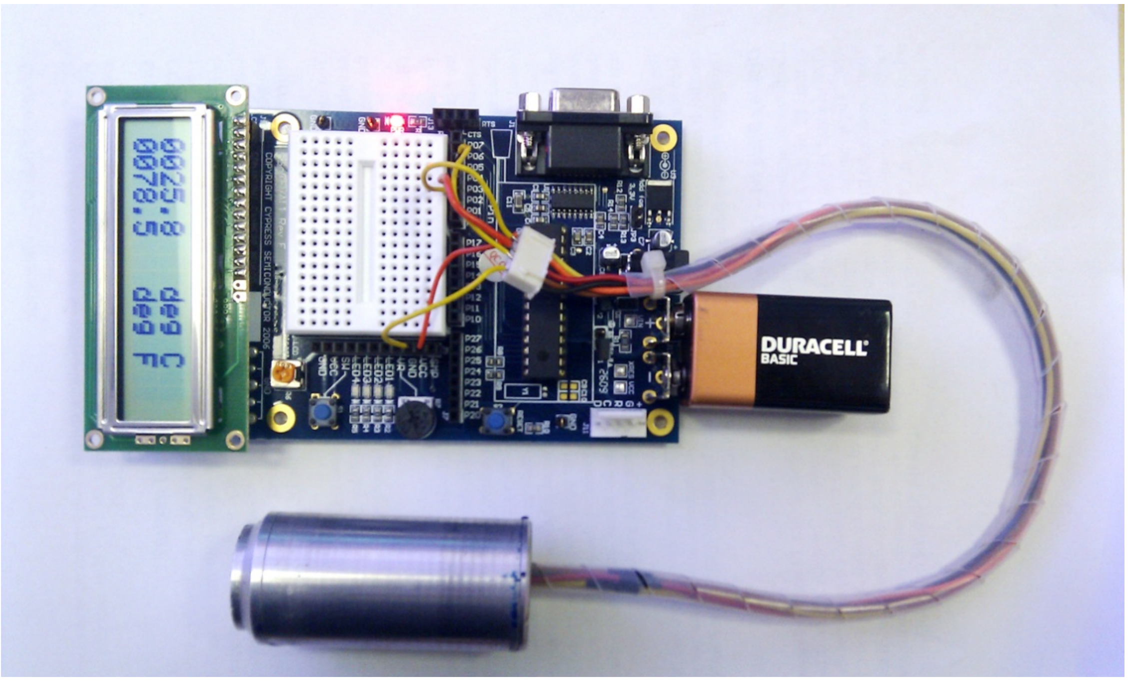
Calibration constant *k* is calculated as

$$K = \frac{V_{Tobj}(theor)}{V_{Tobj}(Sensor)}$$

3. During measurements, all thermopile voltages must first be multiplied with k before further processing with polynomials of lookup-tables.

   The look up table in the attached project is calibrated for the hardware setup including casing sensor etc.

Figure 11. IR Thermometer



Summary

This application note explains how to build an infrared thermometer with zero external active analog components. The project attached with this application note does not include any calibration routine.

Related Application Notes

AN2017 –- PSoC® 1 Temperature Measurement with Thermistor

AN2226–- PSoC® 1 –- Using Correlated Double Sampling to Reduce Offset, Drift, and Low Frequency Noise

AN2099–- PSoC® 1, PSoC 3, and PSoC 5LP–- Single-Pole Infinite Impulse Response (IIR) Filters

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Revision	ECN	Orig. of Change	Submission Date	Description of Change
**	2855922	KUK	1/18/10	New application note
*A	3126363	KUK	01/03/2011	Software version changed from PSoC designer 5.0 to 5.1 Device name in abstract updated from PSoC® to PSoC® 1 AN Changed from CapSense category to PSoC1 category Updated details on casing Updated project to PSoC designer 5.1
*B	3941788	KUK	03/22/2013	Software Version as “PSoC® Designer™ 5.3”. Updated Abstract. Updated Infrared Thermometer Principle (Updated Figure 2 and Figure 3). Removed the Note “Medical demo daughter card is build for internal cypress demo and the same is not sold in cypress web.” below Figure 11. Updated Summary. Updated to new template. Updated project to PSoC designer 5.3. Updated code to match latest CY coding standards.
*C	4729551	ASRI	04/17/2015	Updated Software Version “PSoC® Designer™ 5.4” in page 1. Updated attached associated project with PSoC designer 5.4. Updated to new template. Completing Sunset Review.

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