Application Note
Designing a Low-Cost, High-Accuracy Infrared Thermometer

TEXAS INSTRUMENTS

ABSTRACT

An infrared (IR) thermometer can measure temperature without contact, which can help ease the spread of a contact infection. Highly-accurate, non-contact temperature measurement is one such necessity that is needed everywhere to identify persons at risk. This design demonstrates a low-cost, high-accuracy IR thermometer solution capable of sensing accurate temperature up to a distance of 10 cm. The design uses a 24-bit sigma-delta ADC and an ultra-low-noise signal chain to provide small offset and drift with temperature. The design implements a complete solution with a low-cost MCU, LCD interface, and GPIO controls. The design operates from a 3-V AA battery down to 2.2 V and has < 1 µA of total standby current consumption making it ideal for battery-powered systems.

Table of Contents

Trademarks
All trademarks are the property of their respective owners.

1 Introduction

An IR thermometer can measure temperature without contact, which can help ease the spread of a contact infection. A high-performance analog-to-digital converter (ADC) is required to sample high-precision signals collected by the analog infrared temperature sensor – typically, a single pixel thermopile sensor. The thermometer provides temperature readings by placing the sensor near the object without actually touching it. It provides portable and instant on-the-spot readings to screen patients and gauge the health of a person while still limiting exposure risk of the tester.

This application note describes in detail the complete design of an IR-based thermometer for patient monitoring. The design is implemented using a thermopile infrared sensor which produces an analog voltage proportional to the temperature difference between the object and the ambient. Figure 1-1 shows the system-level block diagram of the IR thermometer. The key advantage of this architecture is that it provides very high performance at a very low cost.
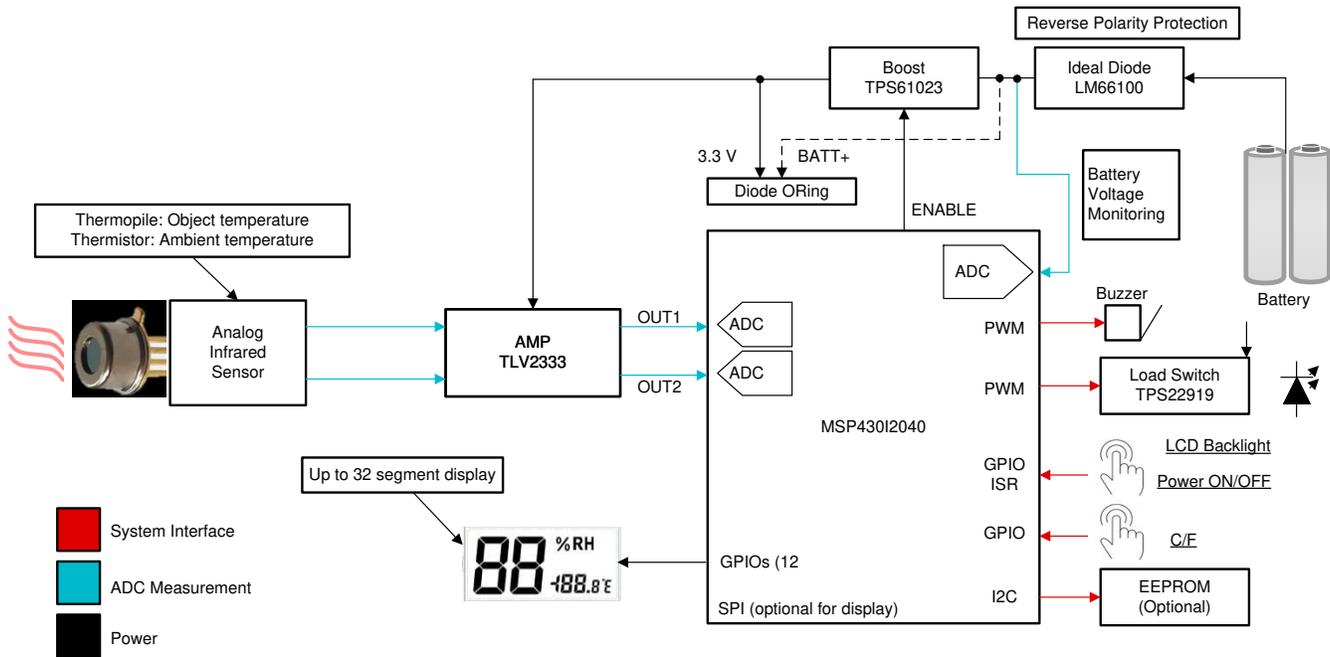
Figure 1-1. System-Level Block Diagram of the IR Thermometer Design

The heart of the system is the MSP430I2040, 16-MHz metering AFE with four 24-bit sigma-delta ADCs, two 16-bit timers, 16KB flash, and 1KB RAM, which provides exactly the adequate resources to implement the temperature measurement. It controls the complete system, in terms of power management, small signal measurement, digitization, and user interface such as display, input buttons, buzzer, and so forth.

2 Key Specifications and Features

The thermometer has the following specifications and features:

- High temperature accuracy up to ±0.2°C with distance up to 10 cm can be obtained by precise calibration of the sensor (this design does not incorporate calibration)
- Object measurement range of 30°C to 45°C with an ambient temperature range of 16°C to 40°C (supports from 0°C to 50°C)
- Supports up to 32-segment LCD using the GPIO pins, additional support of I2C and SPI based smart LCDs
- °C/°F temperature display, changeable using a push button
- Automatic turn ON/OFF of backlight LED; battery reverse polarity protection

3 System Design Challenges and Part Selection

For a high-level overview, read the technical article *How to design an infrared thermometer quickly*.

3.1 Design Challenge #1: Accuracy of Medical Measurement

A high level of precision for each measurement is required, down to ±0.2°C. While the signal from thermopile is very small (less than a few mV), the variation with temperature is even smaller and can be < 10 µV/°C for some sensors. Figure 3-1 shows a reference curve of one such sensor showing thermopile output versus object temperature. Precisely and accurately measuring such a signal in a noisy environment is a challenge.
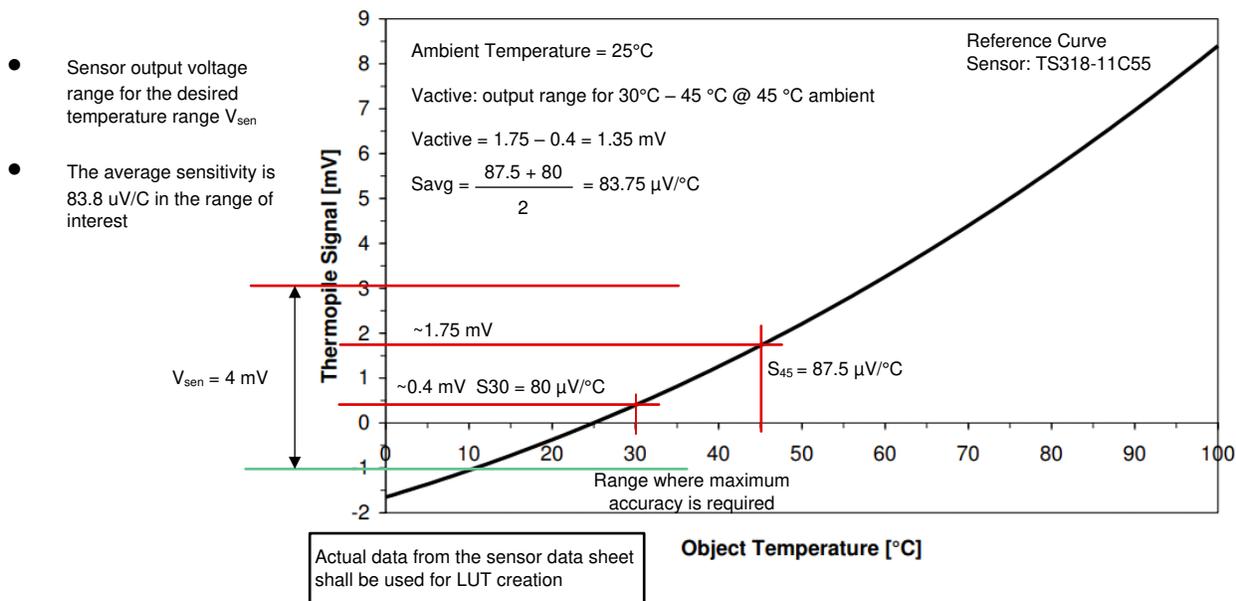
- Sensor output voltage range for the desired temperature range V$_{sen}$

- The average sensitivity is 83.8 uV/C in the range of interest

Ambient Temperature = 25°C

Vactive: output range for 30°C – 45 °C @ 45 °C ambient

Vactive = 1.75 – 0.4 = 1.35 mV

$$S_{avg} = \frac{87.5 + 80}{2} = 83.75 \text{ µV/°C}$$

Reference Curve
Sensor: TS318-11C55

V$_{sen}$ = 4 mV

~1.75 mV

~0.4 mV S30 = 80 µV/°C

S$_{45}$ = 87.5 µV/°C

Range where maximum accuracy is required

Actual data from the sensor data sheet shall be used for LUT creation

Thermopile Signal [mV] / **Object Temperature [°C]**

Figure 3-1. Typical Reference Curve of a Thermopile Sensor Showing Example Calculations and Range of Measurement

3.1.1 TI Solution: Pre-amplification Using LNA to Remove Effect of ADC Offset and Drift

TI precision op amps have extremely low offset voltage and temperature drift. This allows small voltage signals to be amplified.

TLV333:

- Ultra-low input offset voltage, 15 µV (max) optimized to measure low voltage signals
- Low offset voltage drift 0.02 µV/°C (max)

The pre-amplification stage is necessary to gain the signal and must have extremely low offset and offset drift errors in the system. If the signal is fed directly to the ADC of the MSP, the offset and drift parameters of the ADC will cause the error to be very high.

3.2 Design Challenge #2: Maximize the Battery Power of the System

The batteries of the thermometer need to last for 1,000+ measurements and it must minimize current draw when turned off.

3.2.1 TI Solution: TI has High-Efficiency DC/DC With Ultra-low I_Q, MSP430I2040 With Ultra-low Ipm Current Consumption.

TPS61023:
- < 100-nA ultra-low shut down current
- < 21-µA quiscent current
- > 83% efficiency at 10-µA load
- > 90% efficiency at 1-mA to 2-A load

Power Optimization using MSP430I2040: The enable of the regulated 3.3-V supply is controlled by an MSP430 which only turns on the system supply whenever the user wants to take thermal measurements.

3.3 Design Challenge #3: Quickly Generate a Measurement

3.3.1 TI Solution: MSP430 Family

The MSP430 family of products combines an ADC, LCD driver, and processing into one chip ensuring that results are quickly calculated.

MSP430I2040:
- Integrated 24-bit, sigma-delta analog-to-digital converters
- Internal low-noise reference to minimize power supply noise which can affect the measurement

4 IR Thermometer: Hardware Design

A voltage is developed across a metal if the ends are placed at different temperatures. This phenomenon is called the Seebeck Effect. Two dissimilar metals connected at one end (called a thermocouple) will also produce a voltage difference between them due to the Seebeck effect. Modern technology makes it possible to produce thermopile sensors consisting of hundreds of thermocouples in a very small area.

Figure 4-1 shows such a temperature sensor with four leads coming out of it. Two leads are for the thermopile output where the potential due to the Seebeck effect is generated and another two leads are for the thermistor leads which are used for ambient temperature measurement.
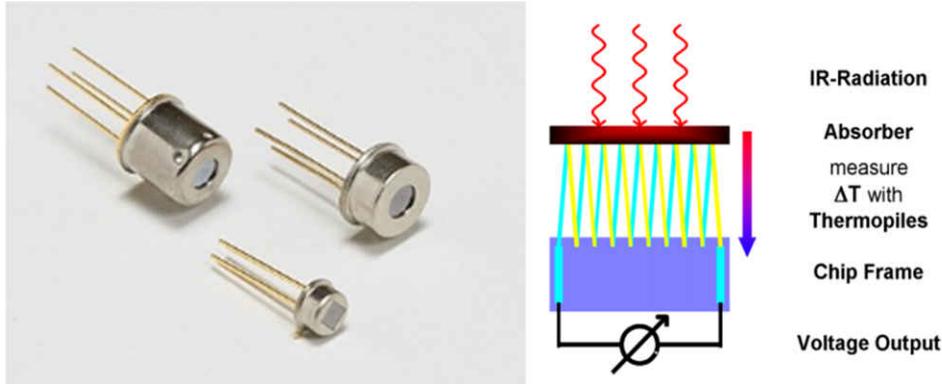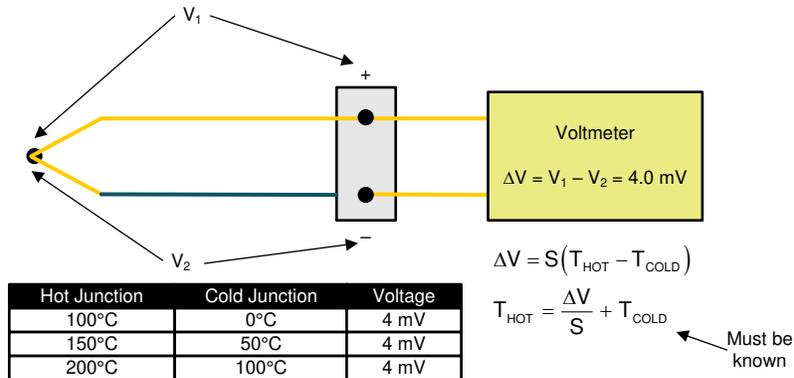

Figure 4-1. Temperature Sensor Composed of Thermopile Sensor and Thermistor

Figure 4-2 explains the reason for using two sets of sensors. To know the temperature of the object, one must know the voltage developed when IR light falls on one end of the thermopile sensor. The voltage (ΔV) will be proportional to the temperature difference (ΔT). Knowing ΔT (using LUT corresponding to ΔV) and ambient temperature T_{COLD} (in Figure 4-2), the object temperature can be determined.

Hot Junction	Cold Junction	Voltage
100°C	0°C	4 mV
150°C	50°C	4 mV
200°C	100°C	4 mV

$$\Delta V = S\left(T_{HOT} - T_{COLD}\right)$$

$$T_{HOT} = \frac{\Delta V}{S} + T_{COLD}$$

Must be known

If the ambient temperature and the voltage difference due to the Seebeck effect is known, the object temperature can be calculated.

Figure 4-2. Object Temperature Calculation

4.1 Low-Noise Signal Chain Design

The signal output of the thermopile sensor TP+ and TP– is fed to a low offset drift op amp with a gain of 201. The signal is offset by V_{REF}. The differential signal is fed to the 24-bit ADC on channel 0 of the MSP430I2040 for digitization.

As illustrated in Figure 3-1, designing the front end requires that the range of the input must be calculated. Assume that the thermopile signal (V_{tc}) varies between –1 mV to 3 mV as shown by the red marking (V_{sen}) in Figure 3-1 to cover the range of object temperatures with ambient variation, which gives Equation 1:

$$V_{tc} = -1\,mV \text{ to } 3\,mV \left(4\,mV \text{ range}\right) \tag{1}$$

This signal is amplified using one channel of the TLV2333 device with a maximum offset of 15 µV. The gain is given by Equation 2:

$$V_{OUT} = \left(1 + \frac{R_3}{R_8}\right) \times V_{tc} + V_{REF1} = 201 \times V_{tc} \times V_{REF1} \tag{2}$$

This V_{OUT} is sent to the ADC in differential mode as shown in Figure 4-3. The ADC input will be varying from 201 × V_{tc} which will be 201 mV to 603 mV (for best performance the signal range should be in ±928 mV).

The system requires a DC voltage shift to the input to have sufficient offset to have a negative signal as well (when ambient is higher than the object temperature, the thermopile output will be negative). This is done by using another channel of the TLV2333 which serves two purposes. First, it provides a buffer for the thermistor voltage measurement, the output is also used as a reference or DC offset for the thermopile measurement.

Note that the input impedance of the ADC in the MSP430I2040 is of the order of 200 kΩ. The typical thermistor output will vary from 35 kΩ at 50°C to 331 kΩ ay 0°C (from the TS318-11C55 data sheet). To measure the signal, a buffer between the thermistor and the ADC channel is absolutely necessary.

The thermistor voltage is measured using a resistor divider followed by the buffer which is used from the second op amp in the TLV2333. Equation 3 calculates the V_{REF} range:

$$V_{REF1} = (R_{19} + R_{NTC}) \times \frac{3.3}{R_{NTC} + R_{17} + R_{19}} \tag{3}$$

Equation 3 shows that VREF1 varies between 383 mV (for RNTC 35 kΩ) to 993 mV (for RNTC 331 kΩ). The value of RNTC at 25°C is approximately 100 kΩ, which translates to VREF1 of 550 mV.
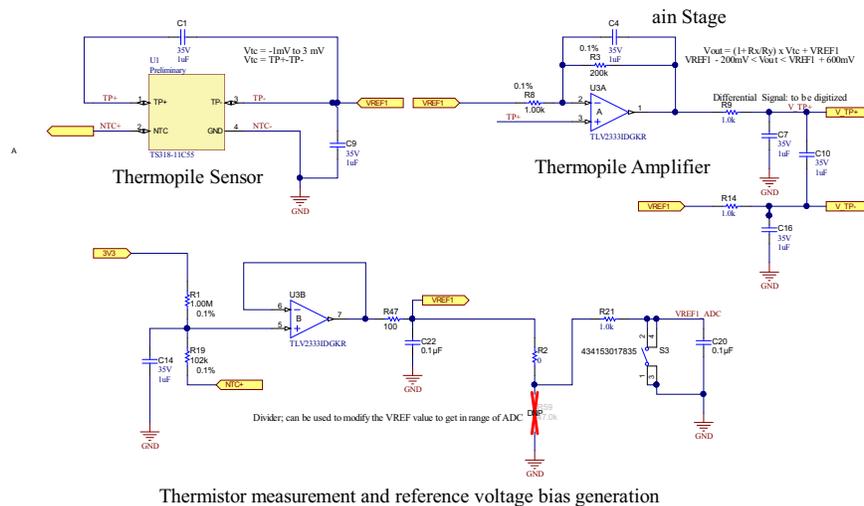
Figure 4-3. Low-Noise Small Signal Chain Implementation

4.2 System Power Generation and Management

The system requires a battery input source whose voltage can vary from 2 V to 3 V. The LM66100 provides **battery reverse polarity protection** to the system. This battery voltage is fed to a boost device (TPS61023) to generate a regulated 3.3-V system voltage. To conserve power drain from passive and other devices, the 3.3 V is controlled by a BOOST_EN signal. When boost is not enabled, only the MCU, MSP430I2040, gets power from the battery and is running in LPM4.5 mode. The battery voltage is ORed with 3.3 V, when the system is active, 3.3 V takes over.

The same pin of the MCU is like a PWM which serves multiple functionalities, to Enable boost, run the buzzer with PWM. Note that the peak detector circuit keeps the Enable HIGH during PWM.
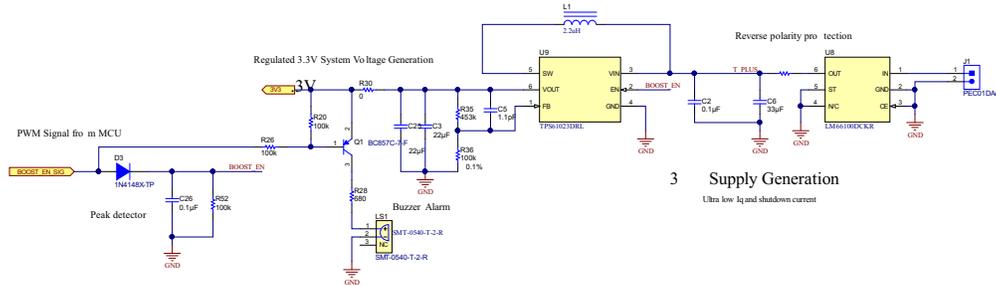

Figure 4-4. System Power Management and Protection

4.3 Microcontroller Section and LCD Display

The heart of the system is the MSP430I2040 device which controls multiple peripherals and complete management in terms of power, display, measurements, timing, and so forth. The MCU in standby mode sleeps in LPM4.5 mode with a current system draw of < 1 µA and 3.3-V rail cutoff while essentially removing excessive power loss.

Upon detection of button press (S1) on P2.2, the system wakes up and turns on the power for various functionalities. When in sleep mode, the battery provides power to the MCU and when 3.3 V is on, it takes over due to the ORing diode D4. Figure 4-5 shows the schematic of the microcontroller section.
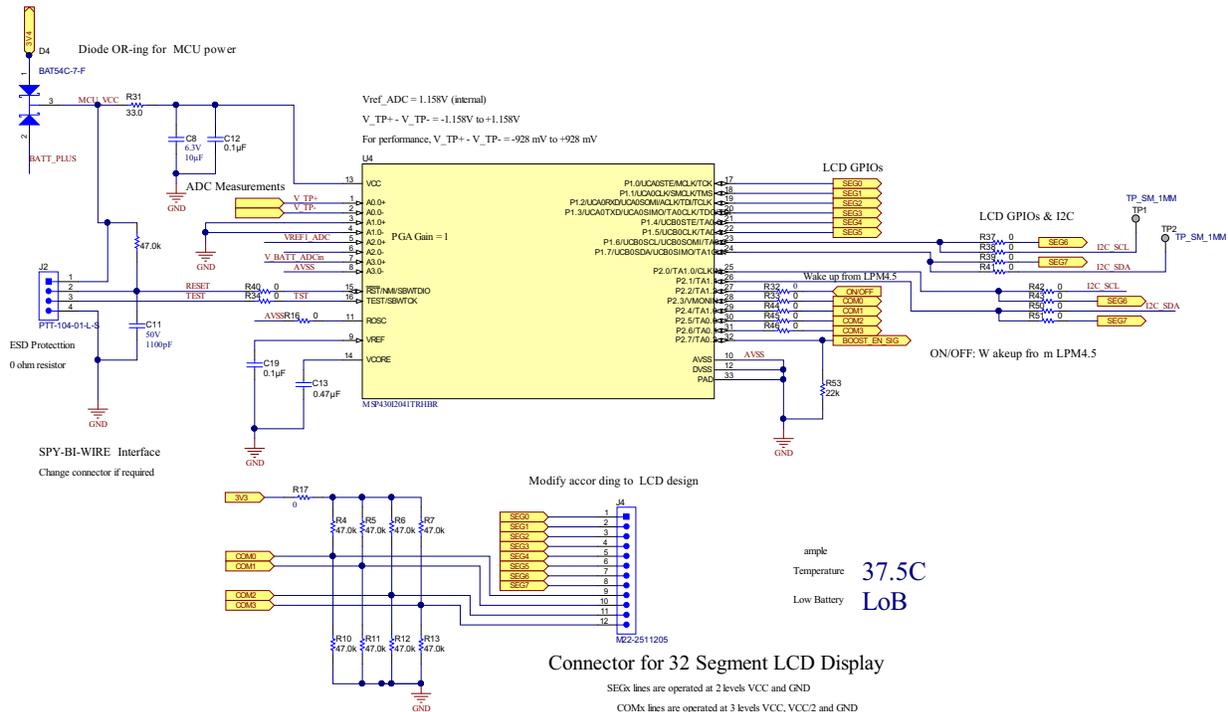

Figure 4-5. Microcontroller Section Implementation

Software LCD: The design uses onboard GPIOs to implement the LCD display functionality. It has 12 GPIOs (8 SEG and 4 COM pins) to support up to 32 LCD segments. The implementation is done in software and is available through TI for evaluation. For detailed information on similar implementation, see *Software Glass LCD Driver Based on MSP430 MCU*.

Especially for one-third bias LCD driving using GPIOs, the TIDA-00848 reference design from TI that shows an alternative, patent-pending solution can be used with any TI MCU without an on-chip display module. Using a few resistors and GPIO control software, the LCD drive functionality was implemented on a CC1310 Wireless MCU. Users can implement the same architecture using the MSP430I2040. One additional PWM pin is needed. The ON/OFF pin can be used in this case (multi-purpose), since after turn on, the ON/OFF pin has no use while the system is working. It can be configured into a PWM pin to support the display. Small hardware modifications are required, contact TI on E2E for more details.
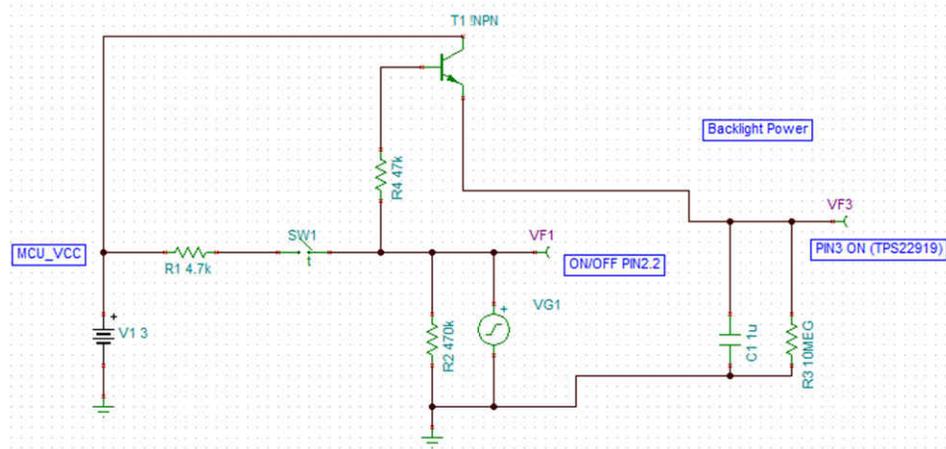

Figure 4-6. Example Implementation Using Same ON/OFF pin as PWM Output

4.4 Power ON, Automatic LCD Backlight Circuit and EEPROM

The system wakes up when the S1 button is pressed which goes to pin 2.2 of the MSP430I2040 and this wakes up the MCU from LPM mode. Simultaneously, the load switch TPS22919 enables the backlight power and the LCD backlight turns on for a specified time interval set by the time constant of the RC network C17 and R23. Figure 4-7 shows the corresponding circuitry.
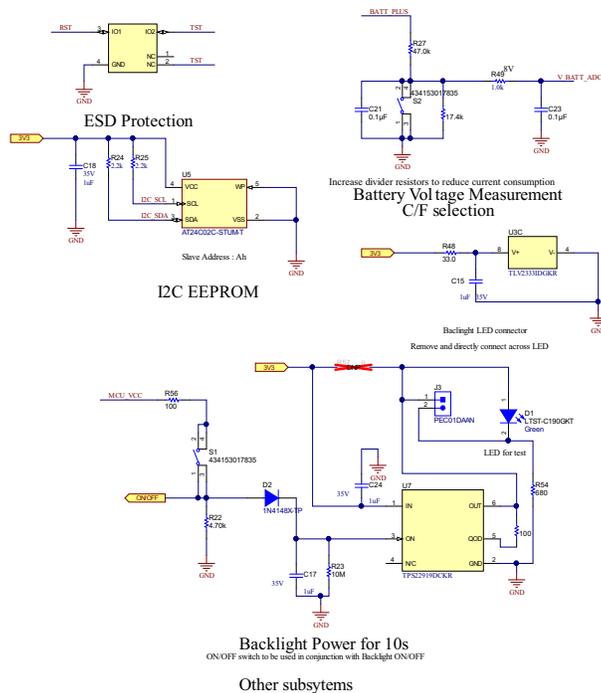

Figure 4-7. Power ON/OFF and LCD Backlight Circuit

The battery voltage is monitored on the second channel of the ADC and the same is also used as a selection switch between C/F displays of temperature. The same ADC channel is periodically sampled and button press and battery voltage is measured using a resistor divider network. The I2C EEPROM (optional) is provided for storing sensor data and other system parameters such as calibration data, sensor constants, and so forth. ESD protection on the Spy-Bi-Wire interface is also placed.

5 Software

Figure 5-1 shows the software flow diagram of the code implemented in the IR thermometer design. Each step in the diagram is self-explanatory. Download project collateral and source code discussed in this application report from http://www.ti.com/lit/zip/sboa501. The software does not include any calibration routine and it must also be must implemented by the customer. The software implements a look up table for the TS-308-11C55 sensor from TE connectivity and implements very basic calculations of the temperature.
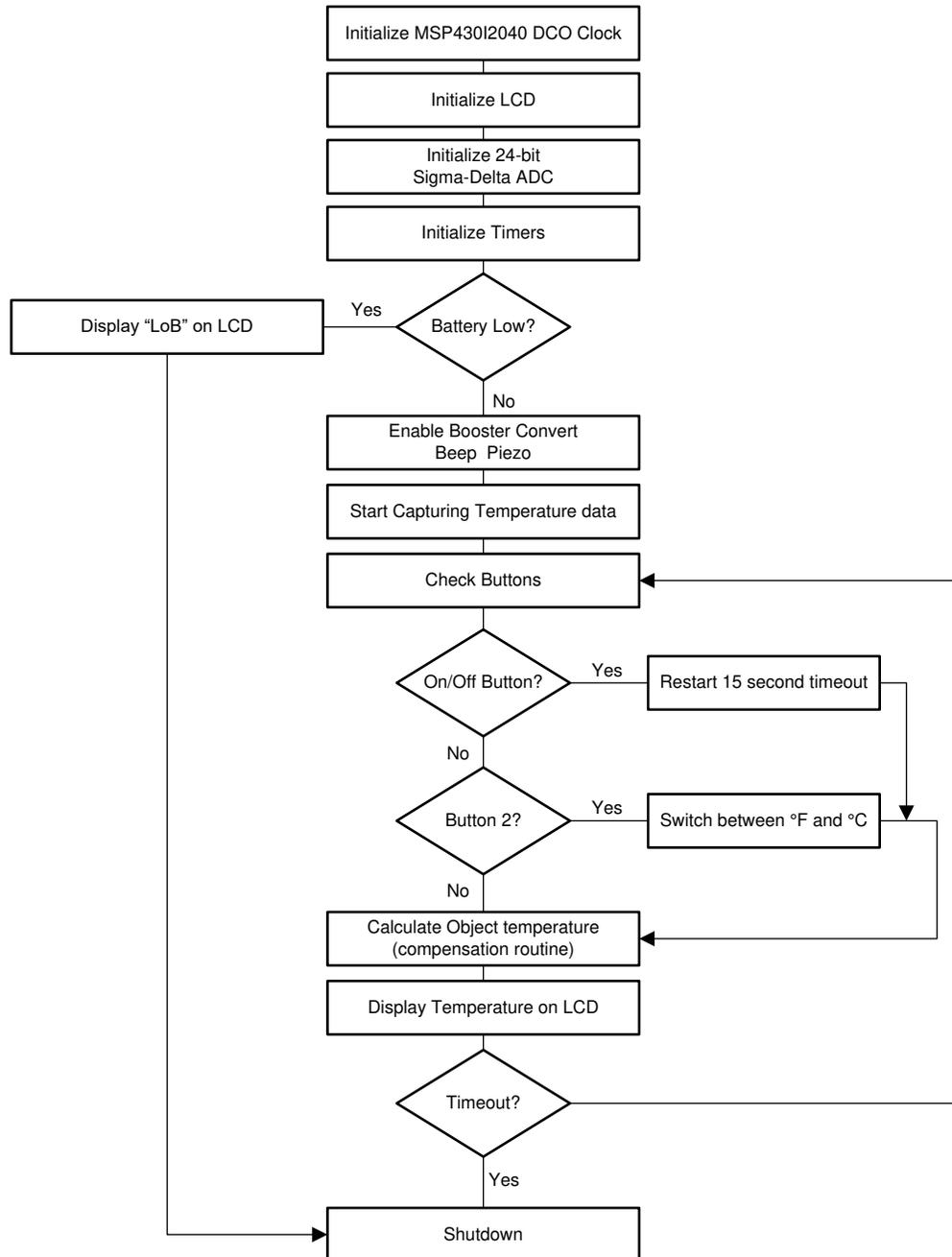
Figure 5-1. Software Flow Diagram

6 Test Results

6.1 Board Images

Figure 6-1 and Figure 6-2 show the board images of front side (right) and back side including the mounted sensor (left). The dimension of the board is 29 mm × 30.84 mm.
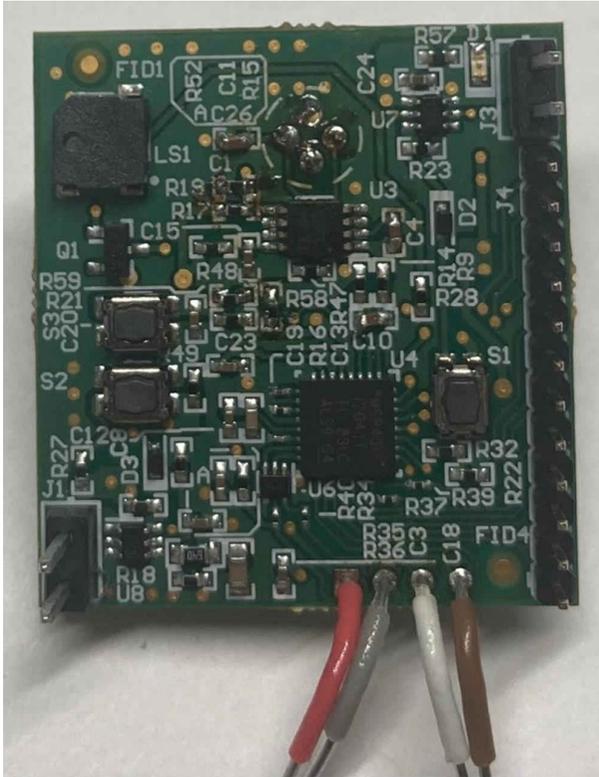

Figure 6-1. Front Side Board Image

Figure 6-2. Back Side Board Image

6.2 Test Setup for Evaluating the Thermometer

Figure 6-3 shows the test setup which is used to evaluate the IR thermometer design. To simulate the object placed at a distance, a Fluke 4180 IR calibrator is used to vary the object temperature. A high-precision $6^{1/2}$ digit multimeter and voltmeter are used to measure the input current and ADC voltages, respectively. The experiment was performed in the lab ambient temperature of in the the range 19°C to 23°C

Figure 6-3. Test Setup to Evaluate the Thermometer

6.3 Test Procedure

To evaluate the performance of the IR thermometer board, two categories of tests were conducted:

1. **Electrical Noise** in the system without the thermopile sensor mounted
   a. Instead of a thermistor, a known resistor is placed
   b. Instead of a thermopile, a high-precision DC supply (order of mVs) is placed
2. **Thermal measurements** with the thermopile sensor mounted on the board as described in the *Test Setup* section

7 Test Results

7.1 Current Consumption

Active current – 36 mA (complete system running including LCD)

Standby – 0.1 µA (with R27 Removed), 47.6 µA (with R27 placed); modify divider R27 accordingly to achieve the desired current

7.2 Electrical Noise

Table 7-1 shows the circuit level test results without a sensor to show low noise in the signal chain. The noise is the measure of the maximum ADC reading fluctuations with known values of thermistor resistor and known thermopile input voltage (0.1 mV–1 mV).

Table 7-1. System Noise Results

Noise (mV)	Resulting Temp Error (°C)	Allowable Noise for ±0.2°C (mV)
−0.395	−0.023	6.914

7.3 Thermal Measurements

Table 7-2 shows the data collected at 36 °C (black body temperature). The following calculations are done by following the compensation described by *Thermopile Sensor for Contactless Temperature – TE connectivity*. In the table, VTP is the thermopile voltage (gained), VNTC is the thermistor voltage, TSEN is the ambient temperature and TOBJ is the calculated object temperature.

Table 7-3 shows the data obtained at various set point temperatures of the black body. The data is taken at 30°C, 36°C, 37°C, and 40°C. The columns show average, maximum, and minimum values obtained doing a similar experiment as shown in Table 7-2. The last two columns show the deviation from the average value.

Table 7-2. Temperature Data for Black Body set at 36°C

Readings	Black Body Set Temp	Measured			Calculations		
		Black Body Temp	VTP (mV)	VNTC (mV)	TSEN (°C)	TOBJ (°C)	SCALING (30\31.7)
1	36	35.7	186.58	576.17	23.79262688	38.44000253	36.13360238
2	36	35.8	185.53	576.64	23.75020865	38.32693104	36.02731518
3	36	35.7	189.4	577.53	23.6698454	38.52675126	36.21514619
4	36	35.8	187.58	577.75	23.64997237	38.37995567	36.07715833
5	36	35.5	186.6	576.96	23.72131993	38.37608767	36.07352241
6	36	35.8	187.03	576.77	23.73847341	38.42219174	36.11686024
7	36	35.8	190.28	578.34	23.59666097	38.52179452	36.21048685
8	36	35.6	189.64	578.45	23.58671905	38.46747604	36.15942748
9	36	35.7	191.22	579.76	23.46825916	38.47037531	36.16215279
10	36	35.7	189.59	578.04	23.6237713	38.49792268	36.18804732
11	36	35.7	187.31	577.02	23.71590256	38.42129665	36.11601885
12	36	35.7	188.25	577.45	23.67707117	38.45212682	36.14499921
13	36	35.7	190.51	578.23	23.60660211	38.54715792	36.23432844
14	36	35.5	187.57	578.82	23.55327225	38.29063466	35.99319658
15	36	35.8	187.66	577.81	23.64455191	38.38063967	36.07780129
16	36	35.7	190.18	577.99	23.62828912	38.54374163	36.23111713
17	36	35.8	186.46	576.69	23.74569523	38.38852466	36.08521318
18	36	35.8	188	577.74	23.65087576	38.41045416	36.10582691
19	36	35.7	187.35	577.1	23.70867902	38.41750379	36.11245356
20	36	35.8	185.93	576.07	23.80165018	38.40231967	36.09818049

Designing a Low-Cost, High-Accuracy Infrared Thermometer

Table 7-2. Temperature Data for Black Body set at 36°C (continued)

Readings	Black Body Set Temp	Measured			Calculations		
		Black Body Temp	VTP (mV)	VNTC (mV)	TSEN (°C)	TOBJ (°C)	SCALING (30\31.7)
21	36	35.8	183.33	574.23	23.96756299	38.37036272	36.06814096
22	36	35.8	182.54	573.53	24.52925434	38.8284961	36.49878633
23	36	35.7	188.45	574.98	23.89996203	38.67059541	36.35035969
24	36	35.7	186.56	576.03	23.80525932	38.45016222	36.14315249
25	36	35.7	187.51	576.27	23.78360293	38.49747329	36.18762489
26	36	35.6	191.88	577.56	23.66713562	38.69947706	36.37750843
27	36	35.8	185.19	575.51	23.85216866	38.39626997	36.09249378
28	36	35.8	188.04	576.21	23.78901738	38.53990008	36.22750608
29	36	35.8	188.98	576.62	23.75201398	38.5724176	36.25807255
30	36	35.6	190.41	578.01	23.62648201	38.55833052	36.24483069
Average	**36**	**35.72**	**187.85**	**577.01**	**23.73343019**	**38.4755791**	**36.16704436**

Table 7-3. Temperature Data Collected at Various Set Points of Black Body

Black Body Temperature	T_{OBJ} (avg)	T_{OBJ} (max)	T_{OBJ} (min)	T_{OBJ} (max) – T_{OBJ} (avg)	T_{OBJ} (min) – T_{OBJ} (avg)
30	29.75545216	30.09368583	29.51515572	0.338233667	– 0.240296446
36	36.16704436	36.49878633	35.99319658	0.331741975	– 0.173847779
37	37.40582747	37.82919839	37.05760415	0.423370918	– 0.348223324
40	40.62476939	40.8565339	40.32927866	0.231764509	– 0.295490737

8 Conclusion

The Fluke BB at a given temperature has 0.2°C (±0.1) maximum deviation as per the specification. Our results show a deviation of more than 0.5°C (Max – Max). There could be several reasons for a deviation greater than the black body.

- Data mentioned does **not** include any kind of sensor calibration. For example, thermal oil bath calibration at multiple points would increase the accuracy significantly.

- Sensors picking up reflections from other sources. (the tests in the laboratory could not be performed in perfectly isolated settings).

9 References

- Texas Instruments, *Software Glass LCD Driver Based on MSP430 MCU Application Report*
- *Thermopile Sensor for Contactless Temperature – TE connectivity*

IMPORTANT NOTICE AND DISCLAIMER