Evaluation Kit

Manual

Contents

1 Quickstart

Step 0:

Before you start, make sure that all compatible drivers are installed on your PC. In order to run the Evaluation Kit software, the LabVIEW 2012 Runtime Engine (dir\Contents\07_Driver_and_Runtime_Engine\LVRTE2012f3std.exe) and the NI VISA Runtime 5.4 (dir\Contents\07_Driver_and_Runtime_Engine\visa540_runtime.exe) have to be installed. The driver for the RS232 adaptor is also provided in the same folder on the USB drive, but may install automatically when you plug the adaptor into your PC for the first time.

Step 1:

Connect the Evaluation Kit base board to the power supply and to the PC through the included RS232 adaptor (see Figure 1). To enable a connection with the PC, it is necessary to know to which COM port the Evaluation Board is connected. The assigned COM port is indicated in the device manager of the operating system.

The Evaluation kit base board and the sensor board have to be connected as shown in Figure 1 or with the provided extension cable.
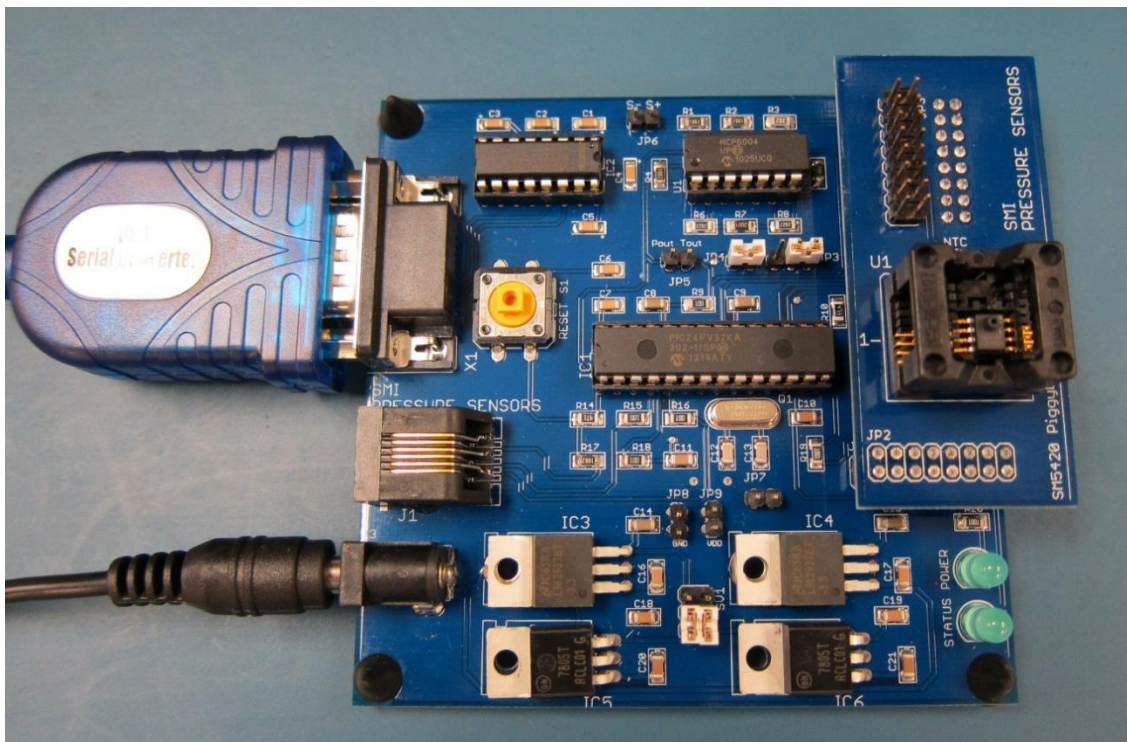
Figure 1: Fully assembled and connected Evaluation Kit

Step 2:

Run the Evaluation Kit Software executable (see Figure 2), which is provided on the USB-Stick that is part of the Evaluation Kit (dir\Contents\06_LabVIEW_Exe\Hybrid Evaluation Kit v3.exe).
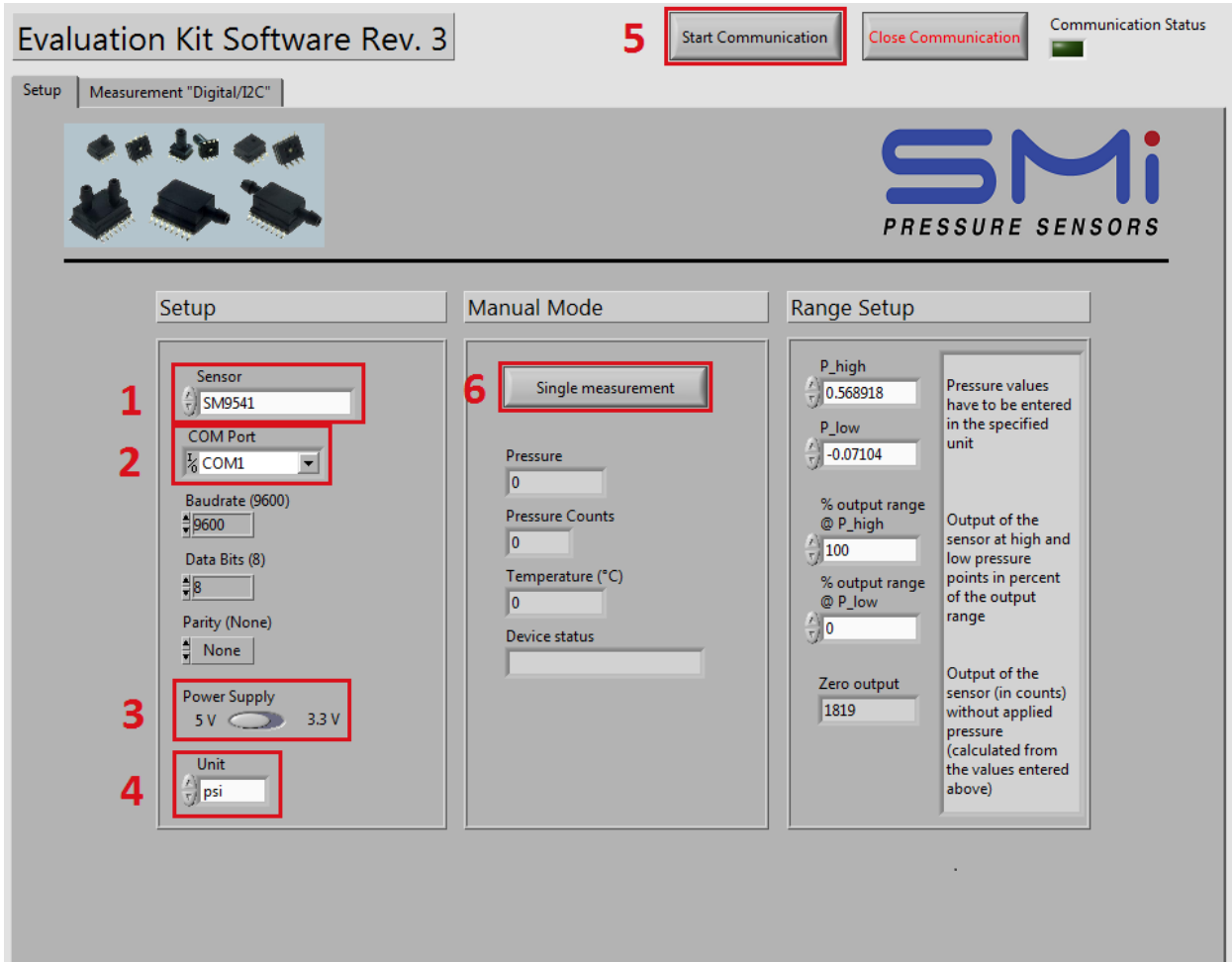
Figure 2: Main page of the Evaluation Kit software

Step 3:

Choose the part number according to the sensor that is connected to the Evaluation Board (see 1 in Figure 2).

Change the COM port to the one that has been assigned to the Evaluation Board (see 2 in Figure 2).The correct COM port number can be found in the operating system's device manager under "Ports (COM & LPT).

Make sure that the supply voltages on the board set by hardware jumper SV1 (see appendix, section 7.5 for more info) and in the software (see 3 in Figure 2) match and are suitable for the used sensor.

The baud rate (9600 bit/s), data bit count (8) and parity bit settings (no parity bit) normally do not need to be changed.

The unit of all pressure values displayed in the software can be chosen by selecting the desired one under "unit" (see 4 in Figure 2).

After the communication setup is adjusted, press the *Start Communication* button (see 5 in Figure 2). The Communication Setup screen should turn gray. If no communication error has occurred, the communication status lamp will turn on.

You can test if the Evaluation board and the communication work correctly by pressing the "Single measurement" button (see 6 in Figure 2). Also check, if the returned values are as expected. If not, make sure that everything is connected properly.

Step 4:

Once the connection is established, it is possible to do a measurement, a calibration or other data operation. To choose the desired operation, change to the related tab in the LabVIEW Software by clicking on the buttons on the top of the page. For more information see section 4 of the manual.

2 Introduction

The Evaluation Kit was designed as an application example for the pressure sensors of Silicon Microstructures, Inc. (SMI) and includes all the hardware and software needed to operate different sensor types. It serves as an example of how to calibrate uncompensated sensors in order to obtain a meaningful pressure reading and also supports SMI's signal-conditioned sensors. Their sensor output can be measured and displayed. Full documentation about all the hardware and software is provided with the Evaluation Kit which can be used as further guidance of how to include SMI's pressure sensors in your application.

2.1 Sensor Types

SMI offers a range of sensors with different working principles, most of which are supported by the Evaluation Kit through different piggyback boards. The following types are supported:

2.1.1 Uncompensated - Constant Voltage Operation

This mode employs a constant voltage that is applied directly to the sensor die. The output of the sensor is the raw bridge output voltage in the mV range, i.e. the voltage measured between the +SIG and -SIG output pins. The raw output voltage of the sensor, however, is not only dependent on the applied pressure, but also influenced by temperature, common process variations, and other factors. Therefore, external means of compensation, like the microcontroller used in the Evaluation Kit, are needed. A calibration has to be performed for each sensor to be able to determine the actual pressure. A typical sensor of this kind is the SM5420.

2.1.2　Uncompensated - Constant Current Operation

Almost every uncompensated sensor (die) for constant voltage can also be operated with a constant current applied. As described in section 3.2.3, the constant current mode offers a reduced temperature influence on the output. And, taking into account known sensor behavior, it allows for a simple calibration.

2.1.3　Signal-Conditioned - Digital/I²C

Digital sensors like SMI's SM9541 include, in addition to the sensor die, an ASIC in their package. The ASIC measures the bridge output voltage with a resolution of 14 bit and the temperature to produce a fully compensated pressure value that can be read via a digital I²C-interface.

2.1.4　Signal-Conditioned - Amplified Analog

Amplified analog sensors also include an ASIC to provide a fully compensated pressure reading. Unlike their digital counterparts the output of these sensors is an analog voltage (between 0 V and 5 V with a supply voltage of 5 V) related to the applied pressure. The SM9542 is an amplified analog sensor offered by SMI.

3　Calibration

SMI offers three principal types of pressure sensors:

1. Uncompensated pressure sensors
2. Temperature compensated and calibrated pressure sensors
3. Signal-conditioned pressure sensors

The **uncompensated pressure sensor** is the basic pressure sensor. The output varies within a specified range as a function of temperature. The zero offset and full-scale span vary from device to device within a specified range.

The package of a **temperature compensated and calibrated pressure sensor** includes a ceramic substrate with thick film resistors that are laser trimmed to *compensate* variation over temperature. The zero offset and full-scale span are *calibrated* so that negligible variance will occur from device to device**.**

Signal-conditioned pressure sensors include temperature compensation and calibration circuitry. They further consist of an amplifier circuit to increase the output signal for full-scale pressure. These features may be on-chip or on a separate, second chip in the same package.

3.1　Why do we need a calibration?

The output of uncompensated pressure sensors is not only a function of the applied pressure, but also dependent on temperature. Also, a number of sensor characteristics, like the zero offset, the span, and their respective temperature behavior, vary from device to device due to inherent manufacturing tolerances within a specified range.

All of SMI's pressure sensors are based on the piezoresistive effect. The piezoresistive effect describes a change in resistivity caused by a change in mechanical stress. In piezoresistive silicon pressure sensors, this effect is used to convert changes in applied pressure into changes in output voltage. Applied pressure results in stress in a thin silicon membrane. This stress in turn results in changes of resistance of four resistors that are arranged in a Wheatstone bridge circuit to maximize the response of the sensor to the applied pressure.

Figure 3 Figure 1shows the equivalent circuit of a Wheatstone bridge. The applied voltage across the bridge leads to an output $V_{OUT}(p)$, if the individual resistors are not identical in value.
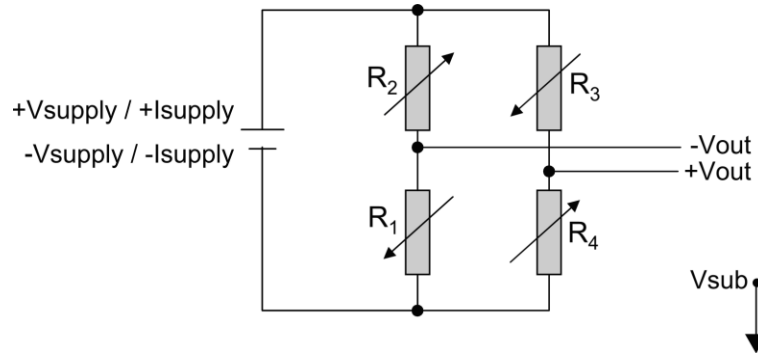

Figure 3: Wheatstone bridge equivalent circuit

In other words, the bridge detects ΔR terms. An approximate relation between the resistance change, the supply voltage and the voltage output is

$$V_{OUT}(p) \approx \frac{\Delta R_1 + \Delta R_3 - \Delta R_2 - \Delta R_4}{4R_B} \cdot V_{SUPPLY} \tag{1}$$

where R_B is the bridge resistance, ΔR_x is the change of the individual bridge resistors and V_{SUPPLY} is the supply voltage.

Ideally, at zero pressure, the resistance value of the individual resistors is identical to the bridge resistance $R_1 = R_3 = R_2 = R_4 = R_B$, and the absolute change of the ΔR terms is also identical for all individual resistors: $\Delta R_1 = \Delta R_3 = \Delta R$ and $\Delta R_2 = \Delta R_4 = -\Delta R$. This results in the following approximation for the bridge output voltage:

$$V_{OUT}(p) \approx \frac{\Delta R}{R_B} \cdot V_{SUPPLY} \tag{2}$$

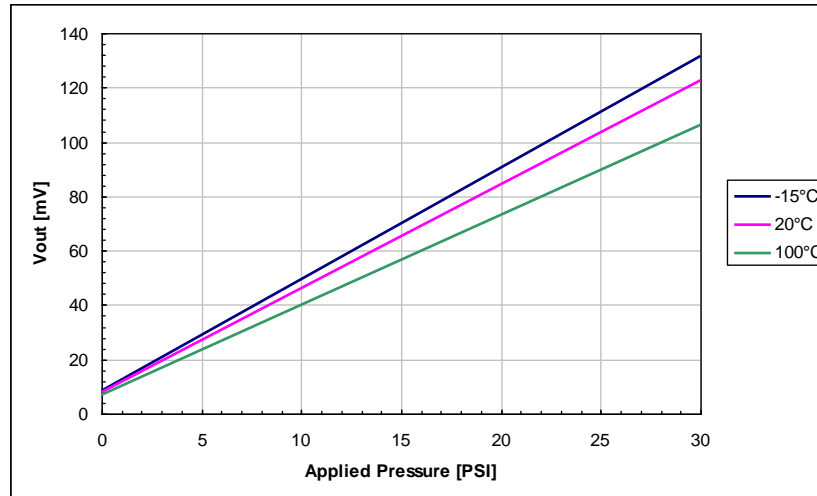Figure 4 shows the output of a typical SM5420 pressure sensor over pressure at different ambient temperatures.

Figure 4: Temperature dependence of sensor output

The zero offset V_{ZERO} and the span V_{SPAN} are the two output parameters of a piezoresistive pressure sensor that change over temperature. This change over temperature results in a need for compensation.

The zero offset voltage V_{ZERO} represents the bridge output voltage without any input pressure. For example the SM5420 is an absolute pressure sensor; therefore, the zero offset is the output of the sensor at an absolute pressure of 0 psi. For practical reasons, the zero offset is usually determined by extrapolating from two pressure values at full-scale and close to zero, e.g., 0.5 psi. For a differential or a gage pressure sensor, the zero offset is the output of the device measured at a gage pressure of 0 psi.

The span V_{SPAN} for a certain temperature is defined as the difference between the bridge output voltage V_{OUT} at full-scale pressure P_{FS} and the bridge output voltage V_{OUT} at minimum pressure P_{MIN} at the respective temperature T and a certain supply voltage $+V_{SUPPLY}$ or supply current. In the case discussed here P_{MIN} equals 0 psi.

Figure 5 illustrates how the zero offset and the span of the SM5420 change vs. ambient temperature when the part is operated in constant voltage mode. The changes in zero offset and span are shown relative to the values at 25°C in percent of full-scale at 25°C (%FS).
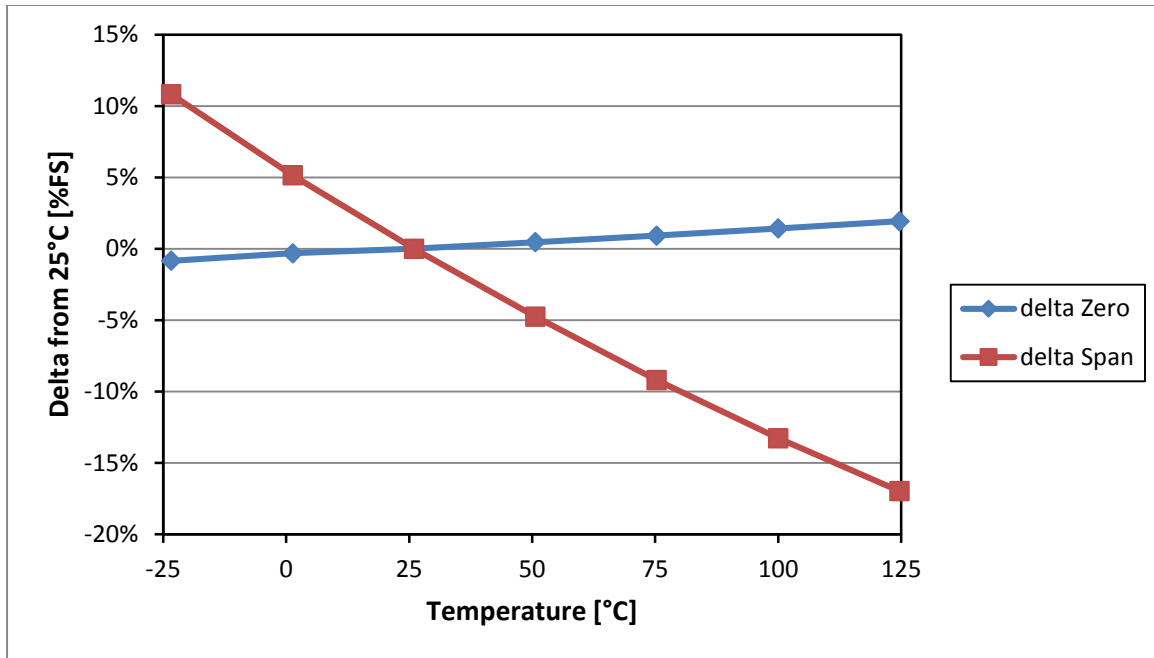
Figure 5: Temperature dependence of zero and span with constant voltage supply

3.2 Theory of Calibration

3.2.1 Compensation approaches for uncompensated pressure sensors

Uncompensated pressure sensors can be compensated in several different ways. They are intended to be used with passive compensation components, a signal-conditioning IC or a compensation approach using a temperature sensor and an existing microcontroller as described in this document. There are advantages and disadvantages to each approach. The goal is always to counter the effects of temperature on zero offset and span.

With this Evaluation Kit the used sensor can be compensated in two different ways. First, the kit offers a constant voltage mode (CV). This calibration process requires to apply several known values of temperature and pressure to the sensor and to measure its output. These data points are used to calculate calibration coefficients. These coefficients together with the output reading of the sensor and a temperature reading are then used to approximate the applied pressure. The accuracy of the approximation of the pressure depends on the compensation scheme. With an optimized scheme this approach can result in very good accuracies. For optimum results, raw readings at two or more temperatures may be required.

The second option, which is provided by the Evaluation Kit, is the constant current mode (CC). When the piezoresistive sensors are supplied with constant current, they self-compensate to a certain extent. This reduces temperature effects and further offers an option to estimate the environment temperature from the bridge resistance without an additional temperature sensor. This information plus known typical temperature behavior allows compensation. For this mode only two output values at different

pressures have to be measured at room temperature. This is a very simple approach that can be especially useful if the application has a narrow operating temperature range and the accuracy requirements are not very tight.

3.2.2 Constant voltage mode

Calibration equations: the most general equation for describing the output as a function of pressure is

$$ABSOLUTE\ PRESSURE\ (T,p) = \frac{(V_{out}(T,p) - V_{zero}(T))}{S(T)} \times SF \tag{3}$$

Where:

- $V_{OUT}(T,p)$ is the output of the pressure sensor at a known temperature T
- *S(T)* is the pressure sensitivity of the sensor at temperature T,
- $V_{ZERO}(T)$ is the zero-pressure output at temperature T, and
- *SF* is a scale factor used to produce the calibrated value of output.

An ideal pressure sensor would have both V_{ZERO} and S be independent of temperature, however, a simple piezoresistive pressure sensor such as the SM5420 has both a zero offset and a sensitivity that are temperature dependent. This dependence is non-linear, as is shown in Figure 6 for a typical SM5420 operated with a constant 5 V supply voltage.

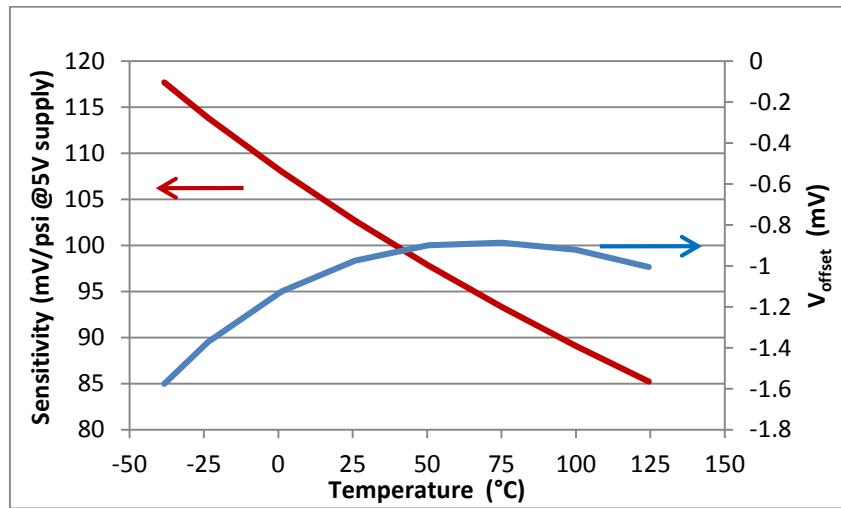Figure 6: Temperature dependence of offset voltage and sensitivity of a typical SM5420 sensor

The purpose of the calibration procedure is to provide the various parameters that the microprocessor on the Evaluation Board uses in the equations to correct the pressure sensor output for:

- The temperature characteristics of sensitivity and offset
- A small amount of non-linearity in the pressure response

- A scale factor to provide a calibrated output at a specified pressure.

Temperature compensation: During the calibration process, data points at several known values of temperature and pressure are taken, with which the curves in Figure 6 can be approximated. The three systems of equations that are included in the Evaluation Kit software are two-point linear approximation, best fit straight line and second order polynomial. Each of these approaches to temperature compensation provides a different level of accuracy for the approximation of the offset and sensitivity curves. For the purposes of this section, the V_{OFFSET} curve of the Figure 6 is shown as a series of 8 data points in Figure 7, to which several approximation lines have been added. Though not shown in this example, a similar set of curves is developed for the various approximations to the sensitivity curve.
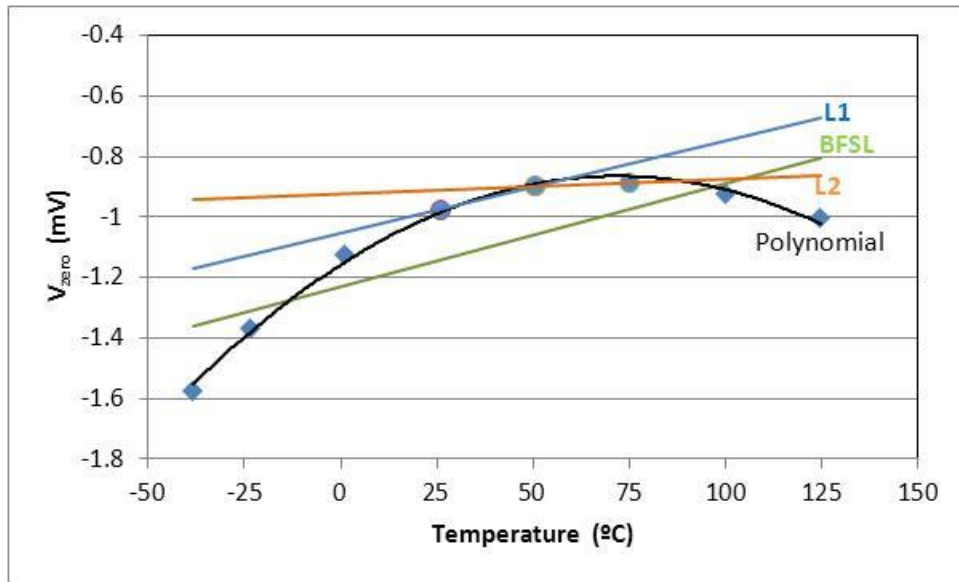

Figure 7: Measured V_{ZERO} points from a typical SM5420 with linear approximation (L1) from points at 25 °C and 50 °C, linear approximation (L2) from points at 50 °C and 75 °C, Best Fit Straight Line approximation, and 2nd order polynomial fit

2-Point Calibration (Linear Approximation)

During calibration at two known temperatures, T_1 and T_2, the output of the sensor is measured at two different pressures, P_1 and P_2. From these measurements, the sensitivities at the two temperatures are first determined with equations 44 and 5. For absolute pressure sensors the output voltage with no applied pressure V_{ZERO} should be measured with a vacuum applied to the sensor. Since it is difficult to generate a good vacuum in test fixtures, often two non-zero pressures are used and the output is extrapolated to a value that represents zero pressure. This is shown in equations 6 and 7. From those calculated values, the linear approximations for the temperature-dependent zero-pressure offset and sensitivity are given in equations 8 and 9. These values are then used in equation 1.

$$S(T_1) = \frac{V_{OUT}(T_1, P_2) - V_{OUT}(T_1, P_1)}{P_2 - P_1} \qquad (4)$$

$$S(T_2) = \frac{V_{OUT}(T_2, P_2) - V_{OUT}(T_2, P_1)}{P_2 - P_1} \qquad (5)$$

$$V_{ZERO}(T_1) = V_{OUT}(T_1, P_1) - S(T_1) \times p_1 \qquad (6)$$

$$V_{ZERO}(T_2) = V_{OUT}(T_2, P_1) - S(T_2) \times p_1 \qquad (7)$$

$$V_{ZERO}(T) = V_{ZERO}(T_1) + \frac{V_{ZERO}(T_2) - V_{ZERO}(T_1)}{(T_2 - T_1)} \times (T - T_1) \qquad (8)$$

$$S(T) = S(T_1) + \frac{S(T_2) - S(T_1)}{(T_2 - T_1)} \times (T - T_1) \qquad (9)$$

An example of the approximation for V_{ZERO} using measured outputs at 25 °C and 50 °C is shown in Figure 7 as line L1. This approximation does not match all 8 data points very well, and if two different temperatures such as 50 °C and 75 °C are chosen for the calculations, the resulting approximation line, L2, will be very different.

Equations for Best-Fit-Straight-Line Pressure and Temperature Compensation

When more than two pressures and two temperatures are used in calibration, a linear response to both temperature and pressure can be determined which minimizes the average error between the assumed linear response and the actually measured calibration points.

The pressure response, similar to equation 1, is expanded to give:

$$ABSOLUTE \;\; PRESSURE \;\; (T) = \frac{V_{out}(T, p) - b(T)}{m(T)} SF = \frac{V_{out}(T, p) - g \times T - d}{f \times T - c} SF \qquad (10)$$

Where

- m and b describe a straight line ($V_{OUT} = mp + b$) that best fits calibration data of the sensor
- f and c describe a straight line ($m = fT + c$) for sensitivity over temperature that best fits the data
- g and d describe a straight line ($b = gT + d$) for offset over temperature that best fits the data
- SF is a scale factor used to produce the calibrated value of output

Given a set of output voltage measurements at k temperatures and n pressures during calibration, $V_{OUT}(T_1, p_1)$ through $V_{OUT}(T_K, p_N)$, the best-fit-straight-line parameters for pressure can be determined at each temperature from:

$$m = S = \frac{\sum (V_{out} \times p) - \frac{(\sum V_{out})(\sum p)}{n}}{\sum p^2 - \frac{(\sum p)^2}{n}} \quad (11)$$

$$b = V_{zero} = \frac{\sum V_{out}}{n} - m \times \frac{\sum p}{n} \quad (12)$$

In pressure sensor terminology, m is the sensitivity and b is the zero-pressure output voltage. In a similar manner, the temperature dependence of V_{ZERO} and Sensitivity can be expressed as best-fit-straight lines for the calculated values of *m* and *b* from the test data over temperature.

$$S(T) = m = fT + c \text{ and} \quad (13)$$

$$V_{zero}(T) = b = gT + d \quad (14)$$

Where

$$f = \frac{\sum (m \times T) - \frac{(\sum m)(\sum T)}{k}}{\sum T^2 - \frac{(\sum T)^2}{k}} \quad (15)$$

$$c = \frac{\sum m}{k} - f \times \frac{\sum T}{k} \quad (16)$$

$$g = \frac{\sum (b \times T) - \frac{(\sum b)(\sum T)}{k}}{\sum T^2 - \frac{(\sum T)^2}{k}} \quad (17)$$

$$d = \frac{\sum b}{k} - g \times \frac{\sum T}{k}. \quad (18)$$

The equations above define the parameters that are used in equation 10. The BFSL approximation for V_{ZERO} is shown in Figure 7, where all of the data points are used in the calculation. Since it is still a linear approximation of the true curve, it still doesn't fit the data very well.

Equations of 2nd Order Polynomial Fit for Pressure and Temperature Compensation

$$P(T) = \left(A(T) \cdot (V_{out}(T, p))^2 + B(T) \cdot V_{out}(T, p) + C(T, p) \right) \cdot SF \quad (19)$$

At a constant temperature the coefficients A, B and C above can be determined from the simultaneous equations:

$$a_1 A + b_1 B + c_1 C = d_1 \tag{20}$$

$$a_2 A + b_2 B + c_2 C = d_2 \tag{21}$$

$$a_3 A + b_3 B + c_3 C = d_3 \tag{22}$$

$$a_1 = \sum (x_i)^4 \qquad b_1 = \sum (x_i)^3 \qquad c_1 = \sum (x_i)^2 \qquad d_1 = \sum \left(x_i^2 y_i \right) \qquad \text{(23, 24, 25, 26)}$$

$$a_2 = \sum (x_i)^3 \qquad b_2 = \sum (x_i)^2 \qquad c_2 = \sum (x_i) \qquad d_2 = \sum \left(x_i\, y_i \right) \qquad \text{(27, 28, 29, 30)}$$

$$a_3 = \sum (x_i)^2 \qquad b_3 = \sum (x_i) \qquad c_3 = \sum (1) \qquad d_3 = \sum \left(y_i \right) \qquad \text{(31, 32, 33, 34)}$$

The x_i *and* y_i values are obtained during the calibration tests with y_i being the provided pressure and x_i being the measured output voltage for the ith test point at a single known temperature.

Once all of the a's and b's are calculated, the A, B and C coefficients can be determined from the following equations

$$C = \frac{\left(d_3 a_1 - a_3 d_1\right)\left(a_1 b_2 - a_2 b_1\right) \ - \left(a_1 d_2 - a_2 d_1\right)\left(a_1 b_3 - a_3 b_1\right)}{\left(c_3 a_1 - a_3 c_1\right)\left(a_1 b_2 - a_2 b_1\right) - \left(a_1 b_3 - a_3 b_1\right)\left(a_1 c_2 - a_2 c_1\right)} \tag{35}$$

$$B = \frac{a_1 d_2 - a_2 d_1}{a_1 b_2 - a_2 b_1} - C\left(\frac{a_1 c_2 - a_2 c_1}{a_1 b_2 - a_2 b_1}\right) \tag{36}$$

$$A = \frac{d_1}{a_1} - \frac{c_1}{a_1} C - \frac{b_1}{a_1} B \tag{37}$$

The equations above give the A(T), B(T), and C(T) coefficients at each of the test temperatures. In a similar fashion, those parameters can themselves be fit to an equation that is a function of temperature

$$A, B, C = \alpha T^2 + \beta T + \delta \tag{38}$$

Use equations 23 through 34 with the x_i being the temperatures used in the calibration process and the y_i being the resulting A values that were previously calculated from equations 35 through 37. With these a's, b's, c's and d's, use equations 35 through 37 to calculate the α, β, and δ values for the A parameter in equation 37. The process gets repeated for the B and C parameters to be fit with an equation with the form of equation 37.

After calibration, the operation of the system should first use the temperature to calculate the values of A, B and C using equations 37, then those values are substituted into the main equation 19. The 2nd order polynomial fit to the data in Figure 7 matches the data quite well.

Scale Factor

In the pressure equations 3, 11, and 19, there is a scale factor that serves to make the calibrated pressure output match the known pressure that was applied during the calibration process. It is sufficient to determine this scale factor at only one pressure/temperature point, ideally one near the most critical operating point for the application.

3.2.3　Constant current mode

Using the constant current mode will self-compensate the sensor to a certain extent and reduces temperature effects. It further offers an option to estimate the ambient temperature from the bridge resistance without an additional temperature sensor. This information plus known typical temperature behavior allows for compensation.

The bridge resistance changes with temperature. This behavior is described by the temperature coefficient of bridge resistance, TCR. In constant-current mode, the change in span over temperature is a superposition of both the pressure sensitivity S(T) and the bridge resistance temperature coefficients.

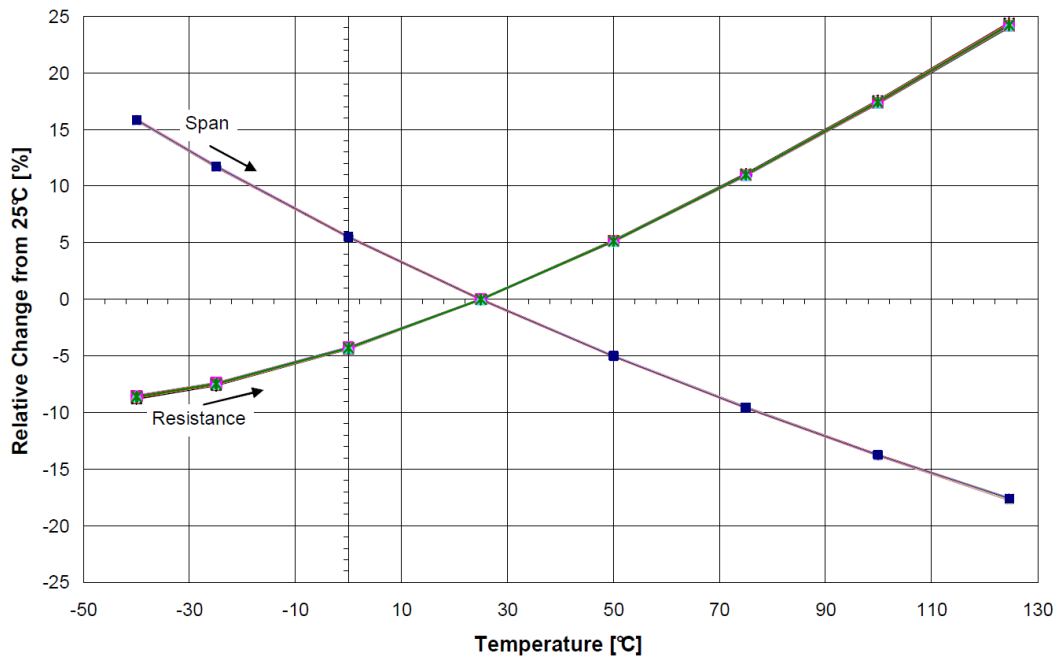$$V_{span}(T) = S(T) * R_b(T) * I_{exc} * p_{fullscale} \tag{39}$$

Figure 8: Bridge resistance and span as a function of temperature (constant voltage supply, before compensation)

As shown in Figure 8 above, the temperature coefficient of the bridge resistance is positive whereas the temperature coefficient of pressure sensitivity is negative. Those two effects combined significantly reduce span variation over temperature, which is depicted in Figure 9 below.
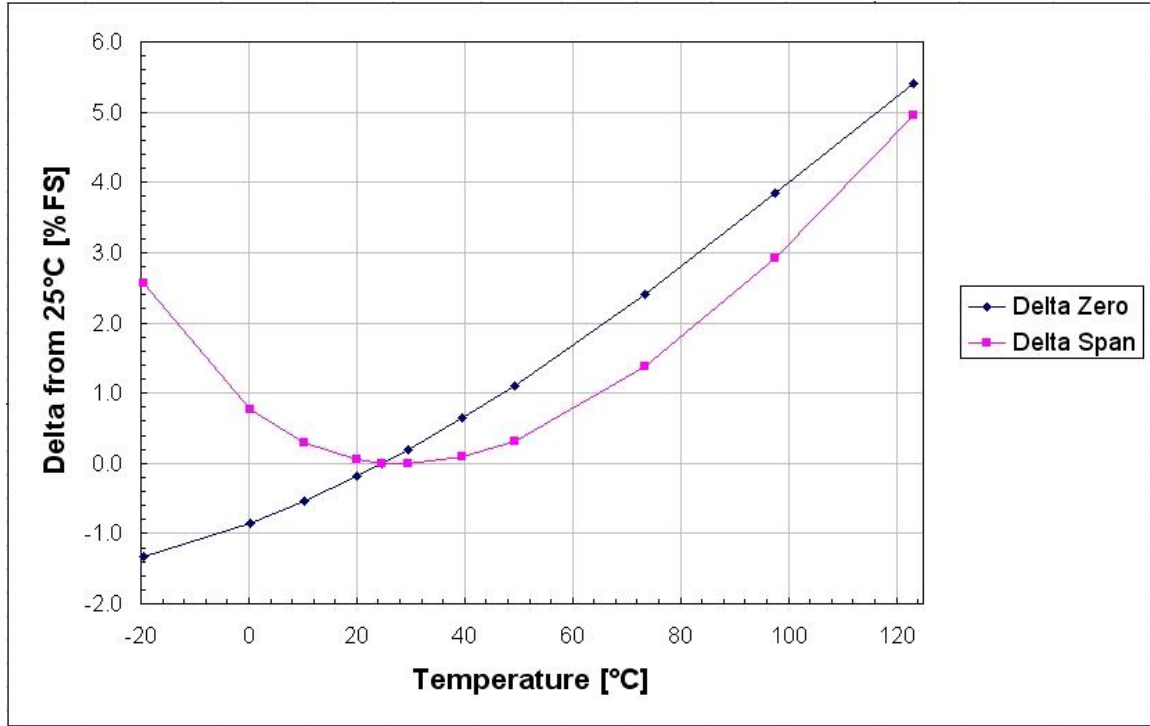
The remaining deviation of the span and zero offset can be calculated with the known temperature coefficients of span (TCS) and zero offset (TCZ). A fairly accurate compensation can be achieved, if the typical values for TCS and TCZ are assumed. A higher degree of accuracy will be reached, if the TCS and TCZ are determined for each sensor individually.

$$V_{span}(T) = V_{span,ref} * \left(1 + TCS * \left(T - T_{ref} \right) \right) \tag{40}$$

$$V_{zero}(T) = V_{zero,ref} + V_{span,ref} * TCZ * \left(T - T_{ref} \right) \tag{41}$$

$V_{SPAN,REF}$ and $V_{ZERO,REF}$ represent the voltage values of span and zero offset at the reference temperature, both of which are measured during the calibration process.

In the constant current mode, the dependence of the output voltage of the Wheatstone-Bridge from the applied pressure is assumed to be linear at the constant reference temperature. Therefore, only two pressure points at room temperature have to be measured to calibrate the sensor. The output voltages of the bridge (V_{LOW} and V_{HIGH}) will be measured for known pressure values P_{LOW} and P_{HIGH}. With the knowledge of these values plus the value of $P_{FULLSCALE}$ which can be adjusted to the expected range of the measured pressure, the zero-offset voltage V_{ZERO}, the fullscale voltage $V_{FULLSCALE}$ and the span V_{SPAN} can be

calculated. Figure 10 provides a visualization of the variables involved in the constant current calibration.
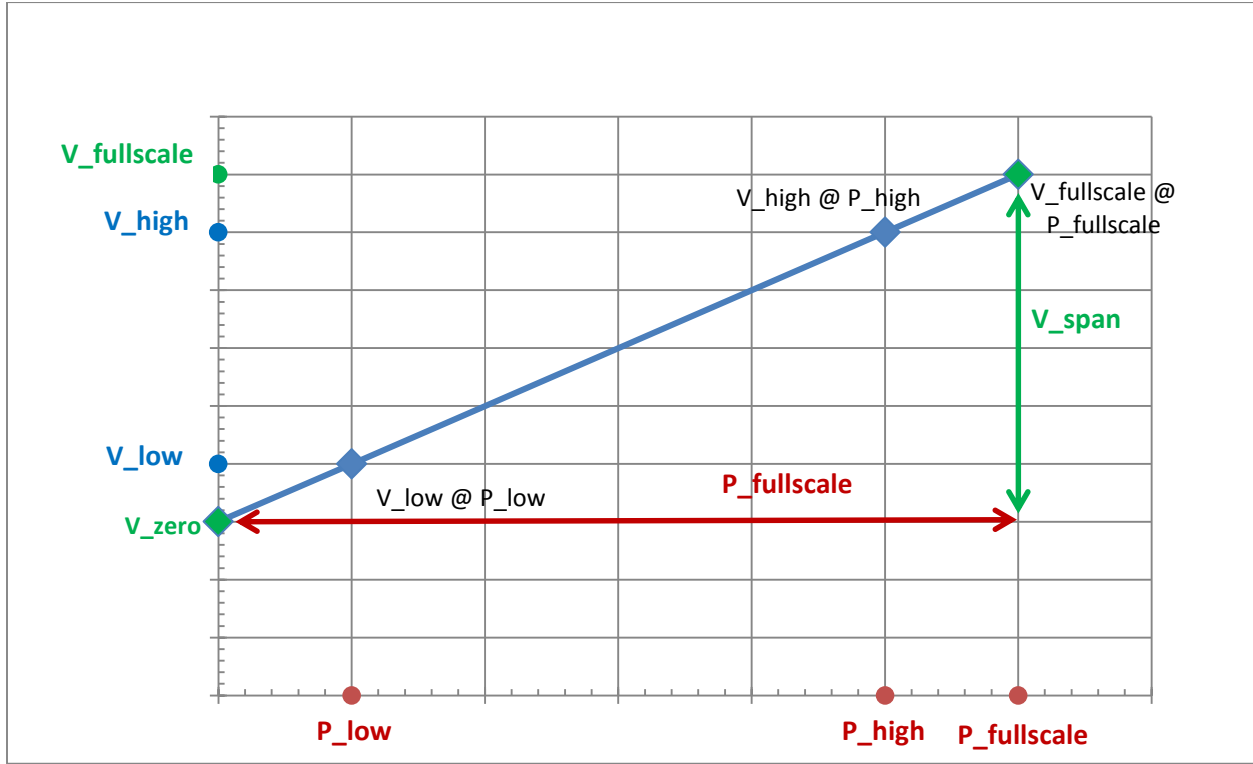

Figure 10: In this graphic the red values have to be adjusted during the calibration process and the blue ones will be measured by the microcontroller. With these values the green variables will be calculated

In this graphic the red values have to be adjusted during the calibration process and the blue ones will be measured by the microcontroller. With these values the green variables can be calculated.

$$V_{high} - V_{low} = V_{diff} \tag{42}$$

$$P_{high} - P_{low} = P_{diff} \tag{43}$$

$$Slope = Sensitivity = S = \frac{V_{diff}}{P_{diff}} = \frac{V_{span,ref}}{P_{fullscale}} \tag{44}$$

$$V_{span,ref} = P_{fullscale} * S \tag{45}$$

$$V_{zero,ref} = V_{low} - P_{low} * S \tag{46}$$

$$V_{fullscale} = V_{zero,ref} + V_{span,ref} \tag{47}$$

$$V_{out}(p) = S * p + V_{zero,ref} \tag{48}$$

For the calculation of the actual pressure value it is necessary to know the ambient temperature. In the constant current mode this value will be calculated by taking advantage of the known temperature behavior of the sensor's bridge resistance.

$$R_{Bridge} = \frac{V_{Bridge}}{I_{exc}} \tag{49}$$

$$R_{Bridge} = R_{ref} * \left(1 + \left(T - T_{ref}\right) * TCR\right) \tag{50}$$

$$\Leftrightarrow T = T_{ref} + \frac{1}{TCR}\left(\frac{R_{Bridge}}{R_{ref}} - 1\right) \tag{51}$$

With the knowledge of the ambient temperature, V_{ZERO} and V_{SPAN} can be calculated using equations 40 and 41. These values are then substituted into equation 52 and, together with the measured output voltage V_{OUT}, yield the actual pressure.

$$P(T) = (V_{out}\,(T,p) - V_{zero}(T)) * \frac{P_{span}}{V_{span}(T)} \tag{52}$$

4 Using the Evaluation Kit

This section explains the functionality of the Evaluation Kit software in further detail.

4.1   Setup

The Evaluation Kit software, which is provided as a LabVIEW executable, can only be run if the following Runtime Engines are installed on your system:

- LabVIEW Runtime Engine 2012 f3 (\07_Driver_and_Runtime_Engine\LVRTE2012f3std.exe)
- NI VISA Runtime Engine 5.4 (\07_Driver_and_Runtime_Engine\visa540_runtime.exe)

The installation files for those Runtime Engines can be found on the included USB-Stick (dir\Contents\ 07_Driver_and_Runtime_Engine) or on the National Instruments website www.ni.com.

Connect the Evaluation Board to the power supply and then to the PC using the USB-to-serial converter included in the Evaluation Kit. In addition to that, connect the sensor board to the base board by using the provided extension cable or by mounting it directly on the top of the base board as seen in Figure 1.

Once you connect the USB-to-serial converter to your PC, the drivers for it should install automatically (note that this and all the following directions given apply to Windows 7 PCs). If not, an installation file is provided on the USB-Stick (dir\Contents\07_Driver_and_Runtime_Engine\Setup_windows.exe). After the installation is done, the device should show up in the Device Manager under "Port (COM & LPT)" as indicated in Figure 11. To open the Device Manager go to: Start Menu > Control Panel > Device Manager. Locate the USB-to-serial adaptor in the Device Manager and note the number of the COM port that has been assigned to it.
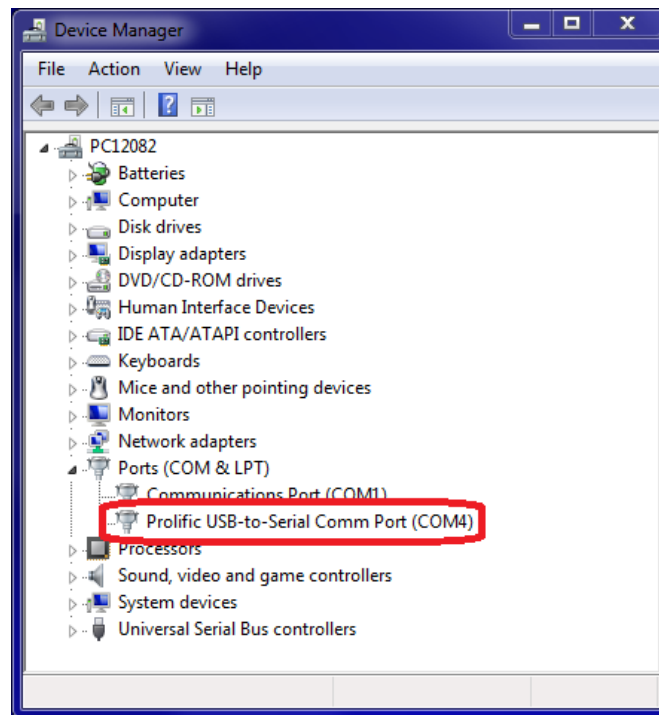
Figure 11: Device manager with connected Evaluation Kit (USB-to-serial converter)

The next step is to open the LabVIEW executable found under dir\Contents\ 06_LabVIEW_Exe. After opening the Evaluation Kit software, its main page will appear as shown in Figure 12 below.
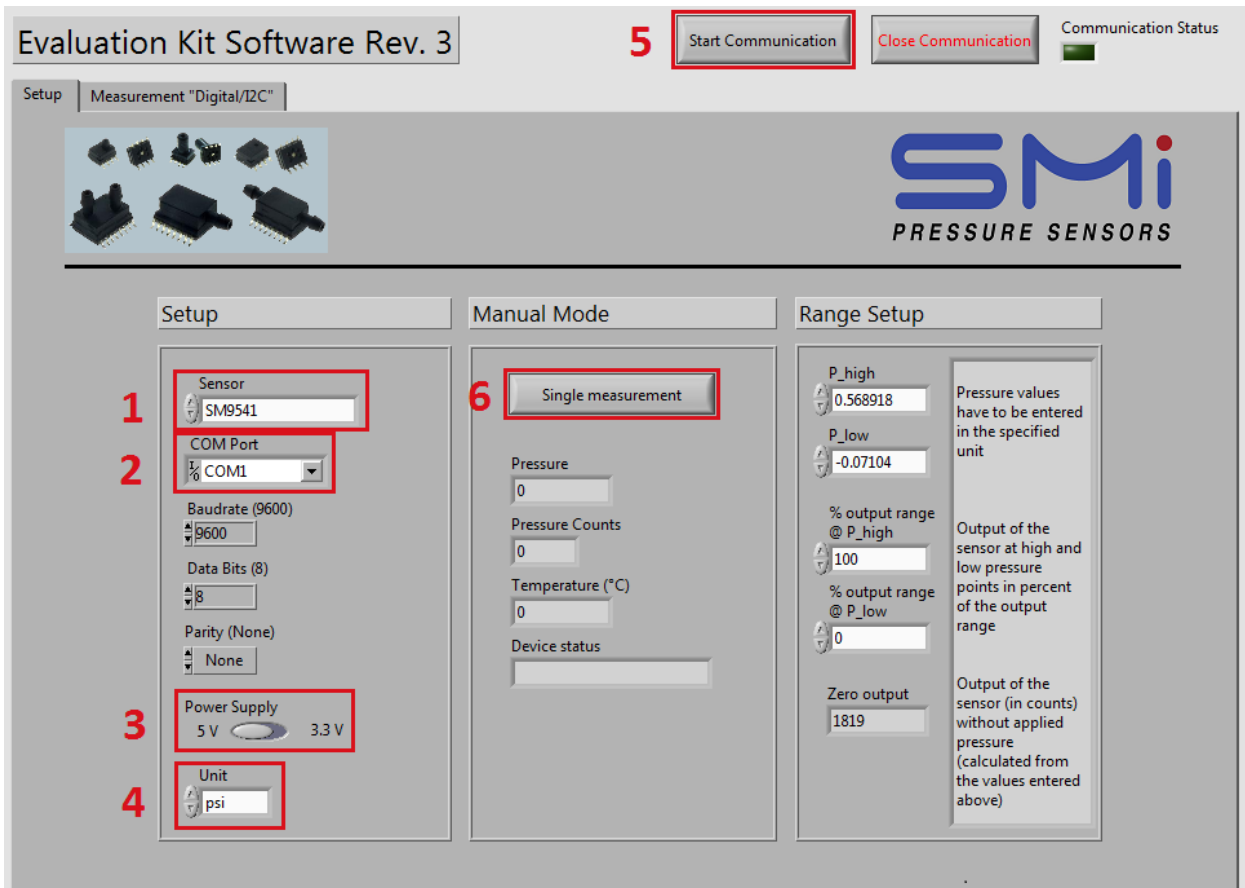
Figure 12: Main page of the Evaluation Kit software

Select the used sensor from the dropdown menu *Sensor* (see 1 in Figure 12) and the same COM port as displayed in the device manager from the dropdown menu *COM Port* (see 2 in Figure 12).

The three options below that, *Baudrate* (9600 bit/s), *Data Bits* (8), and *Parity* (no parity bit), do normally not need to be changed.

Make sure that the supply voltages on the board set by hardware jumper SV1 (see appendix, section 7.5 for more info) and in the software (marked 3 in Figure 12) match and are suitable for the used sensor. If the constant current mode for uncompensated parts is used, the current source on the respective sensor board will generate a supply current of 0.56 mA (5.0 V) or 0.37 mA (3.3 V).

To the bottom of the *Setup* box you can choose from a number of different pressure units (marked 4 in Figure 12). The pressure unit that is chosen here will generally affect every input and output pressure value throughout the Evaluation Kit software. In addition, a different pressure unit can be selected on every Measurement tab, which then is only applied to the pressure value right next to it. It is possible to change the pressure unit while the software is running

After changing those settings, all necessary adjustments are completed. To establish the communication between the Evaluation Board and the computer, press the *Start* communication (marked 5 in Figure 12)

button to the top of the main page. The communication setup screen will turn gray. If no communication error has occurred, the communication status lamp will turn on.

You can test the connection to the Evaluation Board by reading single sensor output points. To do that, press the *Single measurement* (marked 6 in Figure 12) button. Also check, if the returned values match your expectations. E.g. for a gauge sensor without any pressure applied, the returned output voltage should be the zero offset. Keep in mind, that the shown pressure sensor output for uncompensated sensors is by default amplified by a factor of 23 and depending on the jumper settings, it may also be level shifted (for further information see section 5.2.2). The temperature sensor output used for the constant voltage operation calibration of uncompensated sensors is not amplified.

If the displayed output voltages are zero, check the connection between the sensor board and the base board and press the reset button (yellow button on base board). Also, make sure that the sensor is mounted in the socket in the correct orientation with pin 1 towards the center of the sensor board.

4.1.1 Range setup of compensated sensors

Although the amplified analog and digital sensors do not require a calibration, some settings have to be made to correctly calculate the actual applied pressure from their output. These settings are grouped under the Range Setup box on the right of the main page.

All of the compensated sensors have a specified pressure range and, related to that, a full scale span which is measured in percent of the output range (%output range). The values for the pressure and output range can be found in the datasheet of the sensor and have to be entered into the respective fields inside the Range Setup box. From those data points the software creates a linear transfer function, as seen in Figure 13 below, which is then used to relate the sensor output to the actual applied pressure.
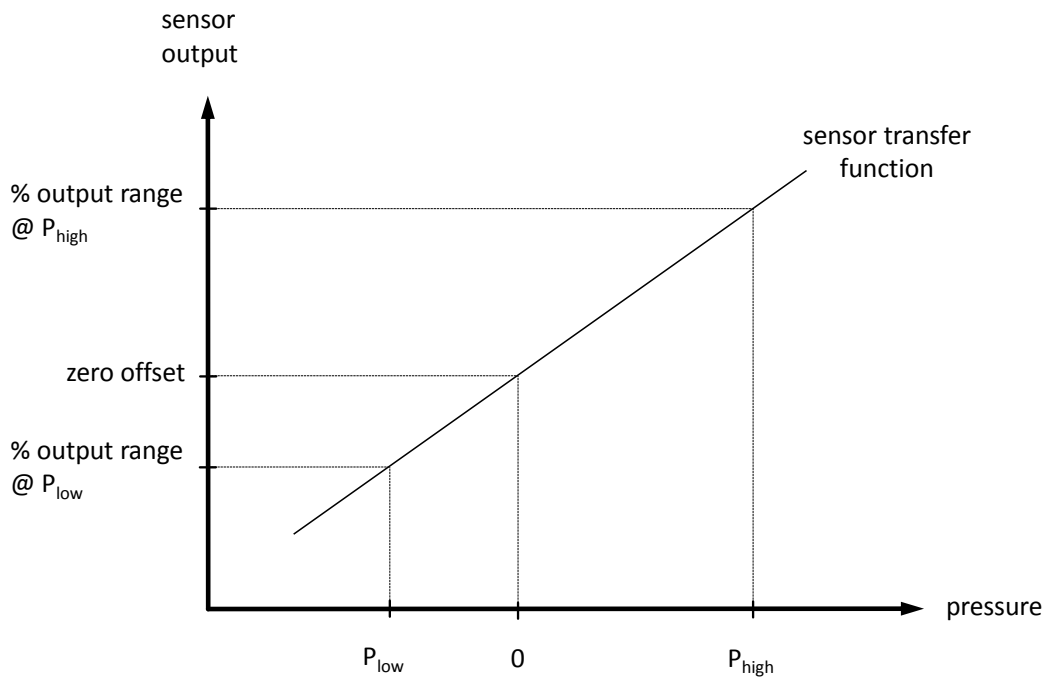
Figure 13: Relation between applied pressure and sensor output

An example: one version of the SM9541 sensor has a pressure range of -5 cmH$_2$O to 40 cmH$_2$O and a full scale span of 1,638 to 14,745 counts. As it is described in the datasheet, these count values will be read from the sensor at an applied pressure of -5 cmH$_2$O and 40 cmH$_2$O, respectively. The count values given above equate to 10% and 90% of the internal ADC resolution of 14 bit or 2^{14} = 16384 counts. Therefore, the correct range setup for this sensor would be: P$_{low}$ = -5 cmH$_2$O, P$_{high}$ = 40 cmH$_2$O, %output range @ P$_{low}$ = 10%, %output range @ P$_{high}$ = 90%.

The zero output, which is the count value with zero pressure applied to the sensor, is calculated from the pressure and full scale percentage values entered above. It makes for an easy way to check, if your range setup is correct.

4.2   Measurement pages

With the connection established, it is now possible to take measurements. The *Measurement* tab holds charts and indicators that will display and log the current pressure and temperature once you press the *Continuous Measurement* button. Depending on the used sensor, a multitude of other options are available as well.

The **uncompensated constant voltage** measurement page (see Figure 14) offers the choice to display either the amplified raw output voltage of the sensor or the compensated values as calculated by the microcontroller. Under *Compensation Type*, you can choose between 2-Point, best-fit-straight-line (BFSL) or polynomial compensation. Note that the compensation option will only work correctly after you have done a calibration.
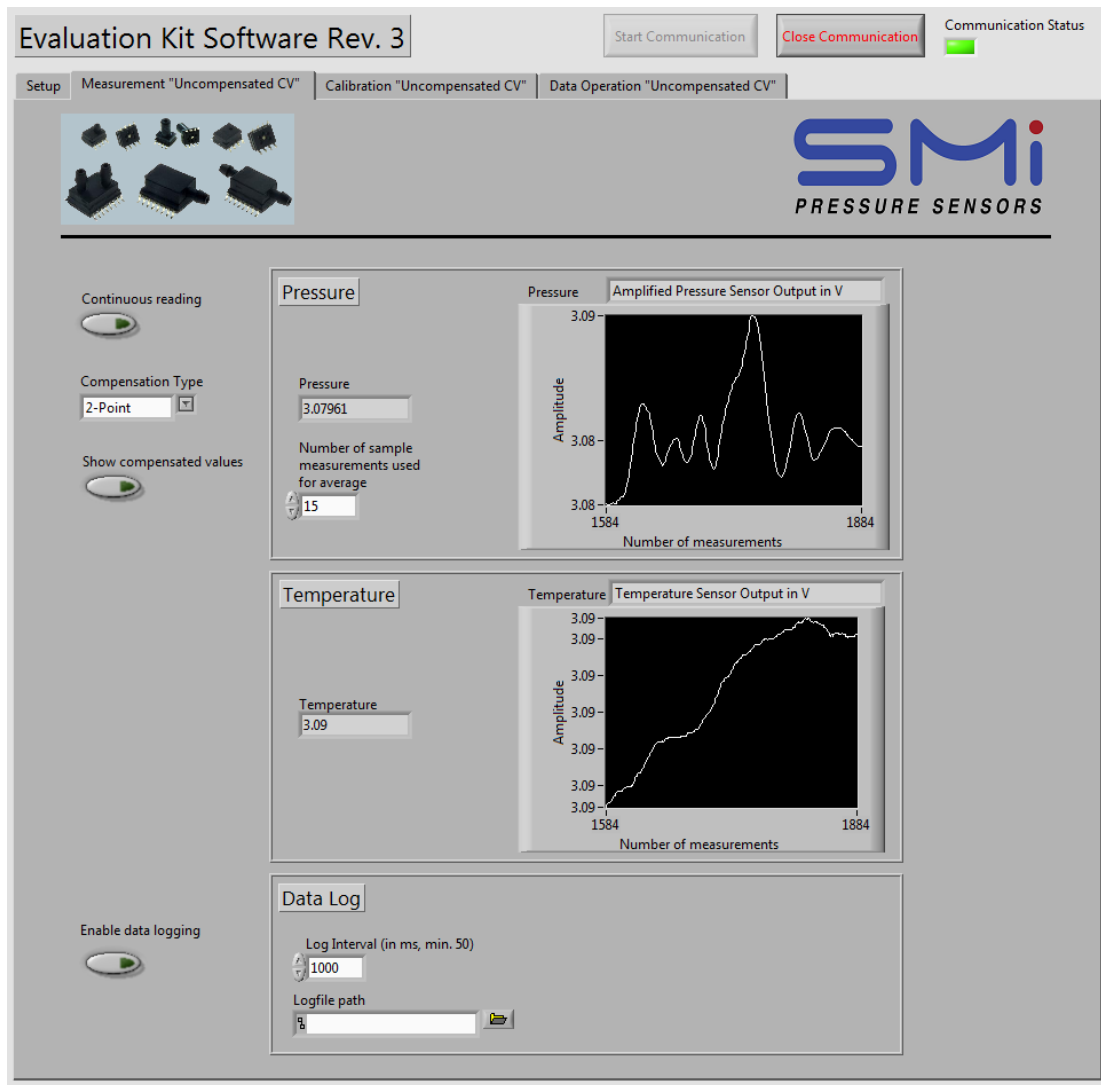

**Figure 14: Measurement page of the constant voltage mode
(measurement pages for other operation modes will look similarly)**

For the **uncompensated constant current** mode only the choice between compensated pressure values and raw output voltages is offered.

Since the output of the **Digital/I²C** sensors is already compensated, the Evaluation Kit will only display the values read from the sensor. For the devices covered by this Evaluation Kit. every reading from the sensor includes two status bits, which are interpreted by the Evaluation Kit software. Following four cases can occur:
- Normal operation

- Device in command mode: Should not occur during normal use. Wrong values might be provided by the sensor in this case
- Stale data: No new measurement has been performed since the last reading of the sensor
- Diagnostic condition: The ASIC in the sensor has detected one of the following errors: invalid EEPROM signature, loss of bridge positive or negative, bridge input short, loss of bridge source, loss of bridge sink, or loss of tail resistor. The sensor will stay in this condition until the cause of the error is removed and a power-on-reset is performed.

The same applies to the **Amplified Analog** reading, though the amplified analog sensors covered by this Evaluation Kit only provide a voltage output corresponding to a pressure value. Therefore, no temperature chart is available on the respective *measurement* page.

The choice of the *output unit* on the *Measurement* tabs only affects the pressure value displayed in the chart and the field next to it.

A moving average has been implemented in the Evaluation Kit software to reduce noise. You can choose the number of samples (between 1 and 100) that the function takes to calculate one averaged value.

For each of the sensors there is an option to log the measurement data. First, enter a log interval in milliseconds into the respective field. Note that the Evaluation Kit software will not be able to handle log intervals shorter than 50 ms. Once you hit the *Enable data logging* button, you will be asked to specify the file location and name. As a filename extension use ".txt". The resulting text file will be in a spreadsheet format that can easily be read into Excel or other data analysis software.

4.3   How to do a calibration

Due to normal process variations, every uncompensated sensor can be different regarding zero offset, span, and bridge resistance. The temperature coefficients for these three parameters vary from part to part as well. Each part needs to be calibrated individually to account for all those possible variations. Depending on the accuracy requirements of the application, it may be sufficient to assume typical values for certain parameters (e.g. the temperature coefficients).

To be able to compensate the pressure sensor output, temperature, and pressure raw data needs to be taken. From this raw data it is then possible to calculate the coefficients for the temperature compensation equations. Usually, the minimal requirements for a calibration are two temperature and two pressure points. The one temperature approach may work for certain application with looser accuracy requirements. For a higher accuracy it is recommended to collect data for up to five temperature and pressure points. Typical are two or three of each.

In order to achieve a good calibration it is also important to provide ideal conditions for the measurement. This includes time for stabilization. Especially temperature tends to deviate in testing environments when reaching 130 °C or -40 °C. Therefore, ample time should be allowed for the system to adjust to changes in temperature. Furthermore, deviations of the temperature within the test chamber, e.g. by fans or heating elements should be kept to a minimum while measuring. Pressure

changes are usually adapted to rather quickly. Nevertheless, it should be made sure that the system has stabilized before taking a measurement for the calibration.

To start a new calibration measurement, go to the *Calibration* tab of the program. The calibration procedures for constant voltage and constant current modes differ from each other and will be discussed separately in the following two sections.

Before starting the calibration, make sure that the bridge output of the sensor is not negative, as this will corrupt the calibration. If the raw voltage reading is zero or close to zero volt, it is probable that the actual sensor output voltage is negative and therefore cannot be amplified. In this case, activate the level shift by setting the corresponding jumpers. Refer to the hardware section (chapter 6) and/or the appendix for further information.

For best results it is recommended to:

- Identify your application's expected temperature range.
- Typically choose maximum, minimum, and one intermediate temperature of the given range. Depending on range and calibration a different choice might be preferable.
- At each temperature, choose three reasonable pressure points, e.g. 0.5, 15, and 30 psi for a sensor with a pressure range of 30 psi, and take measurements.
- If only two temperatures (or two pressures) are used, 15% and 85% of the temperature (or pressure) range are good starting points for the calibration points.
- Choose a calibration algorithm according to the temperature range. At temperatures between -10 °C and 70 °C any approach can be used, if higher or lower temperatures are expected in the application, Polynomial calibration is highly recommended.

4.3.1 Constant voltage calibration

Before starting the calibration, a few settings will have to be made. Under *Calibration Setup* choose the *Type of calibration* and the number of temperature and pressure points you want to use for the calibration. A moving average function with an adjustable sample length can be applied to the raw measurements. For most of the time, the automatic calibration mode will be sufficient. The manual calibration mode offers the possibility to specifically calculate, write and read the calibration coefficients to and from the microcontroller. By default, the outmost of the calibration data points are used for the calculation of the linear compensation modes. You can change that setting by switching from *Use outmost points* to *Choose points manually* and then choosing the data points to be used in the calculation from the appearing dropdown menus.

Set the calibration pressure points on the left of the calibration raw data table and then follow the steps given below:

1. To start the measurement, press the *Collect data* button in the Calibration Raw Data section (see Figure 15). When the *Collect data* button is pressed, a *Reached temperature point* button will appear in its place. The indicator for the first temperature point should now show the current temperature in °C.

2. Once the desired temperature is reached and stable, press the *Reached temperature point* button. Keep in mind that the temperature of the pressure sensor can be different from the temperature shown by the temperature sensor. The difference can be minimized by having a suitable waiting period after reaching the set temperature. The next step is to apply the pressure for the first pressure point to the sensor.
3. Once the output value is stable, press the *Reached pressure point* button to save the output voltage value for first pressure point and then continue in the same manner with the other pressure points.
4. After collecting the raw data for all pressure points, the temperature has to be changed to the next temperature point. Then start measuring all pressure points for the new temperature. Repeat this procedure until you collected all pressure and temperature points.
5. To perform the actual calibration, either the *Automatic* or the *Manual* mode (see Figure 15) can be used. The automatic mode will calculate all coefficients, write them to the microcontroller and then read out the stored values for confirmation. They are to be seen by selecting the corresponding *Type of calibration*. To use it, press the *Calibrate* button while *Automatic* mode is enabled. The calibration is now completed (skip steps 6 – 7).
6. In manual mode the collected data is used to calculate the coefficients for the different kinds of temperature compensations by pressing the *Calculate coefficients* button.
7. The final step is to save the coefficients in the microcontroller by pressing the *Write coefficients to microcontroller* button. You can check the microcontroller's programming with the *Read coefficients from microcontroller* button.

Figure 15: Calibration page of the constant voltage mode (automatic calibration mode)

On the Data Operation (see Figure 16) tab a number of options are available to save, load, and manually enter calibration data.

To save the data, specify a file path and name under *Saving path* and press the save-button. The calibration data including the measurement points and calculation coefficients will be saved as a text file in spreadsheet format.

The files created in this way can be loaded back into the software by selecting the file path and pressing the *Load calibration data* button. If you want to load the calibration data from a spreadsheet file, make sure that the *Load data from an Excel file* option is selected.

Alternatively, you can enter pressure, temperature, and raw voltage data into the Manual Raw Data Entry table. Upon selecting the option *Load data from the Manual Raw Data Entry table* and then pressing the *Load calibration data* button, the software will then fill the table on the *Calibration* tab. To

actually program the coefficients to the microcontroller, go over to the *Calibration* tab and press the *Calibrate* button.
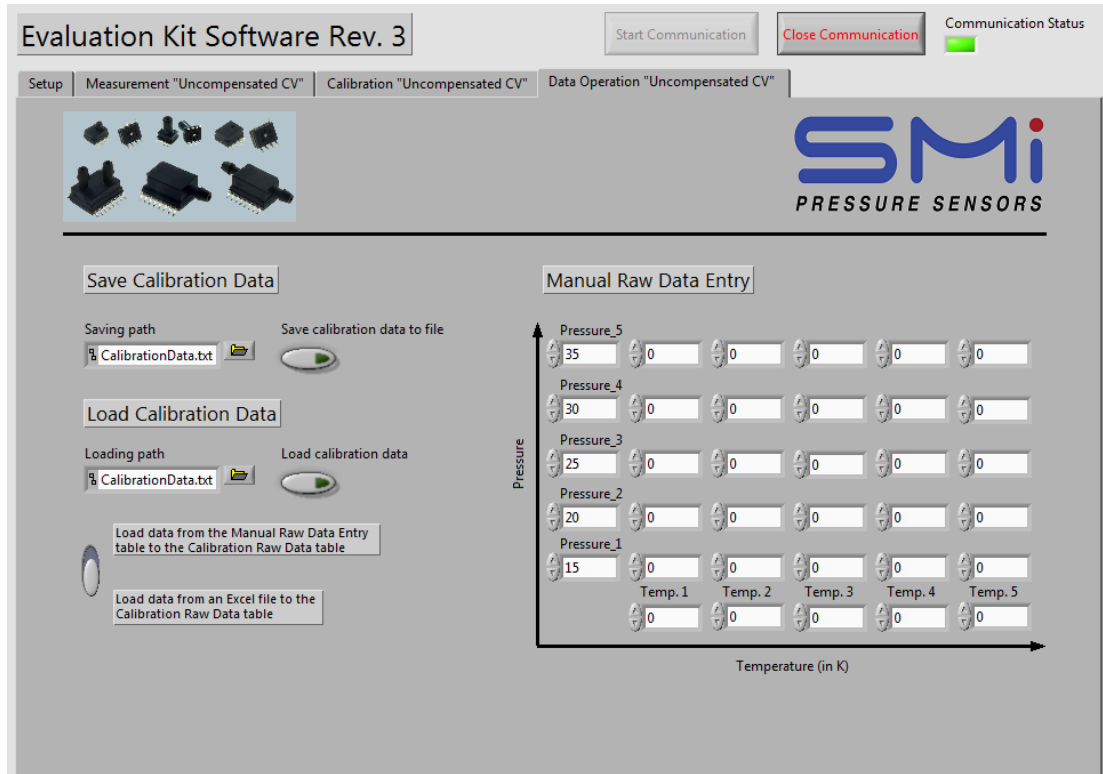

Figure 16: Data operation page of the constant voltage mode

4.3.2 Constant current calibration

The constant current calibration process is, compared to its constant voltage counterpart, quite simple. Only two pressure points at one temperature are needed. Using the typical values for the sensor characteristics like TCS, TCR and TCZ is sufficient to achieve a fairly high accuracy. This makes it an ideal method of compensation for consumer applications, where only small operating temperature ranges are demanded.

First, start the software using a sensor that supports the constant current mode. They will be marked with (CC) behind the part number in the dropdown menu *Sensor*. Start the communication, then go to the tab named *Calibration "Uncompensated CC"* (see Figure 17) and follow the steps given below:

1. In section *Enter Calibration Data*, enter the pressure values for the *low* and *high pressure point* and the *pressure range* that you want to use. Also give a *reference temperature* at which the calibration will be performed.
2. The characteristics of the used sensor have to be specified in section *Enter Part Data*. It is sufficient to use the typical values given on the datasheet for the temperature coefficient of span (TCS), of the bridge resistance (TCR), and the zero offset (TCZ). These values are as follows: $TCS = 0.0651 \frac{\%FS}{°C}$ and $TCZ = 0.0251 \frac{\%FS}{°C}$. The TCR can be found in the sensors' respective

datasheets. An even higher degree of accuracy can be obtained, if the exact characteristics above are measured for each sensor in advance.

3. Go to the *Calibration* section and press the *Start calibration* button. Apply the lower pressure to the sensor and make sure the actual temperature is close to the reference temperature given above. Wait until the values of V_{LOW} and $V_{TEMP,REF}$ are stable and then press the corresponding button. Now apply the high pressure to the sensor and press the corresponding button again after the pressure has stabilized.

4. The compensation coefficients V_{ZERO} and V_{SPAN} will be calculated from the measured values. Press the *Write µC coefficients* to write all the coefficients to the microcontroller.

5. After that the calibration process is finished and compensated pressure values can be taken on the *Measurement* tab of the Evaluation Kit software by enabling *Show compensated values*.

Figure 17: Calibration page of the constant current mode

4.4   Troubleshooting

In case of unexpected behavior, check, if…

-   …the power supply is plugged in correctly

- …the supply jumpers (SV1) are set consistently
- …the power supply setting on the board is the same as selected in the software
- …the USB-to-serial converter is connected properly
- …all drivers are installed correctly on your computer
- …the correct COM port is chosen in the communication setup of the software
- …the sensor board is connected properly to the base board
- …the orientation of the flat cable is connected in the correct orientation
- …the sensor is placed correctly in the socket

Also try to reset the board by pressing the reset button S1. In rare cases, it can happen that miscalculated calibration coefficients outside the microcontroller's numerical limits will crash the algorithm.

5 Evaluation Kit Hardware

5.1 Hardware Design Explained

The Evaluation Kit consists of a base board and a choice of different sensor boards according to working principle of the used sensor. The base board holds the microcontroller, amplification circuitry and means of communication to a PC. The sensor boards connect the different sensors to the base board and can be either mounted directly on the base board or linked to it with the included cable. That way, the sensor board can be placed inside a temperature chamber while the more temperature sensitive electronics on the base board can remain outside. When using the cable, check that the position of the red stripe on the cable is as shown in the Figure 18 below.
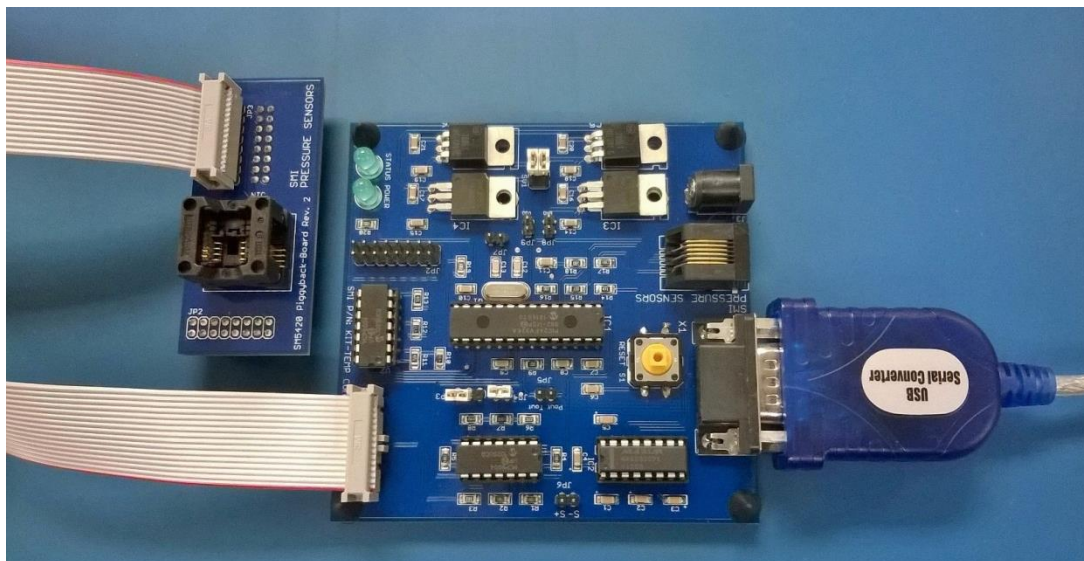

Figure 18: Evaluation Kit and sensor board connected through the included cable

5.2   Circuitry

The central part of the Evaluation Kit base board is a Microchip PIC24 microcontroller. The Universal Asynchronous Receiver/Transmitter (UART) port of the microcontroller is used to connect a computer to the Evaluation Base Board. The communication between the PC running the LabVIEW executable and the microcontroller is established through an RS-232 interface (see Figure 9). Because of the different voltage levels on the PC and the microcontroller, an RS-232 driver/receiver chip (MAX232) is required. The MAX232 shifts the signals to a common level.
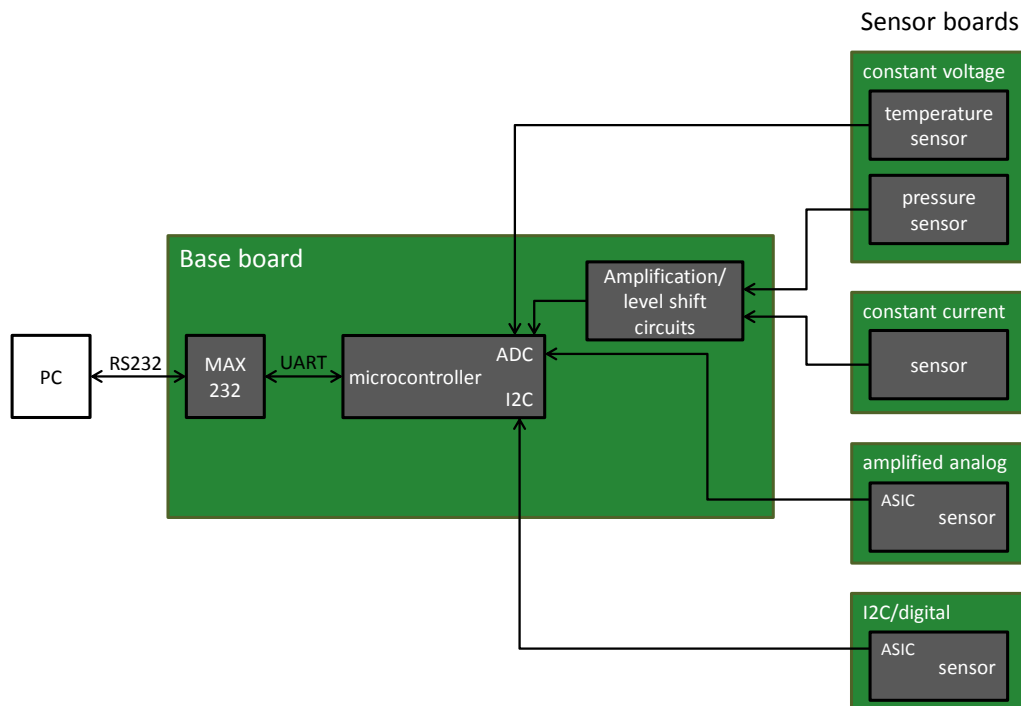

Figure 19: Schematic of the signal flow of the Evaluation Kit

The PIC24 microcontroller features a 12-bit ADC that is used to read the amplified bridge output voltage of the uncompensated constant voltage and constant current sensor. As can be seen in Figure 19, the output of the thermistor and the amplified analog pressure sensor are acquired by means of the ADC as well. The microcontroller also includes an I^2C interface to communicate with the digital/I^2C sensors and handles the actual compensation, which consists of the storage of the calibration coefficients and the calculation of the true pressure.

5.2.1   Amplification Circuit

To be able to use the full range of the analog to digital converter (ADC) of the microcontroller, it is necessary to amplify the differential output voltage of the pressure sensor. Therefore the Evaluation Kit base board uses an instrumentation amplifier as shown in Figure 20.

The standard resistor setup is R7 = 2 kΩ, R6 = R8 = 22 kΩ and R1 = R2 = R4 = R5 = 10 kΩ. The standard resistor setup results in an amplification of 23 (see equation 53). In this configuration the amplification will work with any of the uncompensated sensors. For the use of a particular version of the pressure sensor, it is possible to adjust the resistors setup to use the full range of the ADC by replacing the resistors R6 and/or R7.

$$Vadc = (Vpos - Vneg) * \left(1 + 2 * \frac{R6}{R7}\right) \tag{53}$$
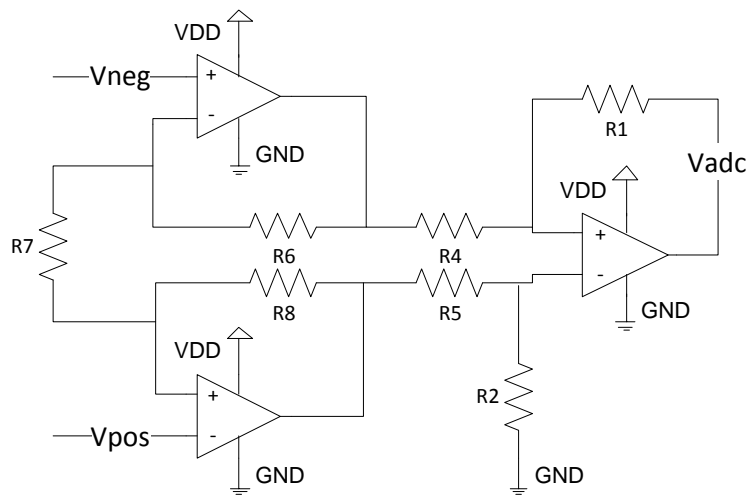
Instrumentation Amplifier

Figure 20: Schematic of the instrumentation amplifier circuit

5.2.2   Optional Level Shift

Another feature of the Evaluation Board is the level shift of the bridge output voltage. If a sensor is used at the limit of its characteristics, where the differential output voltage could be negative (see chapter 2), the instrumental amplifier might stop working properly. In this case it is possible to enable a level shift circuitry on the Evaluation Board, which adds a small offset to the positive sensor output, thus increasing the differential output signal of the sensor. The combined signal then gets amplified by the instrumentation amplifier. It might be necessary to lower the gain of the amplifier to prevent it from railing. This happens, if the theoretical output voltage exceeds the maximum output voltage of the amplifier, which in most cases is defined by the supply voltage. However, a lower amplification of the measurement signal will result in a lower overall measurement accuracy. Therefore, it is recommended to use the level shift only if necessary. To see if a level shift is necessary, go to the lowest pressure that you want to measure and look at the uncompensated pressure sensor output. If it is significantly greater than 0.6 V, there is no need for a level shift. To enable the level shift set jumper JP3 and JP4 accordingly on the Evaluation Board (see section 7.5).

In addition to the level shift operational amplifier, there is a need for an impedance converter to stabilize the sensor output. The impedance converter makes sure that the original sensor output is not loaded down by the level shift circuitry. As a result, the level shift is working with a higher accuracy.

The output of the impedance converter is connected with the level shift circuitry over the resistor R13. The standard setup for the resistors on the Evaluation Board is set to R10 = R12 = 470 Ω and R11 = R13 = 47 kΩ. With that setup the voltage added to V_{POS} is 50 mV for a 5.0 V power supply and 30 mV for 3.0 V power supply (see Figure 21). This ensures that the voltage between the level shift output and negative sensor output is positive. Because of the amplification (x23), the level shift voltage offset of 50 mV (5.0 V supply voltage) causes an additional offset of 1.15 V on the amplified sensor output.

$$Via = \frac{R10+R11}{R10} * \frac{R12}{R13+R12} * Vin + \frac{R10+R11}{R10} * \left(1 - \frac{R12}{R13+R12}\right) * Vdd \qquad (54)$$
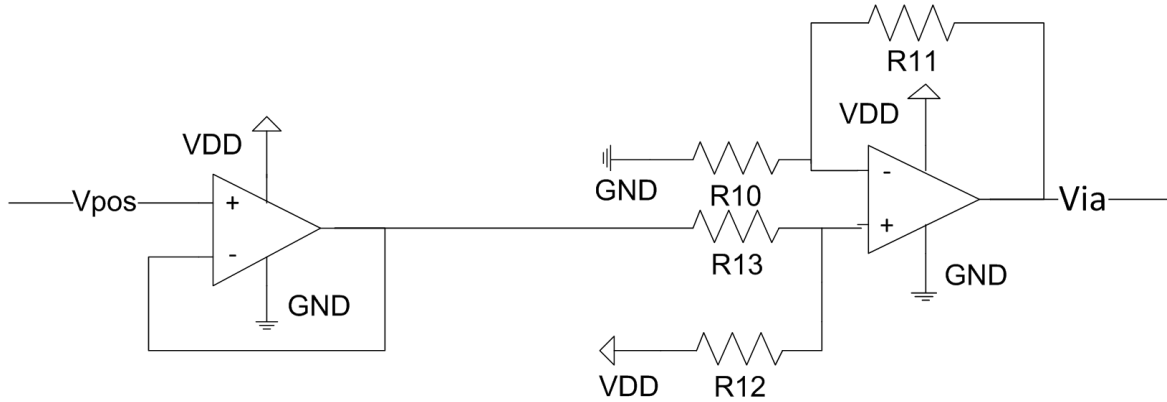
$$= Vin + Vdd * 0.01$$

Figure 21: Schematic of the level shift circuit

5.2.3 Power Supply

The nominal voltage supplied to the board through the power jack is 12 V. The Evaluation Kit base board is equipped with two different DC voltage regulators, to be flexible regarding the supply voltage of the microcontroller and also the pressure sensor. The user can choose between a supply voltage of 5.0 V and 3.3 V by changing the jumper position of jumper SV1. To reduce the noise on the ADC converted signal, there is a second DC voltage regulator of each voltage level on the board supplying the ADC reference voltage. More details about the related jumper settings are given in the appendix, section 7.4.

5.2.4 Temperature Measurement

Temperature information is needed to be able to perform temperature compensation of the output of the uncompensated constant voltage pressure sensor. Therefore, a negative temperature coefficient (NTC) thermistor is part of the circuit for the constant voltage mode. For the most accurate temperature compensation, it is important to measure the temperature very close to the pressure sensor. For this

reason the NTC thermistor is mounted right next to the sensor socket of the constant voltage sensor board.

The resistance of the NTC temperature sensor is determined by using a voltage divider consisting of the thermistor and R3 as a known reference resistor. By measuring the voltage drop over R3 with the ADC, the resistance of the thermistor can be determined. The actual temperature is then calculated from the resistance value with the resistance-temperature-equation given by the manufacturer of the NTC thermistor (see included datasheet for more information).

The analog output of the NTC temperature sensor does not need to be amplified, but it has to be stabilized by an impedance converter before it is measured with the ADC of the microcontroller (see Figure 22).
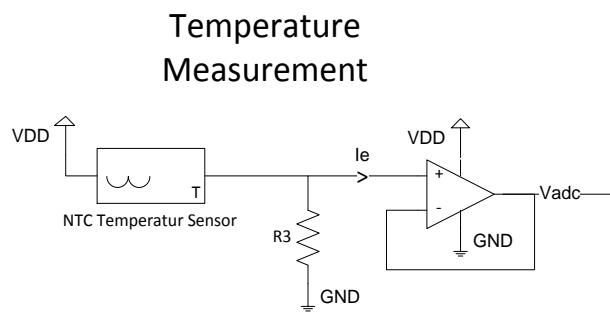
Figure 22: Schematic of the temperature measurement circuit

The impedance converter has a high input resistance and minimizes the current I_E which is flowing out of the voltage divider into the ADC of the microcontroller. This is the case because of the high input resistance of the operational amplifier. A high current I_E would lower the current through the output resistor R3 and with it the output voltage. So the output voltage would be corrupted by the analog to digital conversion. That effect is minimized by the impedance converter.

It is important that the output resistor R3 is not placed on the sensor board to avoid any changes in the resistance caused by temperature. The output resistor R3 (3 kΩ) is placed next to the operational amplifier of the impedance converter (see layout of Evaluation Board in section 7.2). If the value of R3 is modified, the microcontroller software has to be modified as well in order to be able to calculate the temperature properly. Further explanation can be found in the comments on the provided C-code (see code file compensated).

5.3   Uncompensated constant current sensor board

An operational amplifier circuit is implemented on the constant current sensor board to generate the former. The resulting current is dependent on the selected supply voltage. A supply voltage of 5V will lead to a current of 0.56 mA, 3.3V in 0.37 mA, respectively.

6 Expected Performance

Data and plots showcase the expected performance of uncompensated sensors operated in constant voltage mode using the Evaluation Kit and the suggested calibration scheme.

Test descriptions:

- Two sensors tested
- Measure sensor output voltage at 5 different temperatures
- Three "cases"
    - Case 1: Use 3 temperature points in a narrow range
    - Case 2: Use 3 temperature points in a wide range
    - Case 3: Use 5 temperature points in a wide range
- Compare the calibration error for the different calibration equations in second measurement

Table 1: Overview of temperatures and pressures of the three calibration schemes

Case	T1	T2	T3	T4	T5
1	0	25	75	-	-
2	-35	25	120	-	-
3	-30	0	25	75	120

The tested sensors typically show a linear behavior over temperature in the range of -10 °C to 70 °C. This has several consequences which can be seen in the following figures.

Figure 29 and Figure 32 show that for Case 1 within the given range the three calibration schemes provide nearly identical results. This is because the calibration points can be fitted on a straight line approximately. Therefore the Linear and the BFSL calibration return almost the same coefficients, while the Polynomial calibration returns a fitting with a very small second order dependency. This leads to measurements outside the linear range of the sensors being further off.

Figure 30, Figure 31, Figure 33 and Figure 34 analogously show that in Cases 2 and 3 a linear calibration based on the outmost values is very imprecise.

Comparing Figure 30 to Figure 31 or Figure 33 to Figure 34, shows that there is little gain in precision when using 5 instead of 3 temperature points for calibration.

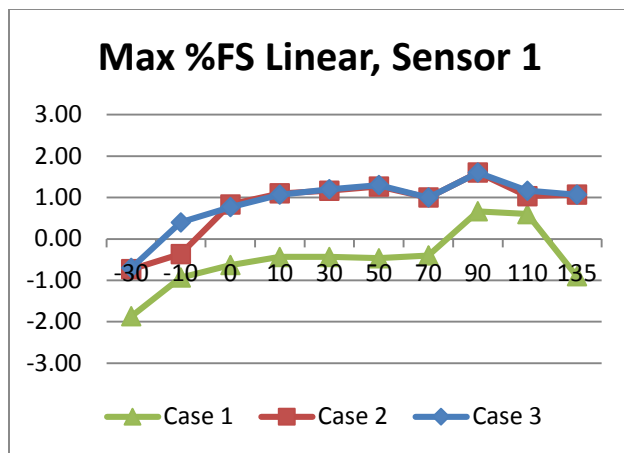Figure 25 and Figure 28 show that, with few exemptions, the Polynomial calibration provides results with an error of less than ± 1 %FS.
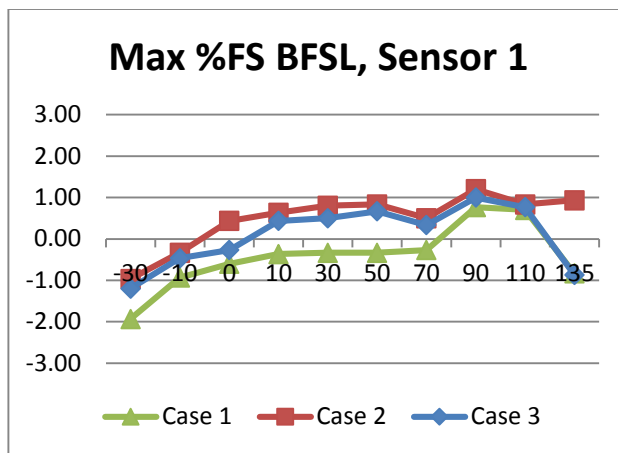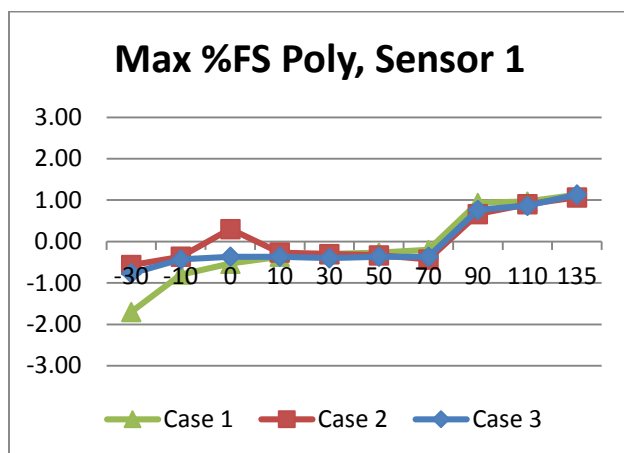
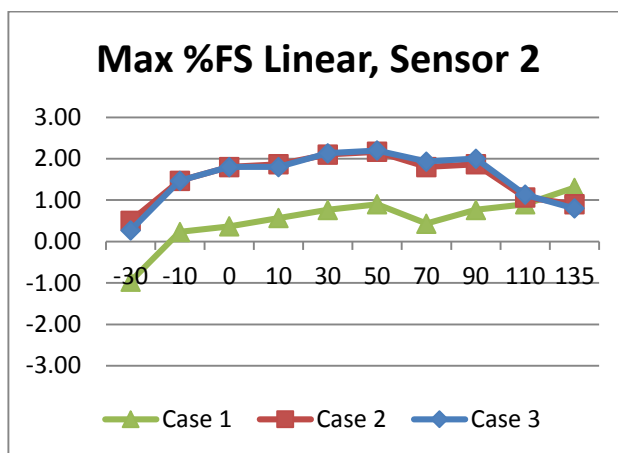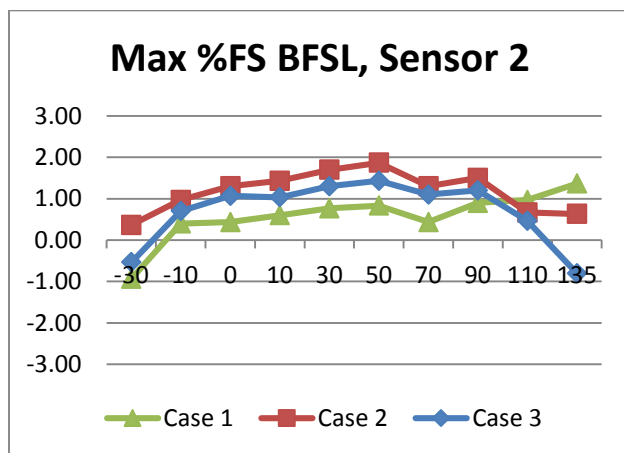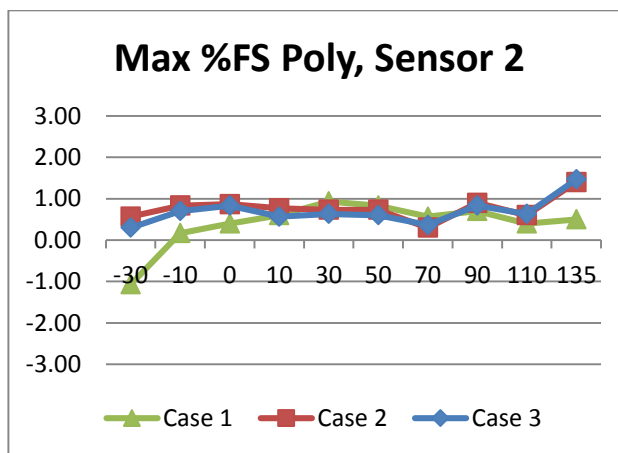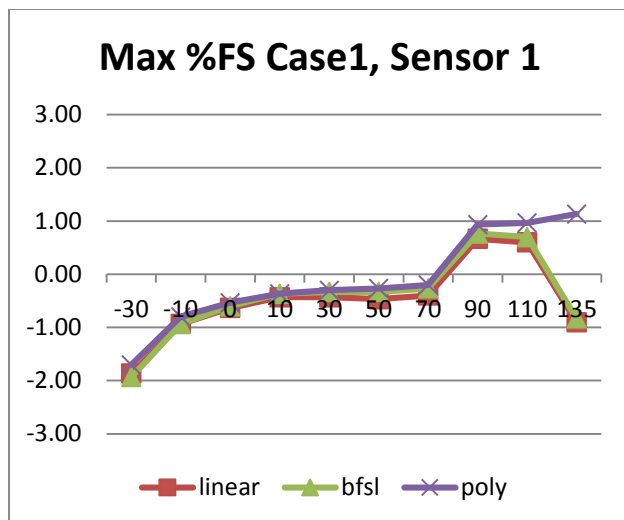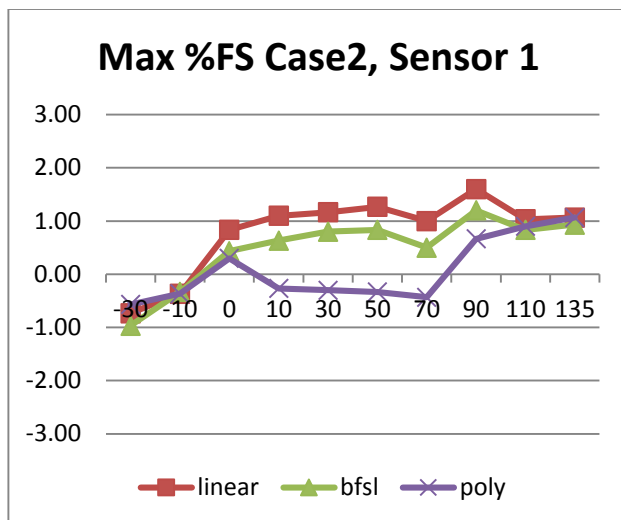Figure 23

Figure 24

Figure 25

Figure 26

Figure 27

Figure 28

Figure 29

Figure 30
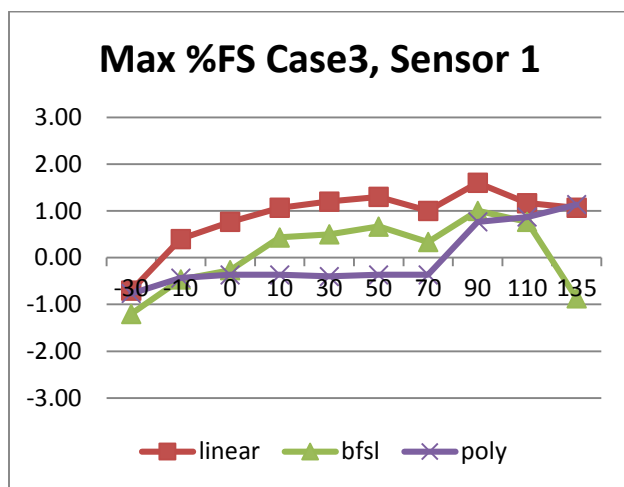
Figure 31
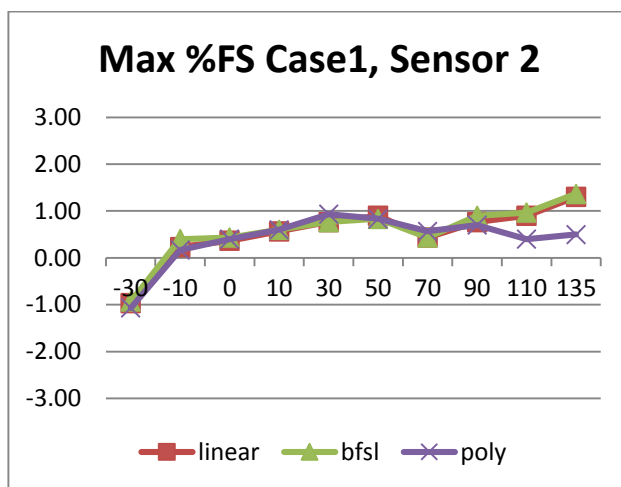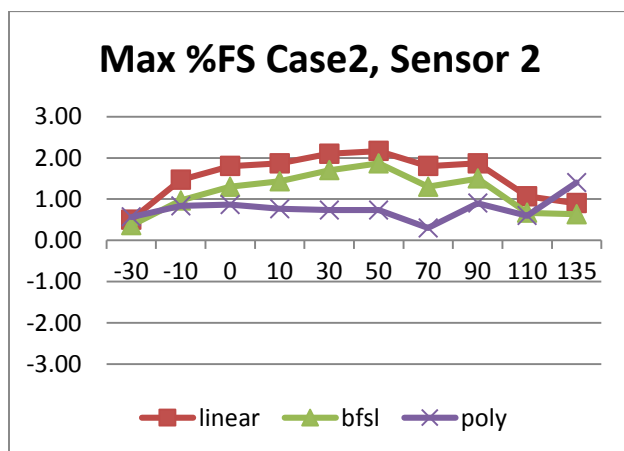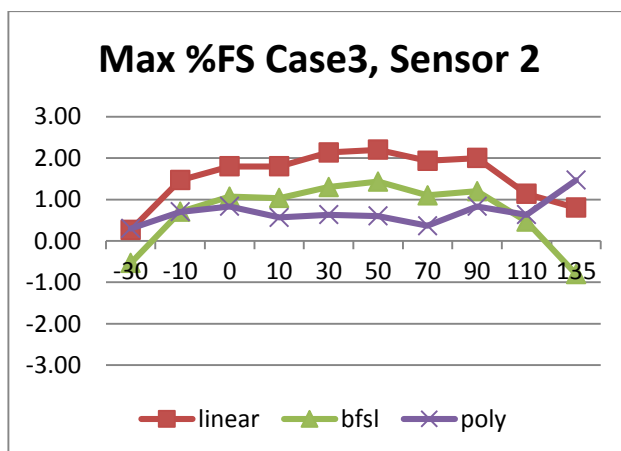

Figure 32

Figure 33

Figure 34

7 Appendix

7.1 Detailed PCB Schematics

The schematic of the Evaluation Kit Base Board is shown in Figure 35. Find the schematics and Layouts of the sensor boards on the included USB drive under \Contents\01_Documentation\Schematics and Layouts.
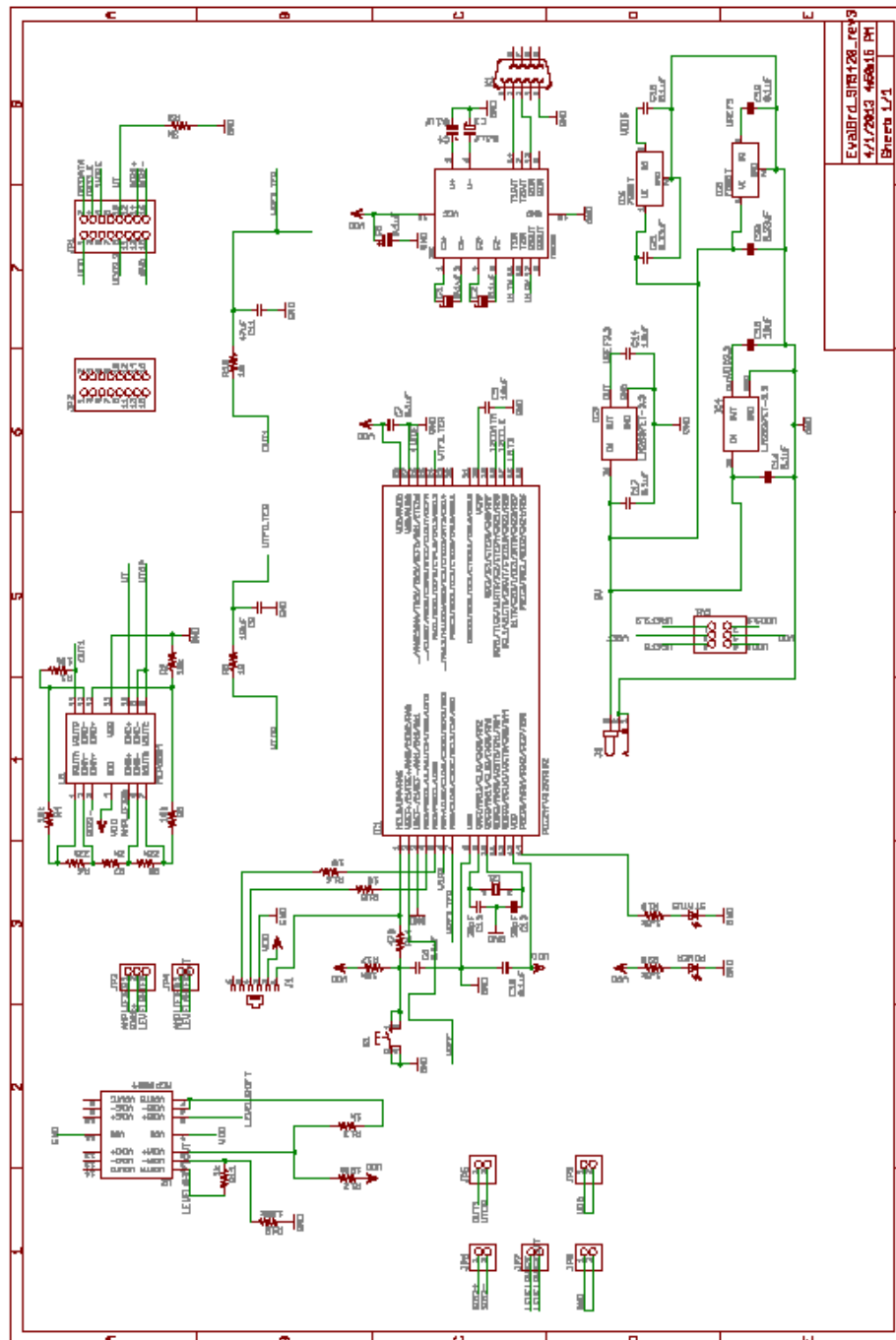
7.2 PCB Layout

Figure 36: Evaluation Kit Base Board Layout, GND and VDD planes hidden (embedded pdf)

7.3 Used Hardware Elements / Bills of materials

Table 2: Bill of materials, Base Board

Description	Manufacturer	Part Number	Qty.	Elements
Resistor		SMD 1206 10 Ω	4	R9, R15, R16, R18
Resistor		SMD 1206 470 Ω	1	R14
Resistor		SMD 1206 1 kΩ	2	R11, R13

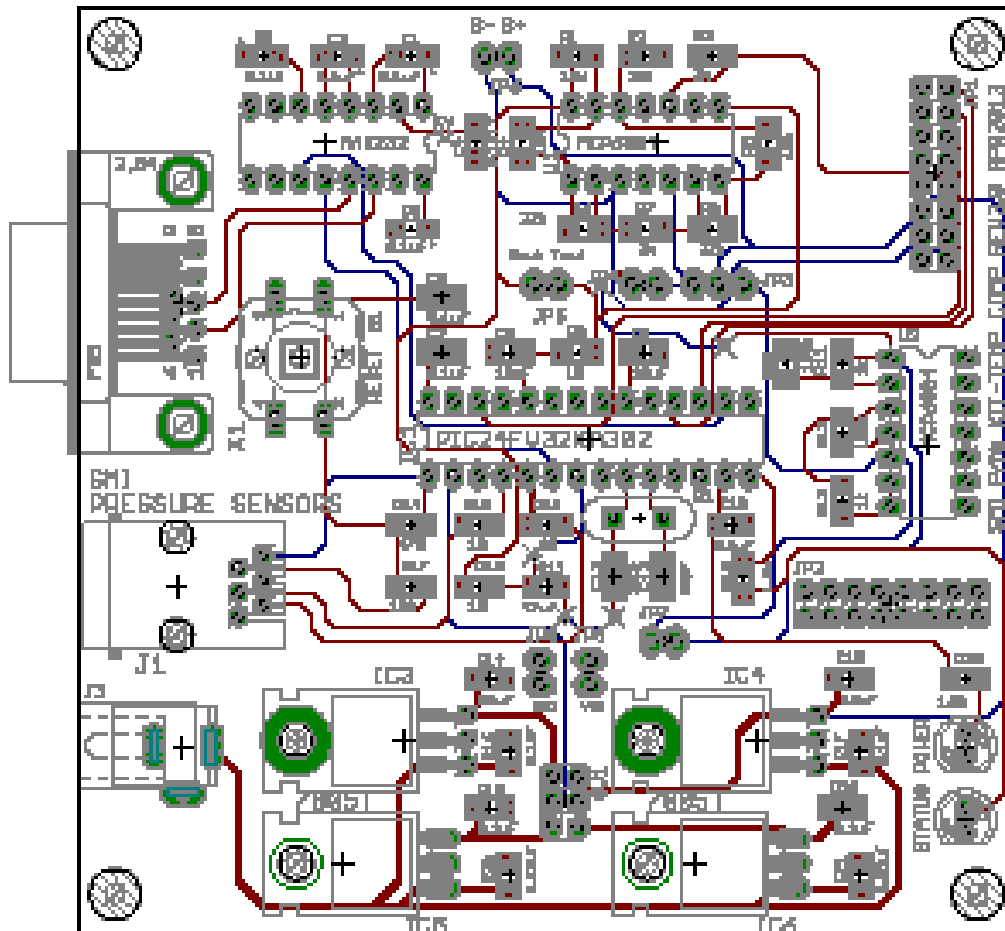|				
Resistor		SMD 1206 1.5 kΩ	2	R19, R20
Resistor		SMD 1206 2 kΩ	1	R7
Resistor		SMD 1206 3 kΩ	1	R3
Resistor		SMD 1206 10 kΩ	5	R1, R2, R4, R5, R17
Resistor		SMD 1206 22 kΩ	2	R6, R8
Resistor		SMD 1206 100 kΩ	2	R10, R12
Capacitor		SMD 1206 20 pF	2	C12, C13
Capacitor		SMD 1206 0.1 µF	12	C1, C2, C3, C4, C5, C6, C7, C10, C16, C17, C18, C19
Capacitor		SMD 1206 0.33 µF	2	C20, C21
Capacitor		SMD 1206 10 µF	4	C8, C9, C14, C15
Capacitor		SMD 1206 47 µF	1	C11
Microcontroller	Microchip	PIC24FV32KA302	1	IC1
RS-232-IC-Interface	Maxim	MAX232CPE	1	IC2
Low dropout regulator	Texas Instruments	LM2937ET-3.3	2	IC3, IC4
Low dropout regulator	On Semiconductor	7805T	2	IC5, IC6
Operational Amplifier	Microchip	MCP6004	2	U1, U2
Crystal		7.3728 MHz	1	Q1
Pushbutton Switch	Omron	4055	1	S1
Phone Jack			1	J1
Power Jack			1	J3
Pin Header		2x8, pitch 0.1"	2	JP1, JP2
Pin Header		1x3, pitch 0.1"	1	JP3
Pin Header		1x2, pitch 0.1"	6	JP4, JP5, JP6, JP7, JP8, JP9
Pin Header		2x3, pitch 0.1"	1	SV1
D-Sub Female Connectors			1	X1
LED (Low Power)			2	STATUS, POWER
Jumper			4	

Table 3: Bill of materials, Constant Voltage sensor board

Description	Manufacturer	Part Number	Qty.	Elements
Capacitor		SMD 1206 0.1 µF	1	C1

Thermistor	Vishay	NTCS0805E3222GMT	1	NTC
Sensor Socket	Enplas	OTS-8(16)-1.27-03	2	U1
Pin Header		2x8, pitch 0.1"	2	JP1
Pin Header		2x8, female, pitch 0.1"	4	JP2, JP3

Table 4: Bill of materials, Constant Current sensor board

Description	Manufacturer	Part Number	Qty.	Elements
Capacitor		SMD 1206 0.1 µF	1	C1
Operational Amplifier	ST Microelectronics	LM358N	1	IC1
Sensor Socket	Enplas	OTS-8(16)-1.27-03	2	U1
Resistor		SMD 1206, 100 kΩ	1	R1
Resistor		SMD 1206, 2 kΩ	1	R2
Resistor		SMD 1206, 174 Ω	1	R3
Pin Header		2x8, pitch 0.1"	2	JP1
Pin Header		2x8, female, pitch 0.1"	4	JP2, JP3

Table 5: Bill of materials, SM5430/5470 sensor board

Description	Manufacturer	Part Number	Qty.	Elements
Capacitor		SMD 1206 0.1 µF	1	C1
Resistor		SMD 1206 0 Ω	2	R0, R0'
Resistor		SMD 1206	2	R1, R2
Thermistor	Vishay	NTCS0805E3222GMT	1	NTC
Sensor Socket	Enplas	OTS-16-1.27-04	2	U1
Pin Header		2x8, pitch 0.1"	2	JP1
Pin Header		2x8, female, pitch 0.1"	4	JP2, JP3

Table 6: Bill of materials, Digital/I²C sensor board

Description	Manufacturer	Part Number	Qty.	Elements
Capacitor		SMD 1206 0.1 µF	1	C1
Resistor		SMD 1206 4.7 kΩ	2	R1, R2
Sensor Socket	Enplas	OTS-16-1.27-04	2	U1
Pin Header		2x8, pitch 0.1"	2	JP1
Pin Header		2x8, female, pitch 0.1"	4	JP2, JP3

Description	Manufacturer	Part Number	Qty.	Elements
Capacitor		SMD 1206 0.1 µF	1	C1
Sensor Socket	Enplas	OTS-16-1.27-03	2	U1
Pin Header		2x8, pitch 0.1"	2	JP1
Pin Header		2x8, female, pitch 0.1"	4	JP2, JP3

Minimum required components for calibration and operation of an uncompensated constant voltage sensor such as the SM5420, including the NTC sensor, low pass filter, and instrumentational amplifier. It is assumed that a system with microcontroller is existing; level shift not required.

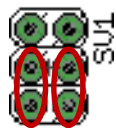| Description	Manufacturer	Part Number	Qty.	Elements	Budgetary Cost
Resistor		SMD 1206 10 kΩ	4	R1, R2, R4, R5	$0.04
Resistor		SMD 1206 3 kΩ	1	R3	$0.01
Resistor		SMD 1206 22 kΩ	2	R6, R8	$0.02
Resistor		SMD 1206 2 kΩ	1	R7	$0.01
Resistor		SMD 1206 10 Ω	2	R9, R18	$0.02
Capacitor		SMD 1206 10 µF	1	C8	$0.03
Capacitor		SMD 1206 47 µF	1	C11	$0.03
Operational Amplifier	Microchip	MCP6004	1	U1	$0.263 @ 250 pcs
Capacitor		SMD 1206 0.1uF	1	C1 sensor board	$0.03
Thermistor	Vishay	NTCS0805E3222GMT	1	sensor board	$0.227 @ 1000 pcs
					$0.84

7.4   Power supply schematic
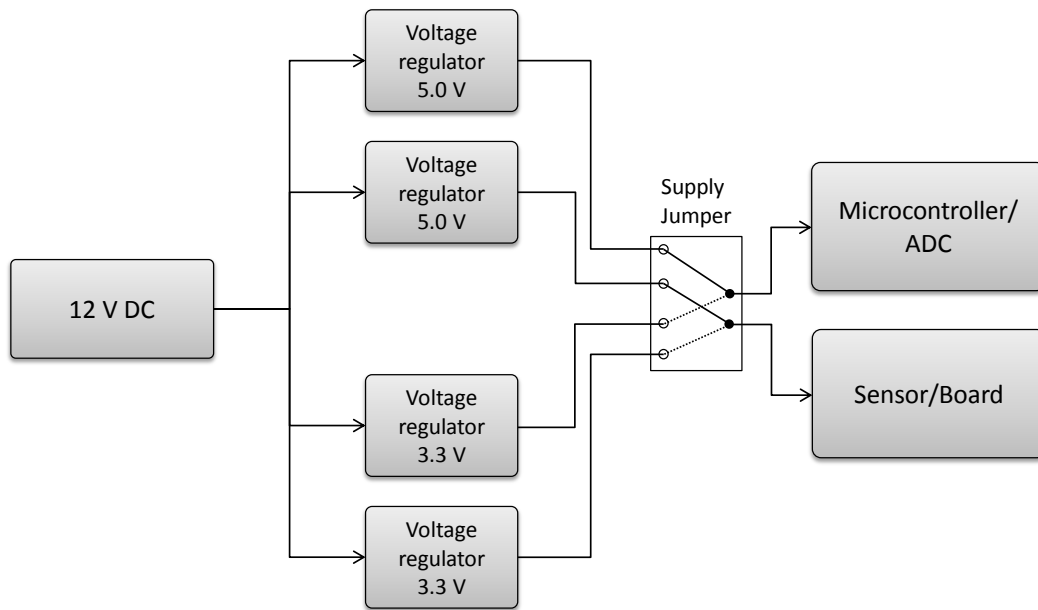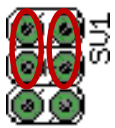
Figure 37: Power supply schematic

7.5   Jumper Settings

Supply Jumper	5 V Supply Voltage	3.3 V Supply Voltage
Levelshift Jumper	Levelshift disabled	Levelshift enabled

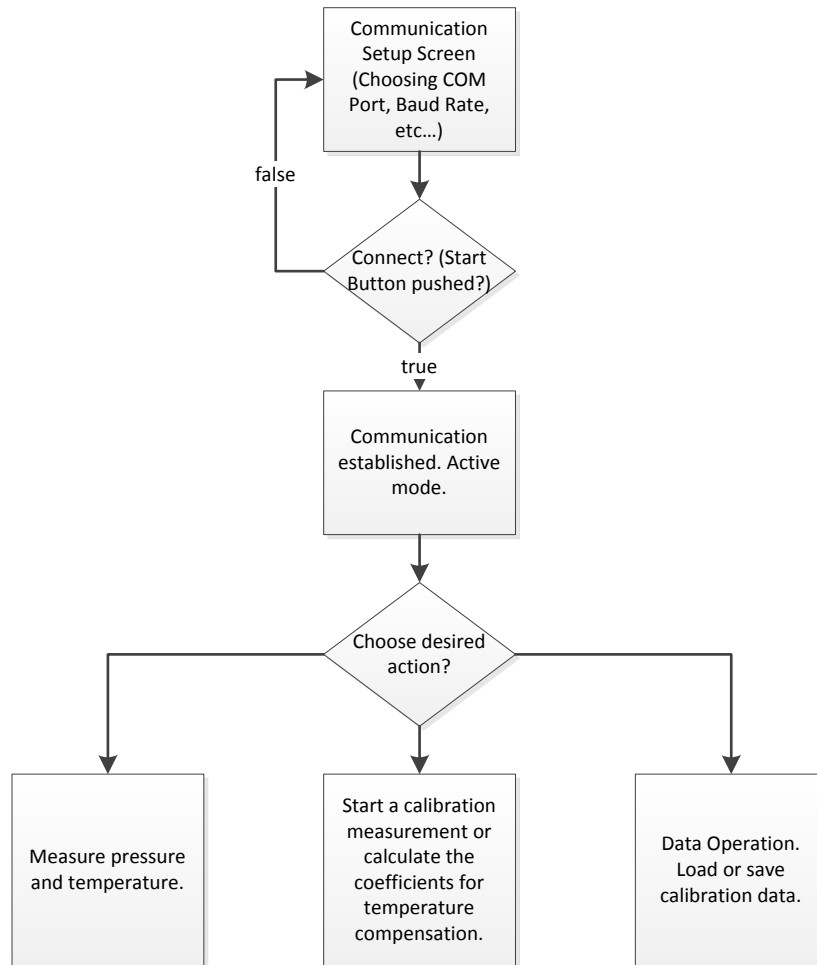## 7.6   Flowchart LabVIEW Software

Figure 38: Flowchart of the Evaluation Kit LabVIEW software

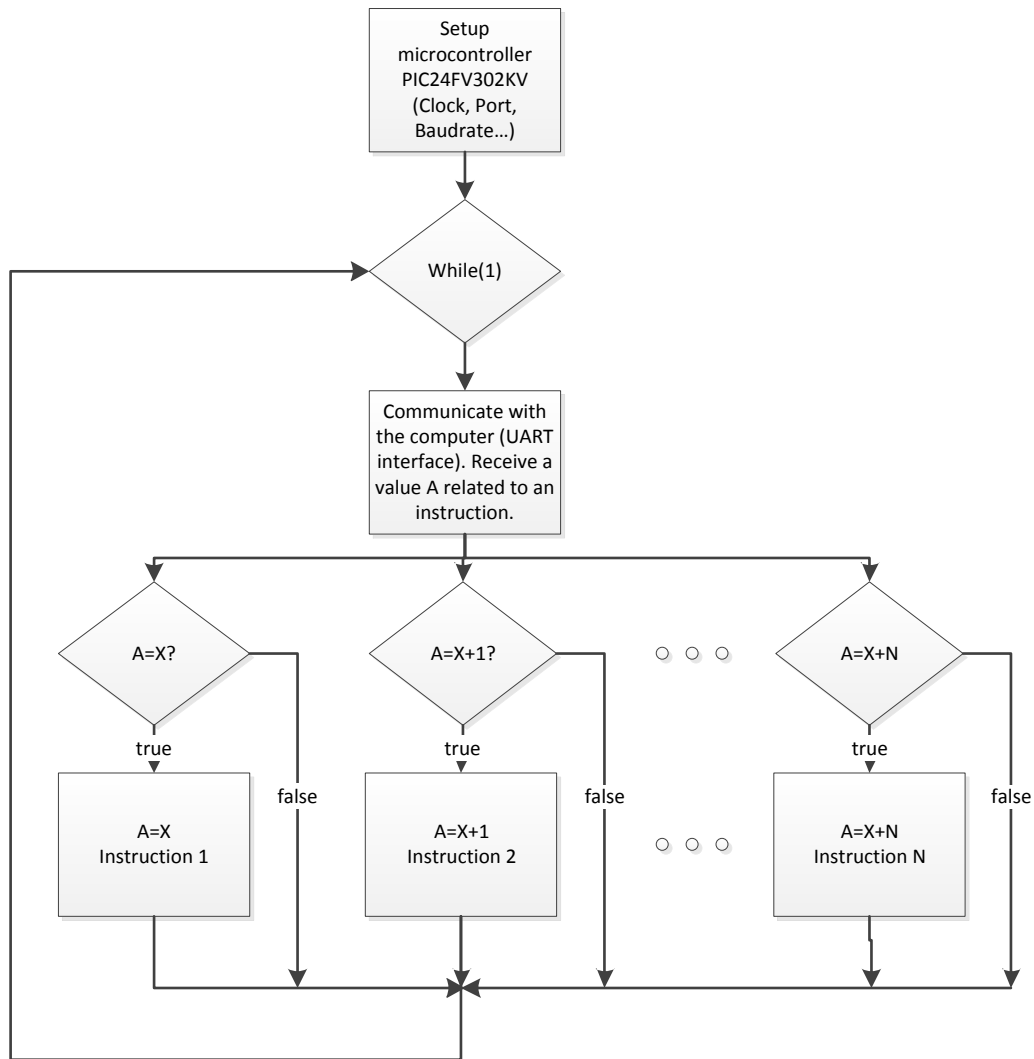## 7.7   Flowchart Microcontroller Software

Figure 39: Flowchart of the microcontroller software

7.8   Microcontroller Command Set

Table 8: Microcontroller command set

Case #	Character	Description
48	0	Read ADC V Bridge of uncompensated CC (constant current) sensor
49	1	Read ADC P of uncompensated CV (constant voltage) sensor
50	2	Read ADC T of uncompensated CV sensor
51	3	Read ADC P Compensated of uncompensated CV sensor
52	4	Read ADC T in K of uncompensated CV sensor

53	5	Read BFSL compensated P of uncompensated CV sensor
54	6	Read Poly compensated P of uncompensated CV sensor
55	7	Read pressure from digital/I^{2}C sensor
56	8	Read P Compensated of uncompensated CC sensor
57	9	Read T in °C of uncompensated CC sensor
97	a	Read Linear coefficients
98	b	Read BFSL coefficients
99	c	Read Poly coefficients
100	d	Write EEPROM Coefficients for Linear
101	e	Write EEPROM Coefficients for BFSL
102	f	Write EEPROM Coefficients for Polynomial
103	g	Status LED on
104	h	Status LED off
105	i	Save Power Supply voltage for pressure calculation
106	j	Read CC coefficients
107	k	Write EEPROM Coefficients CC
108	l	Read ADC P from amplified analog sensor
109	m	Read status bits from digital/I^{2}C ASIC
110	n	Read temperature bits from digital/I^{2}C ASIC
111	o	Read pressure, temperature and status bits from digital/I^{2}C ASIC

8 Revision History

Version	Date of Change	Description of Change
00	14 June 2013	Initial version.
01	18 October 2013	Added constant current mode
02	03 April 2015	Added compensated digital/I^{2}C and analog mode
		Updated the whole manual according to new functionality of the Evaluation Kit