Application Report

Compensating Temperature and Humidity Sensors in HVAC Systems

Brandon Fisher

ABSTRACT

Digital temperature and humidity sensors such as the HDC20xx family provide excellent accuracy for temperature and humidity readings within their immediate surroundings. In systems designed to measure ambient conditions (such as in thermostats and HVAC controllers), the humidity sensor must be shielded from potential contaminants such as dust, moisture, and cleaning solutions by an external case. Inside these cases, poor airflow and heat generating components such as LCD screens and controllers can cause the interior case temperature to climb, reducing sensor output accuracy and slowing system thermal response time. This document provides basic software and characterization solutions for correcting accuracy and response time of temperature and humidity readings in systems with performance issues due to self-heating, airflow, or high thermal mass.

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1 Introduction

In the ideal ambient temperature sensing system, a humidity or temperature sensor is enclosed in enough of a surrounding case to protect the sensing element, but still has sufficient airflow and layout space around the sensor to allow accurate temperature and humidity values. In general, the best and most reliable performance from an IC temperature or humidity sensor can be obtained by following correct design guidelines like those in detailed in Temperature sensors: PCB guidelines for surface mount devices, and Optimizing Placement and Routing for Humidity Sensors.

In some cases, due to restrictions on area or desire for condensation or particulate protection, system engineers may be forced to compromise on layout and case design. When working with ambient temperature and humidity sensing systems, suboptimal design primarily results in three conditions that designers will want to correct for:

- Poor temperature accuracy
- Incorrect RH values
- Slow output response

Each of these can be corrected through a combination of system level characterization and a simple set of mathematical compensation techniques. All three of these manifest as increased system level inaccuracy in the output of the temperature and humidity sensor readings. Analogous to circuit analysis, these effects can be separately considered as steady state error, and transient error.

Section 2 and Section 3 discuss using temperature characterization of a system to correct for steady state inaccuracy in temperature and relative humidity readings. Section 4 discusses how to predict and correct for transient error in the temperature response of a system. This kind of compensation is best in systems where ambient temperature can change continuously, and where slow thermal response can negatively affect other elements of the control loop in the system. This makes thermal response compensation particularly suitable for HVAC systems. Additionally the temperature cycling times in HVAC can be on the order of minutes to hours, improving the tradeoff between processor overhead and compensation benefits.

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2 Temperature Accuracy Compensation

In thermostat and temperature/humidity controllers where a temperature differential exists between the inside and the outside of the case, the sensor will return values consistent with the air temperature and moisture inside the case, rather than the external values. To compensate for this difference, the designer must characterize the entire system for temperature output vs ambient temperature. Figure 2-1 shows an example of a relationship between the ambient temperature and the sensor error from -40 °C to 125 °C. Systems should be characterized across the complete range required by their application requirements.

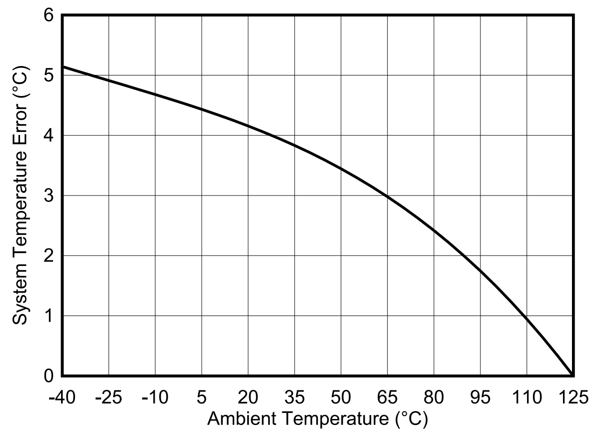

Figure 2-1. System Temperature Error Across Ambient Temperature

In this graph, the effects of the temperature differential are more pronounced at lower temperatures than at higher temperatures. This may or may not be the case in the characterized system, but the temperature compensation methodology is the same regardless. Depending on the distribution the designer should compensate the sensor temperature using either:

- A linear/polynomial regression
- A lookup table

2.1 Linear or Polynomial Regression

Figure 2-2 shows the sensor output vs ambient temperature data for the same data as in Figure 2-1. The goal of regression is to obtain the simplest acceptable relationship between the desired variable (ambient temperature), and the known variable (sensor output). Most data analysis software provides curve fitting/trend line tools that can be used to quickly obtain a linear or polynomial relationship.

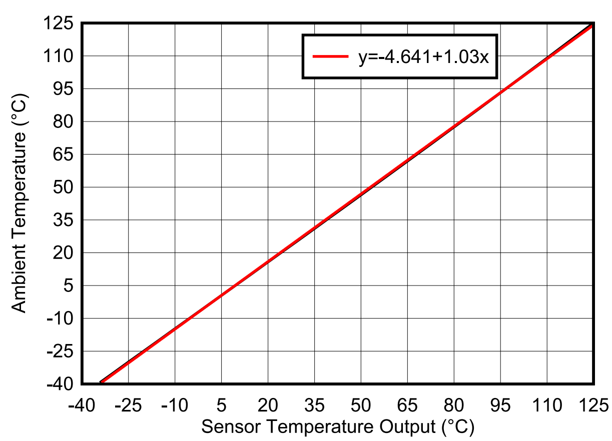

Figure 2-2. Ambient Temperature as a Function of Sensor Output Temperature

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The R^2 value can be used here to evaluate the quality of the regression. A higher R^2 value will result in less system temperature error contributed by the curve fit. Using a linear fit will result in a faster computation time, but in a typically lower R^2 value when compared to a polynomial regression. In this example, a linear regression line of T_{amb} = -4.641 +1.03T_c gives an R^2 value of greater than 0.999. This quality of fit is sufficient for most system requirements. In this case, the regression shows that the error can be corrected with just a simple offset and gain correction. The I^2C host should be used to apply this equation to compensate the sensor temperature readings.

3 Relative Humidity Correction

Relative humidity is the ratio of the environmental vapor pressure to the saturation vapor pressure at a given temperature, and represents how close the atmosphere is to complete water saturation. These quantities both have a strong dependence on temperature. When the interior case temperature of a system is incorrect, it will negatively affect the relative humidity output of the sensor.

After characterization of the system as discussed in Temperature Accuracy Compensation, the correct ambient temperature, the interior case temperature (as read by the sensor), and the case relative humidity are all known. Using these quantities it is possible to create an appropriate look up table to correct for RH offset between the interior and exterior of the case. The only requirement is that the atmospheric moisture (measured as Absolute Humidity) between the sensor surroundings and the ambient environment are equal. This is a reasonable assumption, as absolute humidity is not affected by increases in temperature or the effects of heat-generating ICs.

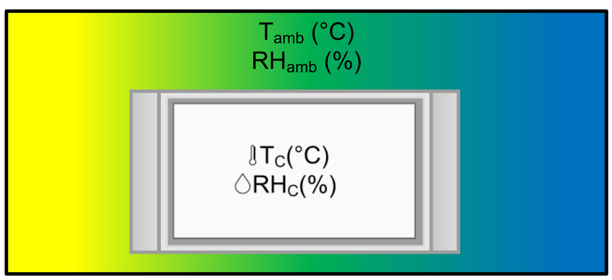

Figure 3-1. Primary Assumption for Relative Humidity Compensation Based on Temperature

Under this assumption, we can derive the following relationship:

$$RH_{AMB} = \frac{P_{WSc}}{P_{WSamb}} \times \frac{T_{amb}}{T_c} \times RH_c \quad (1)$$

Where:

- T_C is the temperature inside the case in kelvin (as measured by the sensor).
- T_{amb} is the ambient temperature in kelvin.
- RH_c and RH_{amb} are the case and ambient relative humidity respectively.
- P_{WSc} is the saturation vapor pressure at T_C
- P_{WSamb} is the saturation vapor pressure at T_{amb}

The saturation vapor pressure can be calculated using the August-Roche-Magnus formula, with only temperature:

$$P_{WS} = 6.1094 \times e^{\frac{17.625 \times T}{T + 243.04}} \quad (2)$$

This version of the equation returns good results between 0 °C to 100 °C. If calculating the exponential on the host microcontroller is not possible, a lookup table of saturation vapor pressures may be used instead.

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4 Response Compensation

4.1 Symptoms of Slow Thermal Response

When system airflow is poor, or the designer omits a proper cutout around the sensor, the system thermal time constant can suffer. This results in system temperature lagging the actual ambient air temperature significantly. For an instantaneous change in temperature, this will appear as in Figure 4-1.

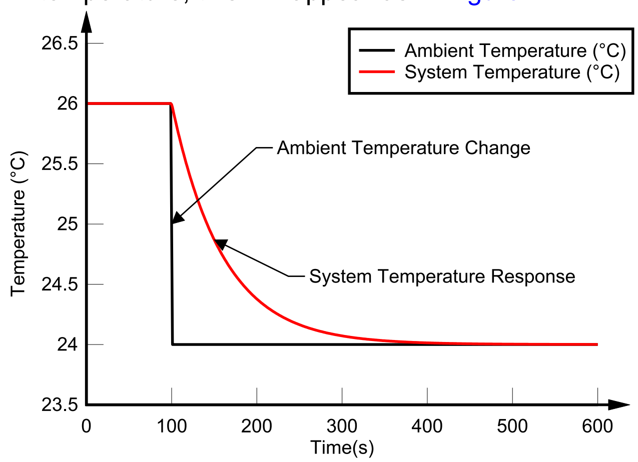

Figure 4-1. Simulated System Thermal Response (τ = 60s) to a Step Change in Temperature

This kind of theoretical instantaneous change in temperature is not realistic in HVAC systems after installation. Most systems will see gradual or cycling changes in temperature in response to heating and cooling action. The response in Figure 4-1 should look like the familiar exponential response of a first-order RC circuit to a step change in voltage. This style of RC circuit is commonly used as an analogue for thermal behavior in ICs and electrical circuits. This concept is described in more detail in Optimizing Placement and Routing for Humidity Sensors.

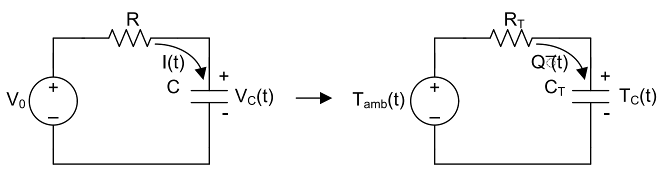

Figure 4-2. Typical RC Circuit and its Thermal Analogue

In a scenario where the ambient temperature is steadily increasing (or decreasing), a system with slow thermal response will exhibit transient error where system temperature lags behind ambient temperature, as shown in Figure 4-3. In cycling environments like in Figure 4-4, the transient error may never settle to zero if the system thermal mass is too large.

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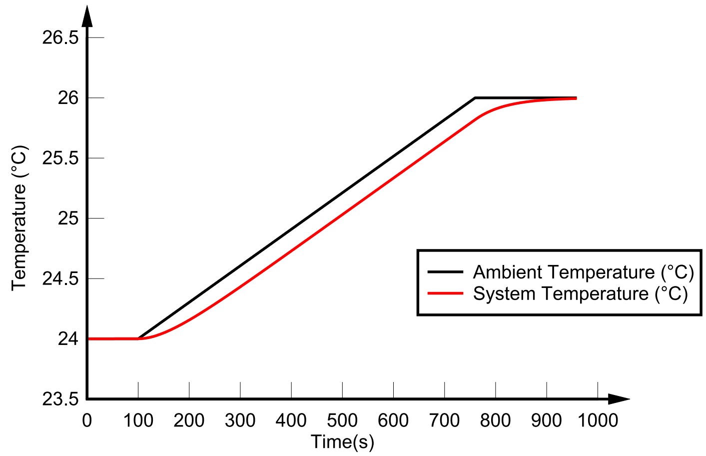

Figure 4-3. Simulated System Thermal Response (τ = 60s) to a Steady Change in Temperature

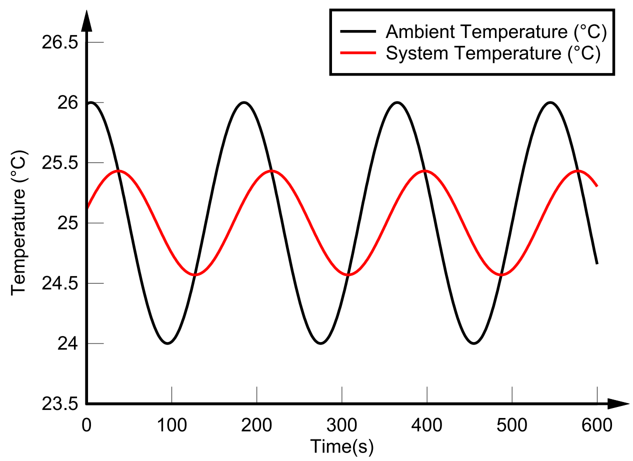

Figure 4-4. Simulated System Thermal Response (τ = 60s) to a Temperature Cycling Ambient Environment

4.2 Simulating Thermal Response Compensation

It is possible to algorithmically correct for this kind of transient error of a temperature/humidity sensing system using only known quantities. To begin the designer should make the following assumptions:

1. The system thermal behavior is approximately that of a first-order system (equivalent to a single pole low-pass filter, like the RC circuit discussed previously)
2. The temperature sampling rate is uniform
3. The system time constant (τ) is known

In a real system, the first assumption will contribute some unavoidable error to the final results of the compensation, but it is a common assumption for temperature sensing applications. For the second assumption, either the sensor controller can configure a timer to trigger and read temperature from the temperature sensor, or if the device allows it (such as with the automatic measurement mode of the HDC20xx family), the sensor itself can be configured to convert temperature regularly.

The third assumption will require the system designer to characterize their system, similar to Section 2. The time constant should be measured as the time it takes for the system to reach roughly 63% of final value when subjected to a step-change in temperature. When selecting a sample rate, ensure that the sample time is much faster than the measured system time constant (at least 20x faster as a best practice).

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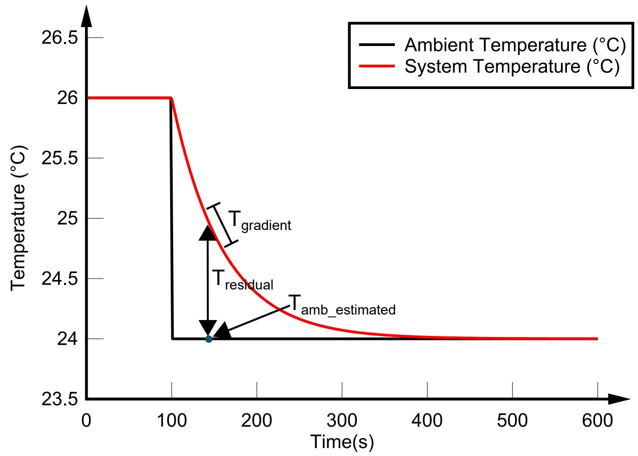

Figure 4-5. Estimation of Residual Temperature

With this information we can calculate the ambient temperature value from the system temperature value by calculating two unknown values: the temperature gradient, and the residual temperature. As shown in Figure 4-5, the temperature gradient is the rate of change of the case temperature, and the residual temperature is the difference between the ambient and interior case temperatures.

$T_{gradient}$ is just a slope calculation and can be found as follows:

$$T_{gradient} = \frac{T_{C\_n} - T_{C\_n-1}}{\Delta t} \tag{3}$$

Where T_{C_n} is the nth temperature sample, T_{C_n-1} is the n-1th temperature sample, and Δt is the time between them.

With $T_{gradient}$ known, we can determine $T_{residual}$ and estimate T_{amb} like so:

$$T_{residual\ \_n} = T_{gradient\ \_n} \times \frac{\exp^{\frac{t_{sample}}{\tau}}}{\exp^{\frac{t_{sample}}{\tau}} - 1} \tag{4}$$

$$T_{amb\ \_estimated} = T_{residual} + T_{system} \tag{5}$$

When calculating $T_{residual}$, t_{sample} should be the time between regular temperature samples.

Figure 4-6, Figure 4-7, and Figure 4-8 show the three kinds of ambient temperature changes modeled before in Section 4.1, with the sensor temperature reported values, and the compensated temperature result in simulation. As can be seen, the results are very nearly ideal, with only the step change in temperature showing any overshoot. As will be shown, this quality of compensation is not attainable in real applications.

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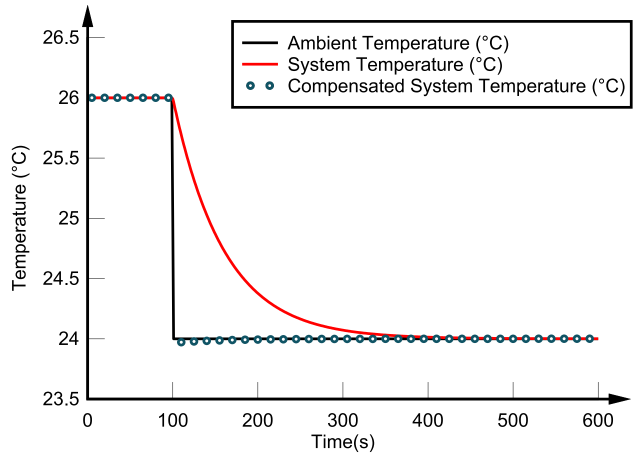

Figure 4-6. Compensated System Temperature Response (Blue) to a Step Change in Temperature

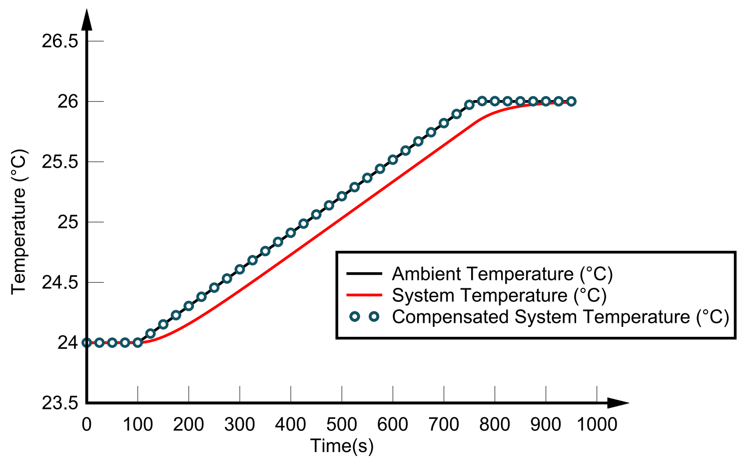

Figure 4-7. Compensated System Temperature Response (Blue) to a Ramp Change in Temperature

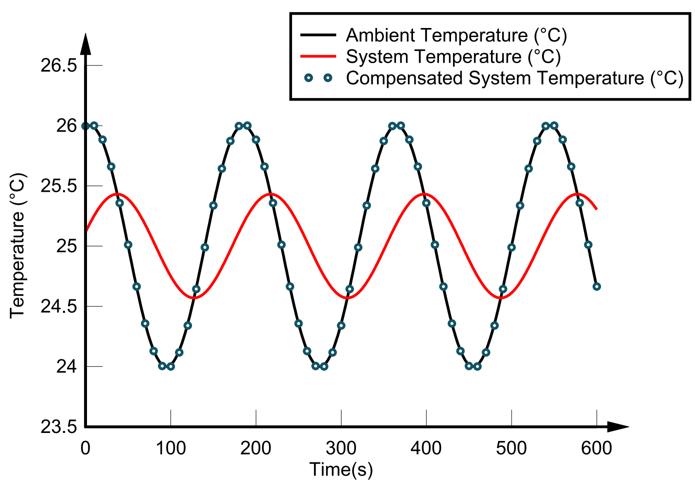

Figure 4-8. Compensated System Temperature Response (Blue) for a Temperature Cycling Ambient Environment

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4.3 Realistic Thermal Response Compensation

For an example of the real application of thermal response compensation, consider the system shown in Figure 4-9.

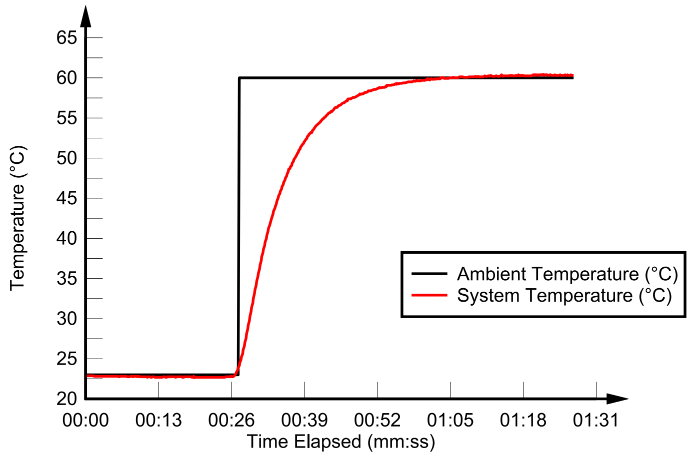

Figure 4-9. System Response to Ambient Temperature Change from Room (~23 °C) to 60 °C, τ ≅ 9.1s

This system has been characterized to have a time constant, τ, of roughly 9.1s, and has a sample time of around 150ms. If the thermal response compensation algorithm as described in Section 4.2 is applied to this system, the results are as shown below in Figure 4-10. As expected, the response time is noticeably improved, however the minor temperature noise in the system is amplified by the compensation algorithm into noise on the order of ±5 °C.

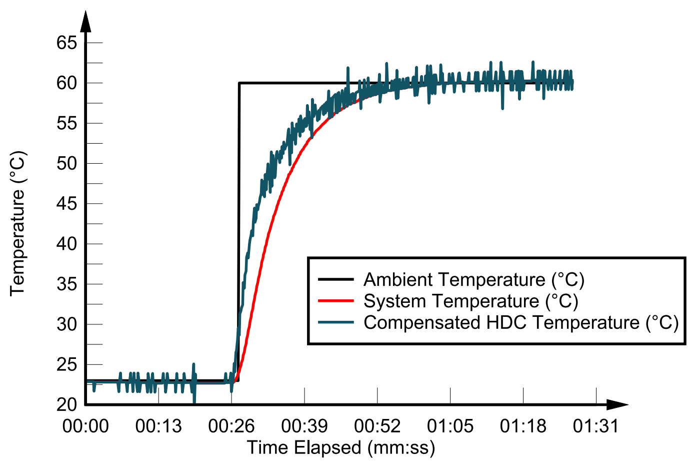

Figure 4-10. Compensated System Response to Ambient Temperature Change From Room (~23 °C) to 60 °C, τ ≅ 9.1s

Introducing a threshold value for the algorithm to ignore the effects of noise can help to correct for this error. When the variance of the portion of the signal being analyzed is higher than the threshold, the predictive algorithm should be active. When it is not, the predictive algorithm should be disabled to avoid the signal being overwhelmed by noise.

$$\sigma^2_{\text{system}} \leq \text{Threshold} \leq 2\sigma^2_{\text{system}} \tag{6}$$

As a rule of thumb, the threshold value should be between 1-2 standard deviations of the noise magnitude, in order to prevent the algorithm from turning on and off at incorrect times. With the wrong threshold value, the predictive algorithm will initiate and end too quickly, and cause discontinuities in the response signal. Figure 4-11

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shows that adding a threshold trigger does help reduce compensation from error in noise during steady-state operation, but does not eliminate the effects of noise entirely.

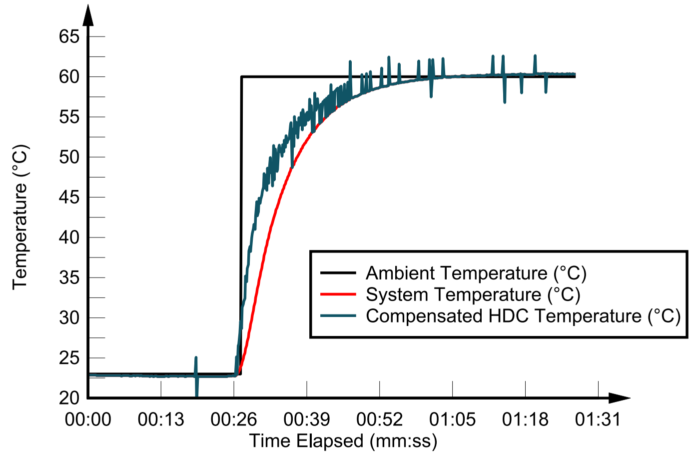

Figure 4-11. Compensated System Response to Ambient Temperature Change from Room (~23 °C) to 60 °C, Including Threshold triggered predictive response

When ambient conditions at the steady-state conditions have real variation, it can contribute noise outside the threshold value considered, and cause occasional erroneous spikes. For any single dataset, the threshold value can be changed iteratively to try and find the optimum value, but this is not practical for a real implementation where the algorithm must provide good results under multiple conditions.

A better option is to smooth the spikes in the values of $T_{gradient}$ by taking the slope estimation over a greater number of samples. Now, calculating $T_{gradient}$ should be done as so:

$$T_{gradient} = \frac{T_{C\_n} - T_{C\_n-k-1}}{t_{sample} \times k} \quad (7)$$

Where k is a designer selected range of samples being considered. In general, the value of k should be between 2, and the number of temperature samples taken in a single time constant τ. Figure 4-12 through Figure 4-14 show the compensated responses with k =10, 50, and 100 for this system. In general, higher k values will contribute to greater accuracy and smoothing of the response signal, but will increase computation time and memory requirements. At very high k-values the compensation will begin to make response time appear slower as well. Designers should use the span of k to make a tradeoff between system temperature performance, and processing time as their application allows.

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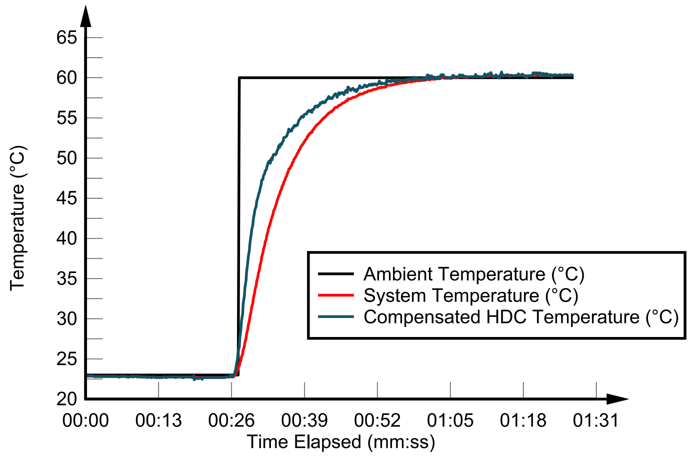

Figure 4-12. Compensated System Response to Ambient Temperature Change from Room (~23 °C) to 60 °C, with k=10

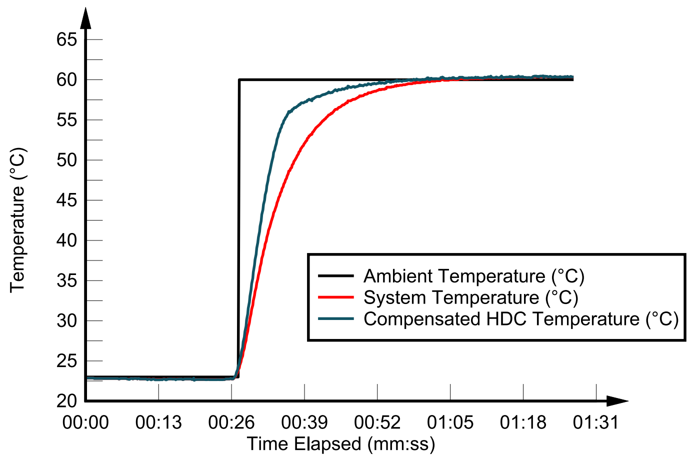

Figure 4-13. Compensated System Response to Ambient Temperature Change from Room (~23 °C) to 60 °C, with k=50

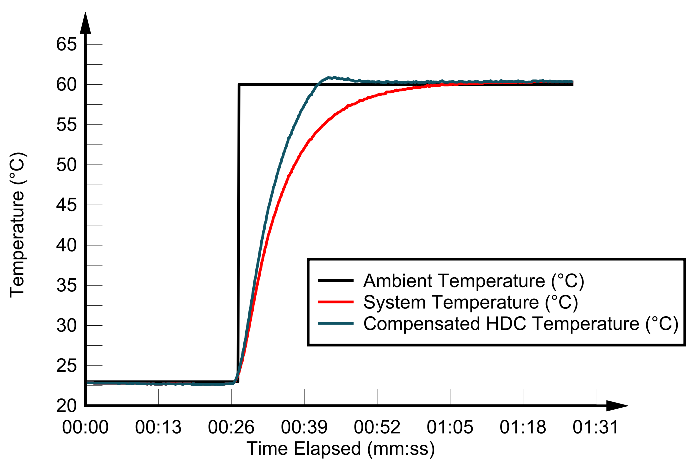

Figure 4-14. Compensated System Response to Ambient Temperature Change From Room (~23 °C) to 60 °C, with k=100

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5 Summary

Here three kinds of compensation techniques for temperature and humidity sensors were presented. Section 2 briefly discussed temperature compensation for ambient temperature systems with steady-state temperature error, which manifests as a difference in accuracy between the system and an external reference after settling time. Similarly, Section 3 discusses how to compensate for steady-state system humidity error, which will also manifest in temperature and humidity sensing systems that have poor temperature accuracy. Both of these are typically due to either poor airflow or sensor proximity to heat generating components. These methods require only system characterization across the desired operating range, and some basic mathematical compensation to be performed.

Section 4 examines a correction technique for transient errors in temperature and humidity sensing systems. This kind of compensation is typically needed in systems with large thermal time constants, and is most useful in applications where transient temperature conditions are regularly expected, and the temperature/humidity sensor is a critical part of the control loop, such as in HVAC systems. The ideal implementation and a practical implementation accounting for noise are both presented here. Threshold and averaging values can be selected to tune performance of a system while providing significant improvements to slow responding temperature systems.

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6 References

For related documentation please see the following

- Texas Instruments, Optimizing Placement and Routing for Humidity Sensors Application Report
- Texas Instruments, Temperature Sensors: PCB Guidelines for Surface Mount Devices Application Report
- Texas Instruments, HDC2080 Low-Power Humidity and Temperature Digital Sensor Data Sheet
- Texas Instruments, HDC2010 Low-Power Humidity and Temperature Digital Sensor in WLCSP Data Sheet
- Texas Instruments, HDC2021 High-Accuracy, Low-Power Humidity and Temperature Sensor With Assembly Protection Cover Data Sheet
- Texas Instruments, HDC2022 High-Accuracy, Low-Power Humidity and Temperature Sensor WithIP67 Rated Water and Dust Protection Cover Data Sheet

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