AN2648
Application note

Increasing the resolution of analog temperature sensors

Introduction

For a recent trade show, a demonstration board was required to display ST's new low-cost temperature sensor, the STLM20. The idea was to connect it to a basic microcontroller with on-board analog-to-digital converter (ADC) and display the temperature on seven-segment LEDs. Any user would be able to affect the temperature by applying his finger directly to the sensor and then watch the display change as a result.

The goal was to keep things simple and use the ADC converter on the micro thus avoiding the expense and engineering effort of using an external ADC.

Using the STLM20 temperature sensor with low-cost microcontrollers

The design flow used for the demonstration board can be applied in many applications. This document describes how any user can implement a temperature sensor design using the LM20 and a low-cost microcontroller with integral A-D converter.

Figure 1.   STLM20 demonstration board
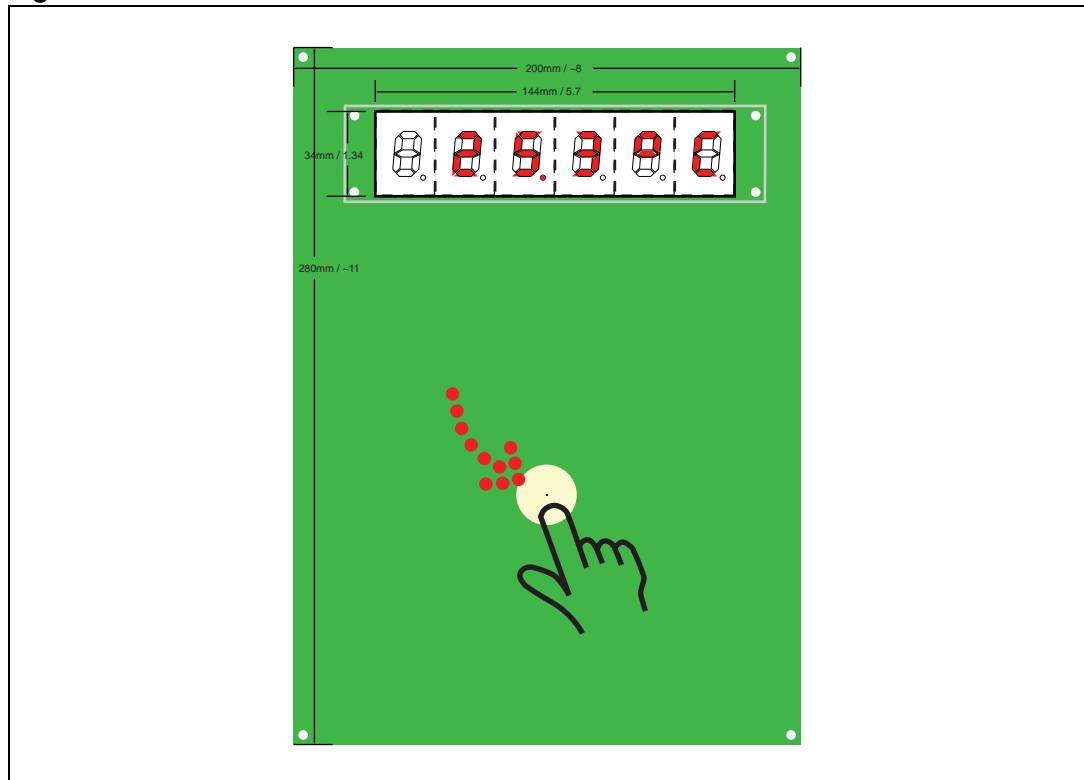
1 STLM20 temperature-to-output transfer function

Upon examining the temperature sensor's output characteristics, several issues become apparent. The STLM20 is a voltage output device with a 2nd order transfer function:

$$V_0 = (-3.88 \times 10^{-6} \times T^2) + (-1.15 \times 10^{-2} \times T) + 1.8639 \, V$$

This is rather unwieldy math for a simple 8-bit micro, but a linear approximation is available which matches the curve very closely. As shown in *Figure 2*, the dashed blue line is a very good fit to the pink parabola of the 2nd order equation above, and has the following equation:

Equation 1

$$V_0 = (-0.01169 \, V/°C) \times T + 1.8663 \, V$$

This is much more manageable for coding in assembly language without a math package. In this figure, the reader will note that the curve deviates only slightly from the line at the extreme ends. In the middle, they are almost indistinguishable.

Figure 2. STLM20 transfer function
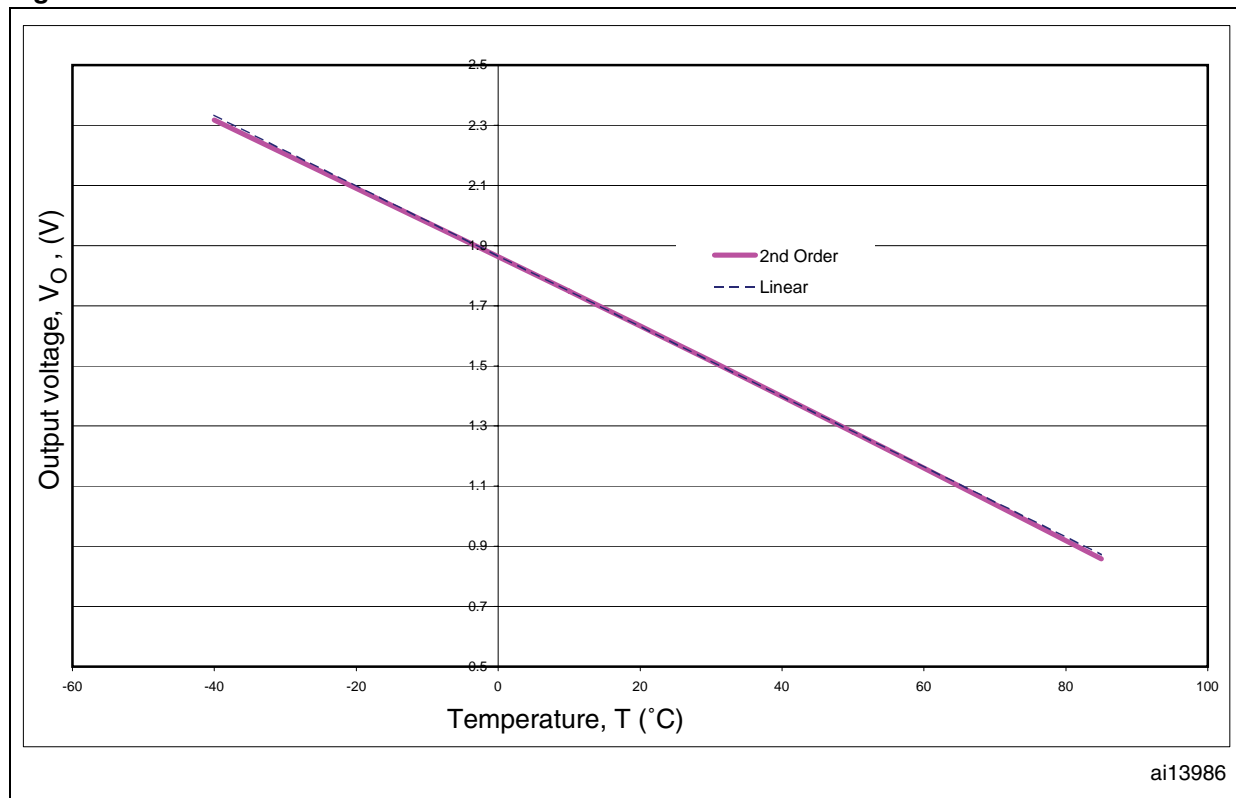
The second issue arises with the output voltage range. The micro's ADC performs ratiometric conversion on the input using V_{CC} and ground as the upper and lower references, respectively. That means that when the input voltage equals V_{CC}, the 8-bit ADC's output will be 255 (FF$_{HEX}$), and when the input is ground, the output will be 0 (00$_{HEX}$). Any voltage in the range V_{CC} to ground is converted proportionally according to the following relationship:

$$\mathrm{ADC\,output\,(dec)} = (V_{IN}/V_{CC}) \times 255$$

For this application, the nominal V_{CC} is 5 V, so this equation becomes:

$$\mathrm{ADC\,output\,(dec)} = (V_{IN}/5) \times 255 = V_{IN} \times 51$$

Referring to *Figure 3*, while the ADC can accept inputs over the full range 0 to 5 V, the temperature sensor output will vary over a much smaller range, between 0.87 and 2.33 volts across the temperature range –40° to +85°C.

Figure 3.   STLM20 output voltage range
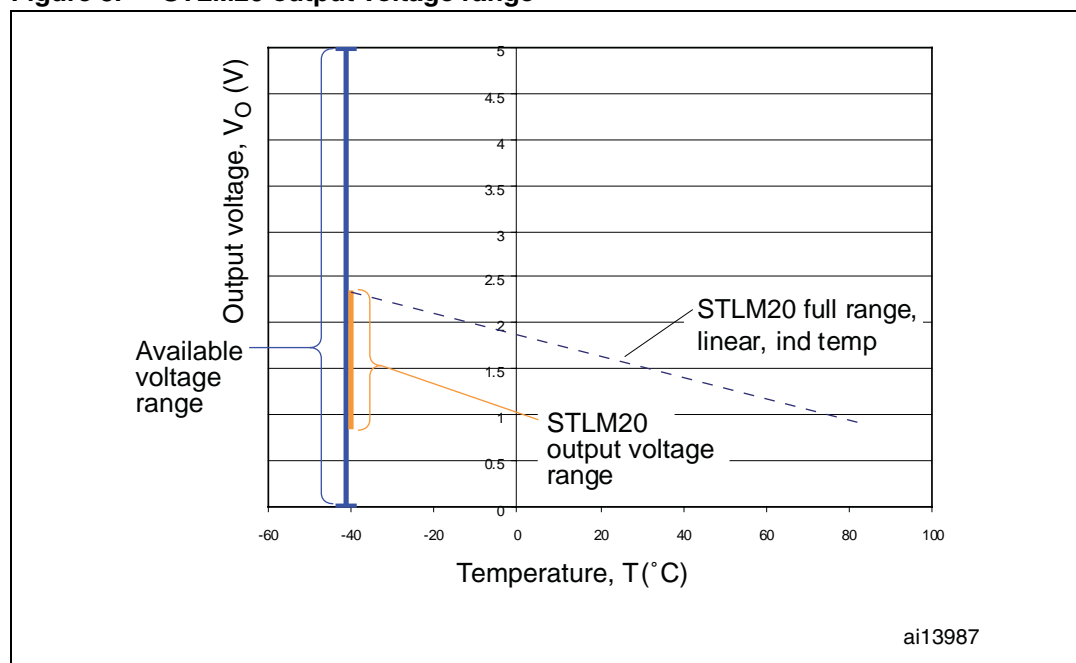
This amounts to using only 1.46 V of the available 5 V range. Furthermore, in the intended demonstration board application, the necessary temperature range was approximately room temperature –15°/+25°, or 10° to 50°C.

For this target temperature range, the voltage range is 1.28 to 1.75 V, an interval of less than 0.5 V, less than one tenth the available 5 V range. This is depicted in *Figure 4*.

**Figure 4.** **Application temperature and voltage ranges**
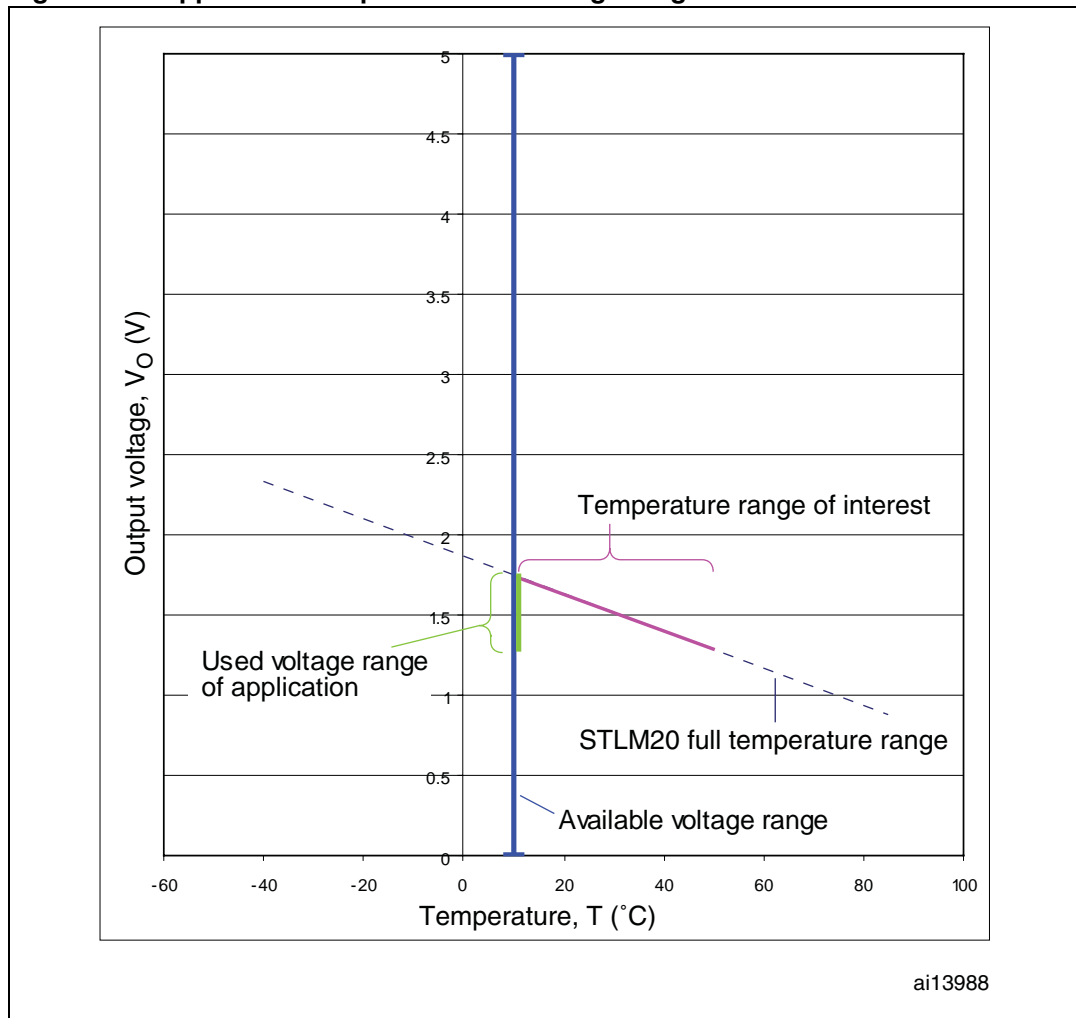
In *Equation 1*, the slope is −11.69 mV per °C. For the 8-bit ADC, the step size is 5 V/255 steps or 0.019608 V/step. Comparing this to the slope, we get:

$$\frac{0.019608 \ \text{V/step}}{-0.01169 \ \text{V/}^\circ\text{C}} = -1.677318 \ ^\circ\text{C/step}$$

This means that, with the temperature sensor connected directly to the ADC, the resolution is only 1.68°C/step. The smallest temperature increment the ADC can resolve is 1.68°C. This is very coarse resolution.

Given that the expected voltage range is less than 0.5 V, it should be possible to amplify the STLM20 output signal so that is uses more of the available voltage range. A 10x amplification should be possible without exceeding the available 5 V range. Furthermore, a positive slope is more intuitive to the user, so inverting it would be helpful, too. Hence, a gain of −10 should be used. Multiplying equation 1 by −10, we get the curve as shown at the bottom in *Figure 5*.

Figure 5.   Application transfer function after gain, inversion and offset
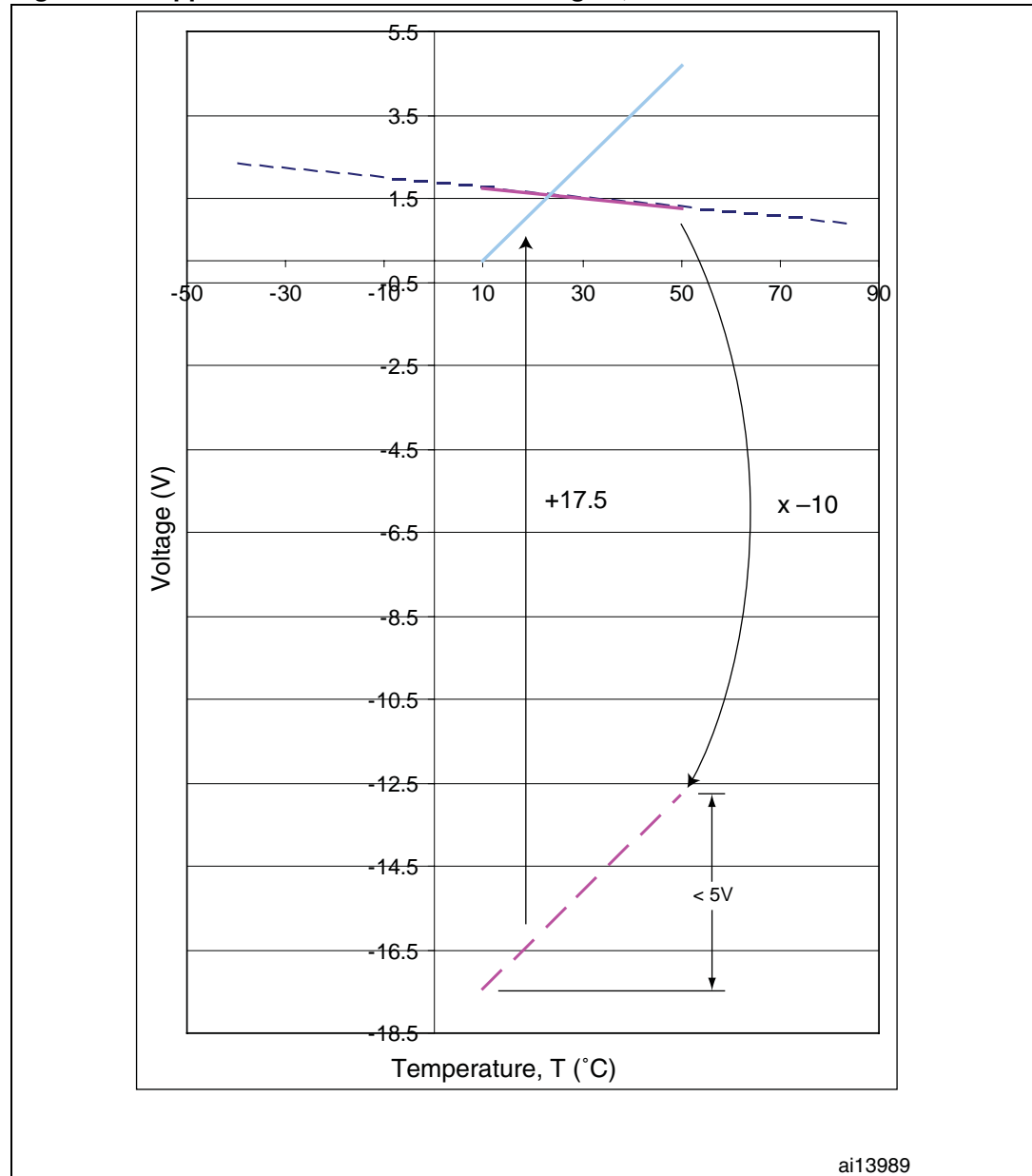
The result has positive slope and spans from −17.5 to −12.8, an interval of about 4.7 V, much closer to the available 5 V range.

With an offset of approximately +17.5 V the curve is moved back into the range 0-5 V to give the transfer function shown as the light blue line in *Figure 5*.

So how is this done? What circuit will perform this transformation without adding intolerable cost to the system?

It turns out that a difference amplifier can be used to add gain and offset, and can do the inversion as well. And it requires only one op-amp to implement.

An additional op-amp is used as a voltage follower out of the temperature sensor to prevent output loading from affecting the STLM20's output level. The net amplifier requirement then is a dual op-amp. A voltage reference is also required to provide the offset level going into the difference amp. The overall circuit is shown in *Figure 6*.

The STLM20 output voltage, V_0, appears identically at the first op-amp output. That then drives the inverting input of the difference amp with a gain of $-50k/5k = -10$.

This translates the curve from a voltage range of 1.28 V to 1.75 V to a range of -12.8 V to -17.5 V so an offset of about +17.5 V must be applied. The 1.7676 V reference sees a gain of 10 (R4/R3 = ~50k/5k = 10) on the op-amp's non-inverting input. Thus, 17.676 volts is added back into the translation.

With this gain and offset, the original curve, which had an interval of less than 0.5 V and a negative slope, is transformed to one which spans close to 5 V and has a positive slope as illustrated by the light blue line in *Figure 5*.

Figure 6.   STLM20 with gain and offset circuit
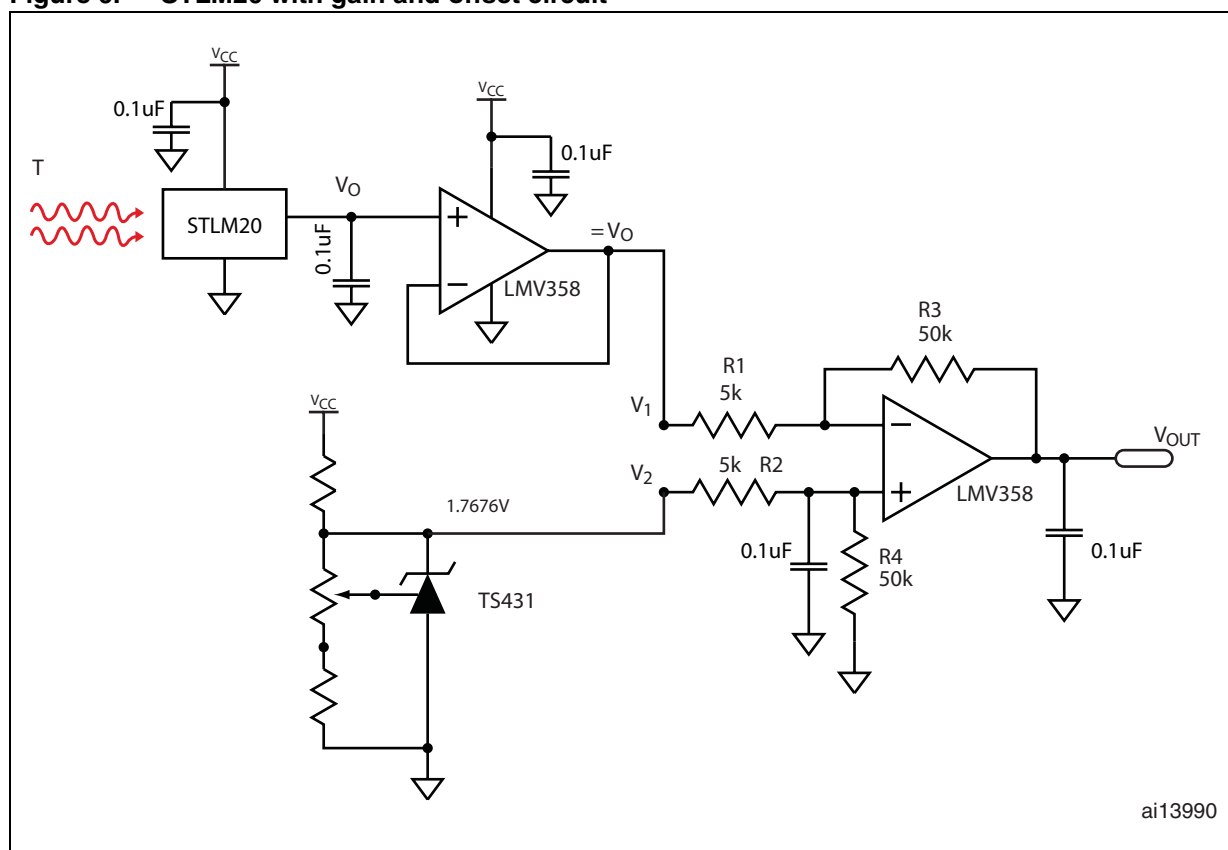
Equation 2 is the basic difference amplifier equation.

Equation 2

$$V_{OUT} = \frac{V2\,(R3+R1)\,R4}{(R4+R2)R1} - \frac{V_1 \cdot R3}{R1}$$

If R1 = R2 and R3 = R4, then it reduces to:

$$V_{OUT} = (V_2 - V_1)\frac{R_3}{R_1}$$

However, obtaining perfectly identical resistors is nearly impossible. Thus, the more complex expression of *Equation 2* is used. Starting with *Equation 1 on page 2*, for *Figure 6*, we have:

$$V_O = -0.01169 \cdot T + 1.8663 \text{ V}$$

In *Figure 6*, V_1 is driven by V_0, so *Equation 2* becomes:

$$V_{OUT} = \frac{V2\,(R3+R1)\,R4}{(R4+R2)R1} - \frac{V_O \cdot R3}{R1}$$

Substituting the expression for V_0 into this, we get:

$$V_{OUT} = V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)\,R1} - \frac{(-0.01169 \cdot T + 1.8663) \cdot R3}{R1}$$

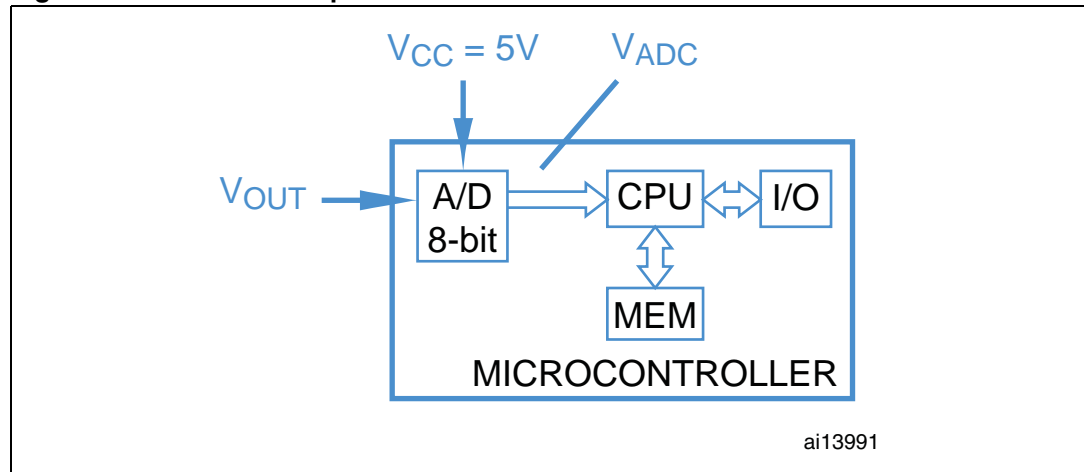$$V_{OUT} = V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R1} + 0.01169 \cdot \frac{R3}{R1} \cdot T - 1.8663 \cdot \frac{R3}{R1}$$

Equation 3

$$V_{OUT} = V2 \cdot \frac{(R3 + R1)\,R4}{(R4 + R2)R1} - 1.8663 \cdot \frac{R3}{R1} + 0.01169 \cdot \frac{R3}{R1} \cdot T$$

The ADC inside the microprocessor is shown in *Figure 7*.

Figure 7.   ADC in microprocessor

For the ADC output, we have the following, where INT means the integer portion of the expression:

$$V_{ADC} = INT\left[\frac{255}{V_{CC}} V_{OUT}\right]$$

Substituting *Equation 3*, we get:

$$V_{ADC} = INT\left[\frac{255}{V_{CC}}\left(V2 \cdot \frac{(R3 + R1)\,R4}{(R4 + R2)R1} - 1.8663 \cdot \frac{R3}{R1} + 0.01169 \cdot \frac{R3}{R1} \cdot T\right)\right]$$

Rearranging, and ignoring the integer notation for now, we get:

$$V_{ADC} \cdot \frac{V_{CC}}{255} = V2 \cdot \frac{(R3 + R1)\,R4}{(R4 + R2)R1} - 1.8663 \cdot \frac{R3}{R1} + 0.01169 \cdot \frac{R3}{R1} \cdot T$$

To get the measured temperature, T_{MEASA}, we must solve for T above:

$$V_{ADC} \cdot \frac{V_{CC}}{255} - V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R1} + 1.8663 \cdot \frac{R3}{R1} = 0.01169 \cdot \frac{R3}{R1} \cdot T$$

$$V_{ADC} \cdot \frac{V_{CC}}{255} \cdot \frac{R1}{R3} - V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R1} \cdot \frac{R1}{R3} + 1.8663 \cdot \frac{R3}{R1} \cdot \frac{R1}{R3} = 0.01169 \cdot \frac{R3}{R1} \cdot \frac{R1}{R3} \cdot T$$

$$V_{ADC} \cdot \frac{V_{CC}}{255} \cdot \frac{R1}{R3} - V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R3} + 1.8663 = 0.01169 \cdot T$$

Equation 4

$$T_{MEASA} = T = V_{ADC} \cdot \frac{V_{CC}}{255} \cdot \frac{R1}{R3} \cdot \frac{1}{0.01169} - V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R3} \cdot \frac{1}{0.01169} + \frac{1.8663}{0.01169}$$

This has the form:

Equation 4b

$$T_{MEASA} = V_{ADC} \cdot K_S + K_O$$

But, rather than using this equation, it is better to filter the temperature, to average multiple samples together for display. This has two benefits. It smoothes the changes resulting in a displayed value which updates more gradually. And it increases the effective resolution of the sensor. By adding two more bits, this essentially makes the A/D appear to have 10-bit resolution.

So, we use a modified version of the previous math, but sum four consecutive samples together:

$$V_{ADC} = INT\left[\frac{255}{V_{CC}} V_{OUT}\right]$$

$$V_{ADC} = INT\left[\frac{255}{V_{CC}}\left(V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R1} - 1.8663 \cdot \frac{R3}{R1} + 0.01169 \cdot \frac{R3}{R1} \cdot T\right)\right]$$

V_{SUM4} = 4 samples of V_{ADC}, range 0 to 1020.

$$V_{SUM4} = 4 \cdot INT\left[\frac{255}{V_{CC}}\left(V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R1} - 1.8663 \cdot \frac{R3}{R1} + 0.01169 \cdot \frac{R3}{R1} \cdot T\right)\right]$$

Rearranging and ignoring the integer operator, we get:

$$V_{SUM4} \cdot \frac{V_{CC}}{1020} = V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R1} - 1.8663 \cdot \frac{R3}{R1} + 0.01169 \cdot \frac{R3}{R1} \cdot T$$

$$V_{SUM4} \cdot \frac{V_{CC}}{1020} - V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R1} + 1.8663 \cdot \frac{R3}{R1} = 0.01169 \cdot \frac{R3}{R1} \cdot T$$

$$V_{SUM4} \cdot \frac{V_{CC}}{1020} \cdot \frac{R1}{R3} - V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R1} \cdot \frac{R1}{R3} + 1.8663 \cdot \frac{R3}{R1} \cdot \frac{R1}{R3} = 0.01169 \cdot \frac{R3}{R1} \cdot \frac{R1}{R3} \cdot T$$

$$V_{SUM4} \cdot \frac{V_{CC}}{1020} \cdot \frac{R1}{R3} - V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R3} + 1.8663 = 0.01169 \cdot T$$

Equation 5

$$T_{MEAS4} = T = V_{SUM4} \cdot \frac{V_{CC}}{1020} \cdot \frac{R1}{R3} \cdot \frac{1}{0.01169} - V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R3} \cdot \frac{1}{0.01169} + \frac{1.8663}{0.01169}$$

This is a linear equation and has the form:

Equation 5b

$$T_{MEAS4} = V_{SUM4} \cdot K_S/4 + K_O$$

Notice that the upper limit for the sum of four samples is 1020 (4 x 255) and not 1023 as might be inferred for a 10-bit number.

The actual values of $K_S/4$ and K_O depend on the four resistors in the difference amp, the voltage reference output and V_{CC}. In the case of the temperature sensor demonstration board, we have these values:

$$R1 = 5107\,\Omega$$
$$R2 = 5105\,\Omega$$
$$R3 = 50850\,\Omega$$
$$R4 = 50850\,\Omega$$
$$V_{CC} = 4.9058\,V$$
$$V2 = V_{REF} = 1.7676\,V$$

For K_S, we insert these values into *Equation 4* and get this for a single sample:

$$T_{MEASA} = T = V_{ADC} \cdot \frac{V_{CC}}{255} \cdot \frac{R1}{R3} \cdot \frac{1}{0.01169} - V2 \cdot \frac{(R3+R1)\,R4}{(R4+R2)R3} \cdot \frac{1}{0.01169} + \frac{1.8663}{0.01169}$$

$$T_{MEASA} = V_{ADC} \cdot 0.16528 + 8.43771$$

Thus, for *Equation 4b*, $K_S = 0.16528$ and $K_O = 8.43771$. Therefore, $K_S/4 = 0.04132$. Substituting this into *Equation 5b*, we get:

$$T_{MEAS4} = 0.04132 \cdot V_{SUM4} + 8.43771$$

This gives the four-sample average of the temperature. However, more processing is still required to get it into a form suitable for implementing in a simple processor. Since the processor is an 8-bit, integer machine, multiplication by a real number - in this case a fraction - is difficult and requires lots of math software.

Instead of doing such complicated math, it's easier to first multiply by 1000, then later divide by 1000.

So, *Equation 5b* becomes:

$$1000 \cdot T_{MEAS4} = 41 \cdot V_{SUM4} + 8438$$

Since the numbers are strictly integers, some truncation error has occurred. Running error analysis on the calculated results shows an average error of –0.21°C, so as a final adjustment, an additional 0.2(x1000) is added to get this equation:

$$1000 \cdot T_{MEAS4} = 41 \cdot V_{SUM4} + 8438 + 200 = 41 \cdot V_{SUM4} + 8638$$

The above equation is then implemented in the software. The final step is dividing the result by 1000 and writing it to the demonstration board's display.

The overall solution looks like this (*Figure 8*):

Figure 8.   Overall solution
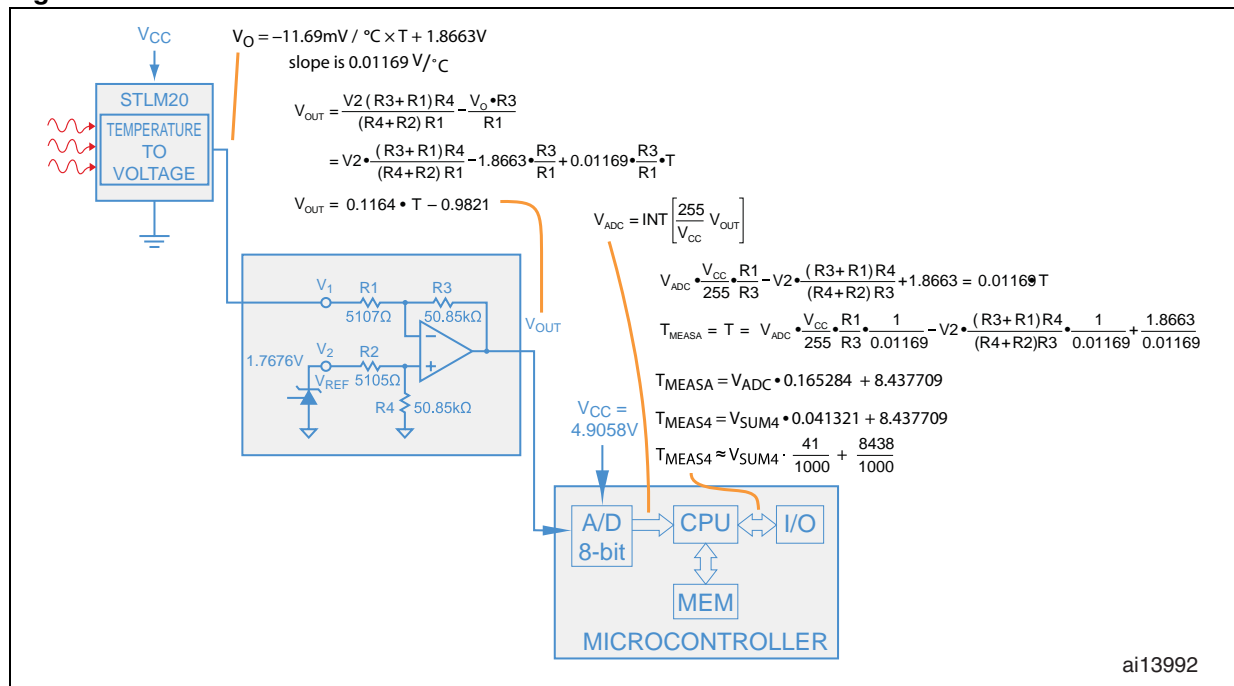
Thus, for the minor expense of a voltage reference and dual op-amp, the resolution has been improved from 1.677°C per ADC step to better than 0.1°C steps on the display.

2   Summary

The STLM20 is very accurate over a wide temperature range and has a nearly linear output which spans the voltage range 2.33 down to 0.87 volts over the corresponding temperature range –40° to +85°C. While it can be directly connected to an 8-bit A-D converter such as those often found integrated into low-cost microcontrollers, the resolution may be too coarse for some applications, amounting to –1.677°C per A-D step. For applications requiring higher resolution, users can use an op-amp and a voltage reference to add gain and offset to the STLM20 output. This has the effect of increasing the resolution over the temperature range of interest while avoiding the need for a more expensive, higher resolution A-D converter. Using averages of four samples also increases the effective resolution. The final result is that users can achieve resolution as fine as 0.1°C with the STLM20.

3 Revision history

Table 1. Document revision history

Date	Revision	Changes
20-Dec-2007	1	Initial release.

Please Read Carefully:

Information in this document is provided solely in connection with ST products. STMicroelectronics NV and its subsidiaries ("ST") reserve the right to make changes, corrections, modifications or improvements, to this document, and the products and services described herein at any time, without notice.

All ST products are sold pursuant to ST's terms and conditions of sale.

Purchasers are solely responsible for the choice, selection and use of the ST products and services described herein, and ST assumes no liability whatsoever relating to the choice, selection or use of the ST products and services described herein.

No license, express or implied, by estoppel or otherwise, to any intellectual property rights is granted under this document. If any part of this document refers to any third party products or services it shall not be deemed a license grant by ST for the use of such third party products or services, or any intellectual property contained therein or considered as a warranty covering the use in any manner whatsoever of such third party products or services or any intellectual property contained therein.

UNLESS OTHERWISE SET FORTH IN ST'S TERMS AND CONDITIONS OF SALE ST DISCLAIMS ANY EXPRESS OR IMPLIED WARRANTY WITH RESPECT TO THE USE AND/OR SALE OF ST PRODUCTS INCLUDING WITHOUT LIMITATION IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE (AND THEIR EQUIVALENTS UNDER THE LAWS OF ANY JURISDICTION), OR INFRINGEMENT OF ANY PATENT, COPYRIGHT OR OTHER INTELLECTUAL PROPERTY RIGHT.

UNLESS EXPRESSLY APPROVED IN WRITING BY AN AUTHORIZED ST REPRESENTATIVE, ST PRODUCTS ARE NOT RECOMMENDED, AUTHORIZED OR WARRANTED FOR USE IN MILITARY, AIR CRAFT, SPACE, LIFE SAVING, OR LIFE SUSTAINING APPLICATIONS, NOR IN PRODUCTS OR SYSTEMS WHERE FAILURE OR MALFUNCTION MAY RESULT IN PERSONAL INJURY, DEATH, OR SEVERE PROPERTY OR ENVIRONMENTAL DAMAGE. ST PRODUCTS WHICH ARE NOT SPECIFIED AS "AUTOMOTIVE GRADE" MAY ONLY BE USED IN AUTOMOTIVE APPLICATIONS AT USER'S OWN RISK.

Resale of ST products with provisions different from the statements and/or technical features set forth in this document shall immediately void any warranty granted by ST for the ST product or service described herein and shall not create or extend in any manner whatsoever, any liability of ST.

ST and the ST logo are trademarks or registered trademarks of ST in various countries.

Information in this document supersedes and replaces all information previously supplied.

The ST logo is a registered trademark of STMicroelectronics. All other names are the property of their respective owners.

STMicroelectronics group of companies

Australia - Belgium - Brazil - Canada - China - Czech Republic - Finland - France - Germany - Hong Kong - India - Israel - Italy - Japan - Malaysia - Malta - Morocco - Singapore - Spain - Sweden - Switzerland - United Kingdom - United States of America

www.st.com