

# Analog linearization of resistance temperature detectors

By Bruce Trump  
Staff Technologist

Resistance temperature detectors (RTDs) are commonly used in industrial and scientific temperature measurements. The most common types are pure platinum (Pt) formed into wire or evaporated in a thin film on a substrate. They rely on the fundamental temperature-dependent resistance properties of this noble metal. They are very stable and useful at temperatures ranging from cryogenic to over 800°C. A wide range of physical configurations, resistance ranges and accuracies is available.<sup>1</sup> The commonly used notation “Pt100” indicates a 100-Ω resistance at 0°C. The relationship between the RTD’s resistance and temperature is described by the Callendar-Van Dusen equation,

$$R_{\text{RTD}} = R_0[1 + AT + BT^2 + C(T - 100)T^3],$$

whose values are defined as follows:

$$R_0 \text{ is a } 100\text{-}\Omega \text{ resistance at } 0^\circ\text{C (Pt100)}$$

$$A = 3.9083 \times 10^{-3}$$

$$B = -5.775 \times 10^{-7}$$

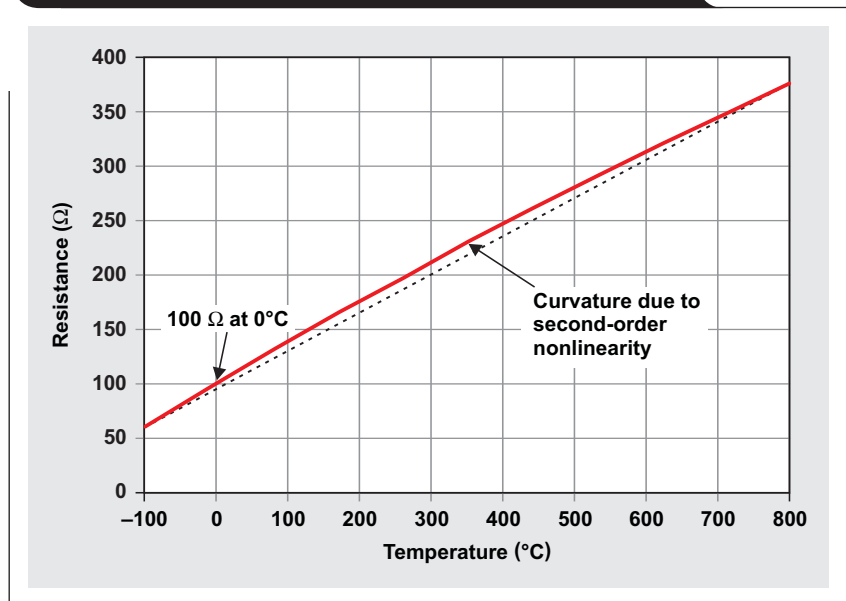
$$C = 0 \text{ for } T > 0^\circ\text{C, or } C = -4.23225 \times 10^{-12} \text{ for } T < 0^\circ\text{C.}$$

The resistance of a Pt100 RTD increases with temperature at approximately 0.39%/°C. While they are far more linear than thermocouples, RTDs have a significant second-order nonlinearity of approximately 0.38% per 100°C measurement range (see Figure 1). This nonlinearity is often corrected digitally, but there are many applications for purely analog processing and linearization of the RTD.

This article explains an analog technique for linearization of the RTD. The same technique is also used with bridge sensors such as pressure and load cells. The principles can be applied to other ratiometric devices with primarily second-order nonlinearity; i.e., any sensor or system with an output that is proportional to an excitation voltage or current.

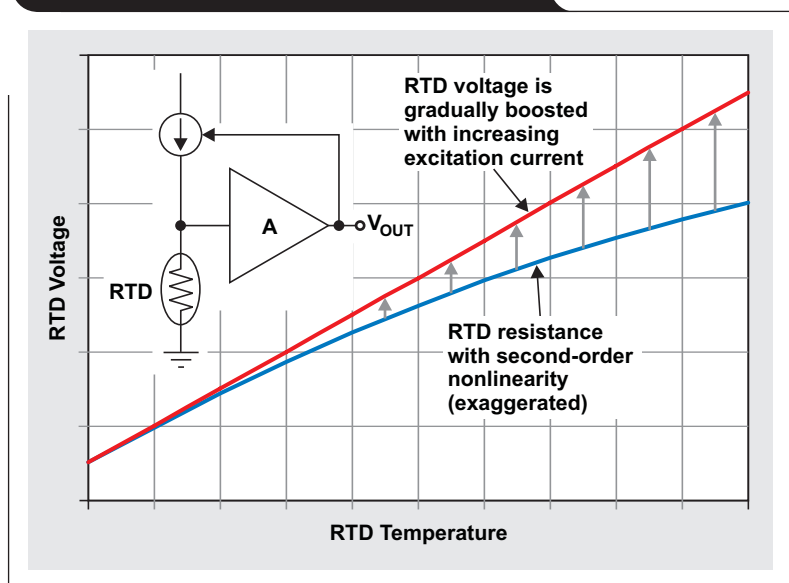
The exaggerated graph in Figure 2 shows that the temperature coefficient decreases with increasing temperature, producing an upward bow in the middle. Above 0°C, standardized data for the Pt100 has a purely second-order or parabolic function. Assuming calibration at two endpoint temperatures, this produces an error that is greatest at the midpoint temperature.

Figure 1. Resistance of Pt100 RTD versus temperature



When the RTD is excited with a current source, the resulting RTD voltage is directly proportional to the resistance, yielding the same nonlinearity. If, however, the excitation current is gradually increased as the RTD temperature

Figure 2. RTD voltage versus temperature



is increased, the nonlinearity can be greatly reduced. Figure 2 shows an increasing excitation current derived from the output of the amplified RTD voltage. This current is, in effect, a controlled amount of positive feedback. It yields an interesting “chicken-or-egg” dichotomy: The RTD voltage at the input of the amplifier is linearized when the output of the amplifier is linearized—and vice versa. The correct amount of positive feedback results in both.

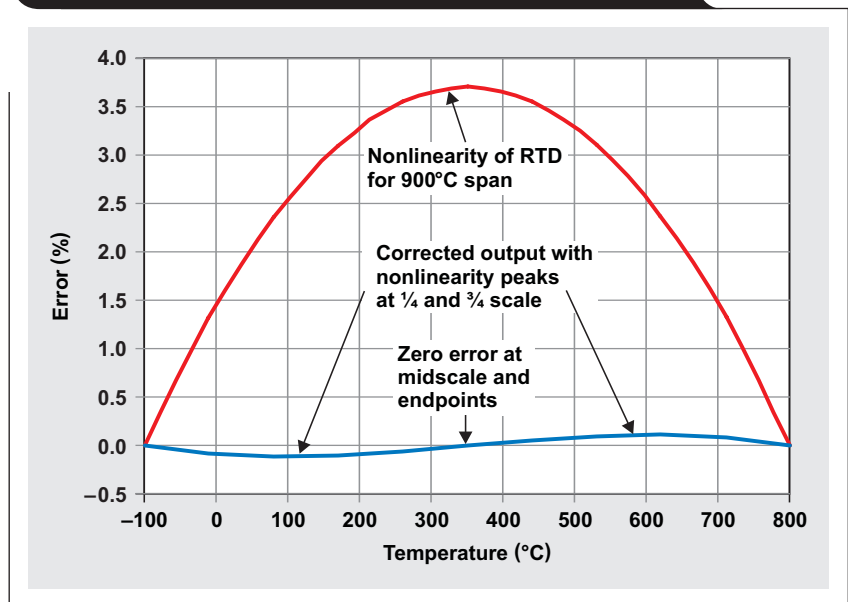
When positive feedback is optimized, a much smaller s-shaped error remains with nearly equal negative and positive values, reaching maximums at ¼ and ¾ full scale (see Figure 3). This primarily third-order nonlinearity does not come from the RTD but is an artifact of the linearization technique. Its magnitude depends on the temperature range chosen for linearization. Figure 3 shows the initial nonlinearity error for a –100°C to +800°C temperature range—a 900°C span. The 3.7% RTD nonlinearity at midscale is reduced to approximately ±0.11%, a 33:1 improvement. The improvement is even greater for narrow temperature ranges, approaching 150:1 for a 200°C range.

The use of positive feedback might raise the concern of possible circuit instability. The magnitude of this feedback is small enough, however, to have negligible effect on the stability of commonly used circuits.

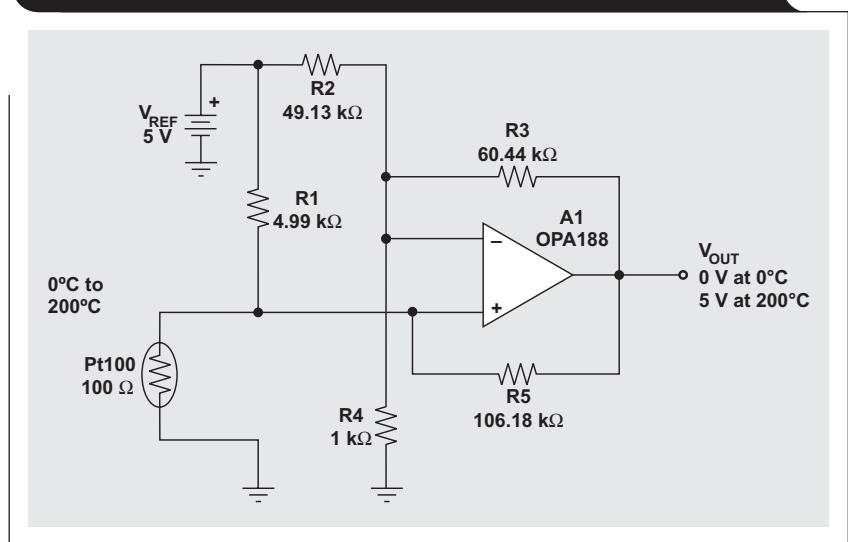
Figure 4 shows a practical implementation of an RTD. R1 provides the primary excitation current from  $V_{REF}$ , a stable voltage reference. R5 provides the temperature-varying component of excitation current from the output of A1. R2, R3, and R4 set the required amplifier gain and offset to produce the desired output-voltage range. The Texas Instruments (TI) OPA188\* shown in this example is a new low-noise, chopper-stabilized operational amplifier that contributes negligible error to the circuit. Its very low and stable offset voltage makes it a possible upgrade to TI's OPA277 precision industrial amplifier.

The resistor values to achieve best correction can be calculated with iterative techniques. Many designers might optimize this type of circuit by using creative calculations or approximations. A closed-form solution is possible by

**Figure 3. Percentage of RTD error versus temperature**



**Figure 4. Typical RTD configuration with error compensation**



solving the nodal equation that relates the RTD voltage, RTD resistance,  $V_{REF}$ , R1, R5, and  $V_{OUT}$ :

$$V_{RTD} = V_{REF} \times \frac{\frac{R_{RTD} \times R5}{R_{RTD} + R5}}{\frac{R_{RTD} \times R5}{R_{RTD} + R5} + R1} + V_{OUT} \times \frac{\frac{R_{RTD} \times R1}{R_{RTD} + R1}}{\frac{R_{RTD} \times R1}{R_{RTD} + R1} + R5}$$

\*The OPA188 is expected to be available in early 2012. For general specifications, please refer to the dual version, OPA2188, at [www.ti.com/product/OPA2188](http://www.ti.com/product/OPA2188)

Three conditions must be met to achieve zero error at the calibration endpoint temperatures and the midpoint temperature. Three separate variations of the preceding equation are written to describe the three zero-error conditions and are solved simultaneously for the only unknown variable,  $R_5$ . The resistance of the RTD at the midpoint temperature is not halfway between the endpoint resistances. This midpoint condition holds the key to the solution for best linearity correction.

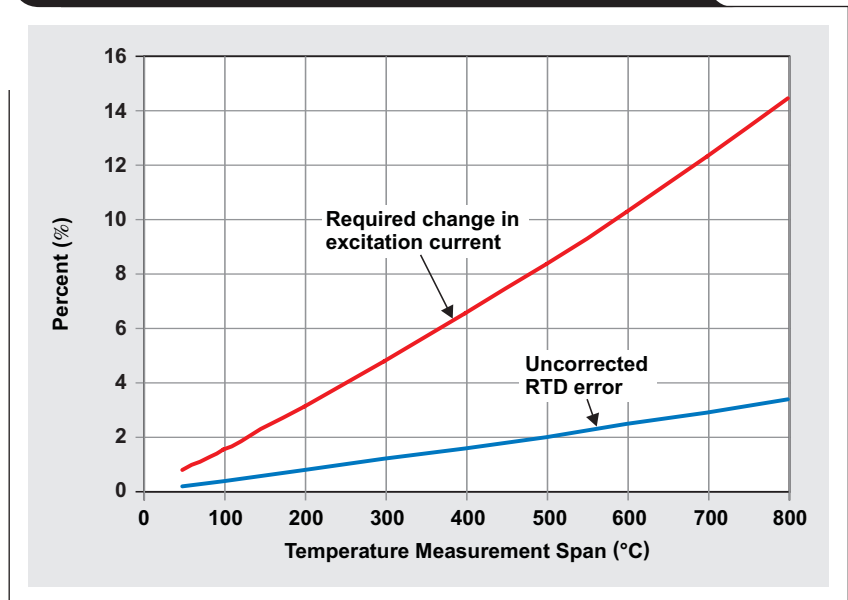
The math yields three results for  $R_5$ ; only one is a positive resistance. The expression for  $R_5$  is very long and impractical to present here. To download an Excel® worksheet that provides the calculations, go to <http://www.ti.com/lit/zip/SLYT442> and click Open to view the WinZip® directory online (or click Save to download the WinZip file for offline use). Then open the file RTD\_Linearization\_v7.xls to view the calculation worksheet. This closed-form solution is intellectually satisfying and avoids possible problems with convergence, but the results are no better than those produced with iterative calculations. Practical implementations often require trimming of resistors for calibration because accurate, non-standard values are often required. SPICE simulation can help determine actual performance with the nearest standard values. The WinZip file download listed above also includes two RTD simulation examples in TINA-TI™ SPICE files. One file implements an RTD linearization circuit based on an operational amplifier, and the other file is based on an instrumentation amplifier. Please see Reference 2 for more information on an RTD simulator for SPICE.

Figure 5 shows that uncorrected non-linearity of the RTD increases as the calibrated temperature range is increased, reaching approximately 2% for a 500°C span. The variation in the RTD's excitation current to compensate for this nonlinearity is approximately four times the nonlinearity. Thus, for a 500°C measurement span, the excitation current increases by approximately 8% from low-scale temperature to full scale.

Low-resistance connections to the RTD are crucial in maintaining accuracy with this circuit. For this reason, high-resistance RTDs such as Pt1000 or Pt5000 may be most practical. With a four-wire (or Kelvin) connection to the RTD and an additional operational amplifier, errors induced by wire resistance can be eliminated.

An integrated instrumentation amplifier with a three-wire RTD connection can provide an alternative solution (see

**Figure 5. Correlation of excitation current to RTD error**



**Figure 6. Amplifier with three-wire RTD connection**

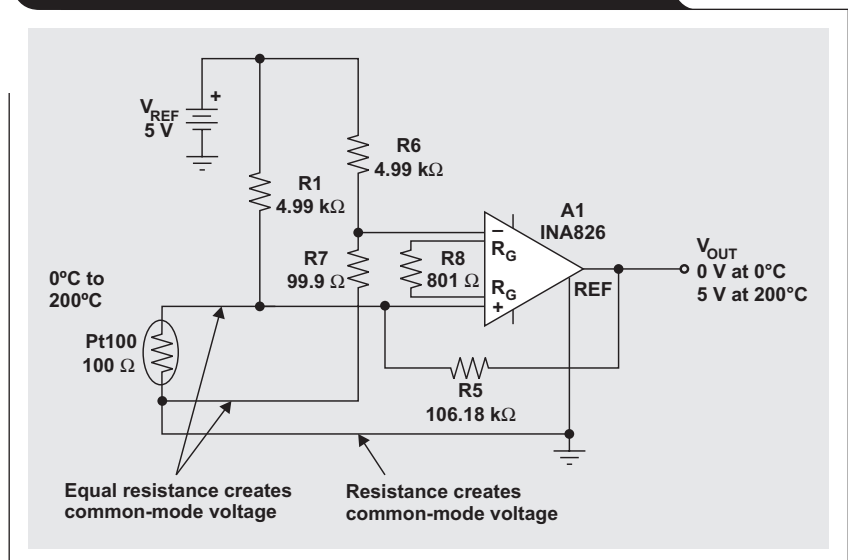


Figure 6). In the three-wire connection, two connections are used on the ground side of the RTD. Equal currents flowing in equal line resistances create a common-mode input voltage that is rejected by the instrumentation amplifier. Current flowing in the ground-wire connection also creates a common-mode voltage. Note that the currents in signal connections are not precisely equal. They differ due to the varying linearity correction current from  $R_5$ . Nevertheless, this configuration removes most of the error that is due to line resistance.

**Table 1. Partial listing of TI's integrated circuits for RTDs and bridge sensors**

PRODUCT	SENSOR TYPE	EXCITATION	OUTPUT	FEATURES
XTR105	RTD	Dual 1-mA current	4 to 20 mA	Resistor-programmed range and linearization
XTR106	Pressure bridge	Voltage	4 to 20 mA	Corrects positive or negative second-order nonlinearity
XTR108	RTD	Dual programmable current	4 to 20 mA or voltage	Programmable excitation current and linearization
XTR112	High-impedance RTD	Dual 100- $\mu$ A current	4 to 20 mA	Excitation for Pt1000 RTD
XTR114	High-impedance RTD	Dual 250- $\mu$ A current	4 to 20 mA	Excitation for Pt5000 RTD
PGA309	Pressure bridge	Programmable voltage	Voltage	Digitally controlled analog-signal path with linearization

## Other sensor types

Bridge sensors such as strain gauges and load cells frequently require linearization with similar techniques. Voltage excitation is generally used for these applications, but the concept is the same. Excitation voltage is varied with amplifier output voltage. These sensors can have a downward bowing nonlinearity requiring that the excitation voltage decrease as pressure increases. Furthermore, nonlinearity may vary significantly from unit to unit, so individual calibration may be required.

## Integrated solutions

TI uses variable excitation for linearization in several integrated circuits intended for RTDs and bridge sensors (see Table 1). Some circuits are designed specifically for remote sensors with two-wire, 4- to 20-mA current-loop output. XTR106 and PGA309 provide voltage excitation, which is preferred for many strain-gauge bridge-sensor applications. Though designed for specific sensor types, these devices have been successfully adapted to a variety of sensor applications, with and without variable excitation for linearization.

## References

1. Resistance thermometer. *Wikipedia* [Online]. Available: [http://en.wikipedia.org/wiki/Resistance\\_thermometer](http://en.wikipedia.org/wiki/Resistance_thermometer)
2. Thomas Kuehl. (2007, May 28). Developing a precise Pt100 RTD simulator for SPICE. *EN-Genius Network: analogZONE: acquisitionZONE* [Online]. Available: [http://www.analogzone.com/acqt\\_052807.pdf](http://www.analogzone.com/acqt_052807.pdf)
3. Bruce C. Trump. (1994, March 3). Pressure gauge responds linearly to altitude. *EDN* [Online]. Available: <http://www.edn.com/archives/1994/030394/05di5.htm>

## Related Web sites

[www.ti.com/product/partnumber](http://www.ti.com/product/partnumber)

Replace *partnumber* with INA826, OPA277, OPA2188, PGA309, XTR105, XTR106, XTR108, XTR112, or XTR114

Support files with Excel spreadsheet and TINA-TI™ simulation examples:

[www.ti.com/lit/zip/SLYT442](http://www.ti.com/lit/zip/SLYT442)

# TI Worldwide Technical Support

---

## Internet

### TI Semiconductor Product Information Center Home Page

support.ti.com

### TI E2E™ Community Home Page

e2e.ti.com

## Product Information Centers

<b>Americas</b>	Phone	+1(972) 644-5580
<b>Brazil</b>	Phone	0800-891-2616
<b>Mexico</b>	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	support.ti.com/sc/pic/americas.htm

## Europe, Middle East, and Africa

Phone	
European Free Call	00800-ASK-TEXAS (00800 275 83927)
International	+49 (0) 8161 80 2121
Russian Support	+7 (4) 95 98 10 701

**Note:** The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax	+ (49) (0) 8161 80 2045
Internet	support.ti.com/sc/pic/euro.htm
Direct Email	asktexas@ti.com

## Japan

Phone	Domestic	0120-92-3326
Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	support.ti.com/sc/pic/japan.htm
	Domestic	www.tij.co.jp/pic

## Asia

Phone	
International	+91-80-41381665
Domestic	<u>Toll-Free Number</u>
<b>Note:</b> Toll-free numbers do not support mobile and IP phones.	
Australia	1-800-999-084
China	800-820-8682
Hong Kong	800-96-5941
India	1-800-425-7888
Indonesia	001-803-8861-1006
Korea	080-551-2804
Malaysia	1-800-80-3973
New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
Thailand	001-800-886-0010

Fax	+8621-23073686
Email	tiasia@ti.com or ti-china@ti.com
Internet	support.ti.com/sc/pic/asia.htm

**Important Notice:** The products and services of Texas Instruments Incorporated and its subsidiaries described herein are sold subject to TI's standard terms and conditions of sale. Customers are advised to obtain the most current and complete information about TI products and services before placing orders. TI assumes no liability for applications assistance, customer's applications or product designs, software performance, or infringement of patents. The publication of information regarding any other company's products or services does not constitute TI's approval, warranty or endorsement thereof.

**A122010**

E2E is a trademark of Texas Instruments. Excel is a registered trademark of Microsoft Corporation. WinZip is a registered trademark of WinZip International LLC. All other trademarks are the property of their respective owners.

## IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal, regulatory and safety-related requirements concerning their products and any use of TI products in such safety-critical applications, notwithstanding any applications-related information or support that may be provided by TI. Further, Buyers must fully indemnify TI and its representatives against any damages arising out of the use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or "enhanced plastic." Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer's risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

### Products

Audio	<a href="http://www.ti.com/audio">www.ti.com/audio</a>
Amplifiers	<a href="http://amplifier.ti.com">amplifier.ti.com</a>
Data Converters	<a href="http://dataconverter.ti.com">dataconverter.ti.com</a>
DLP® Products	<a href="http://www.dlp.com">www.dlp.com</a>
DSP	<a href="http://dsp.ti.com">dsp.ti.com</a>
Clocks and Timers	<a href="http://www.ti.com/clocks">www.ti.com/clocks</a>
Interface	<a href="http://interface.ti.com">interface.ti.com</a>
Logic	<a href="http://logic.ti.com">logic.ti.com</a>
Power Mgmt	<a href="http://power.ti.com">power.ti.com</a>
Microcontrollers	<a href="http://microcontroller.ti.com">microcontroller.ti.com</a>
RFID	<a href="http://www.ti-rfid.com">www.ti-rfid.com</a>
OMAP Mobile Processors	<a href="http://www.ti.com/omap">www.ti.com/omap</a>
Wireless Connectivity	<a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a>

### Applications

Communications and Telecom	<a href="http://www.ti.com/communications">www.ti.com/communications</a>
Computers and Peripherals	<a href="http://www.ti.com/computers">www.ti.com/computers</a>
Consumer Electronics	<a href="http://www.ti.com/consumer-apps">www.ti.com/consumer-apps</a>
Energy and Lighting	<a href="http://www.ti.com/energy">www.ti.com/energy</a>
Industrial	<a href="http://www.ti.com/industrial">www.ti.com/industrial</a>
Medical	<a href="http://www.ti.com/medical">www.ti.com/medical</a>
Security	<a href="http://www.ti.com/security">www.ti.com/security</a>
Space, Avionics and Defense	<a href="http://www.ti.com/space-avionics-defense">www.ti.com/space-avionics-defense</a>
Transportation and Automotive	<a href="http://www.ti.com/automotive">www.ti.com/automotive</a>
Video and Imaging	<a href="http://www.ti.com/video">www.ti.com/video</a>

TI E2E Community Home Page

[e2e.ti.com](http://e2e.ti.com)

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265  
Copyright © 2011, Texas Instruments Incorporated