

## FEATURES

- Measures Voltage, Current, Temperature
- Measures Four Remote Diode Temperatures
- 0.7°C (Typ) Accuracy, 0.06°C Resolution
- 1°C (Typ) Internal Temperature Sensor
- Series Resistance Cancellation
- 14-Bit ADC Measures Voltage/Current
- PWM Temperature Output
- 3V to 5.5V Supply Operating Voltage
- Eight Selectable Addresses
- Internal 10ppm/°C Voltage Reference
- V1 to V8 Inputs ESD Rated to 6kV HBM
- 16-Lead MSOP Package

## APPLICATIONS

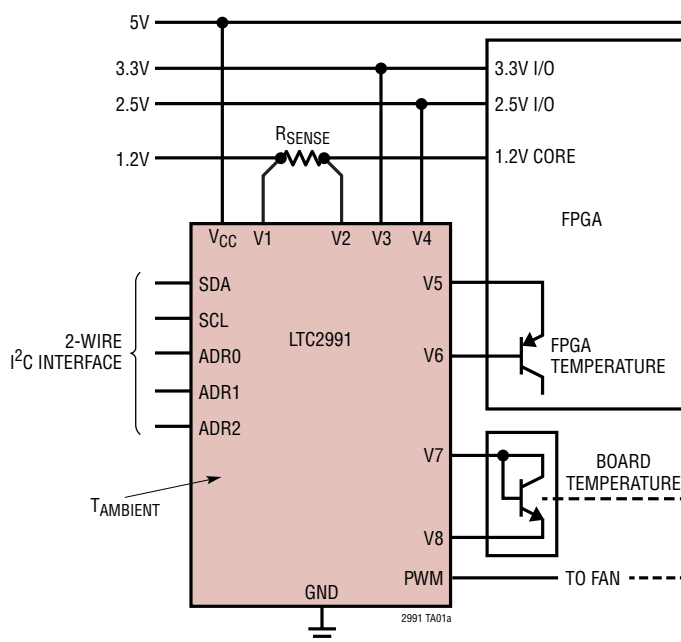
- Temperature Measurement
- Supply Voltage Monitoring
- Current Measurement
- Remote Data Acquisition
- Environmental Monitoring

## DESCRIPTION

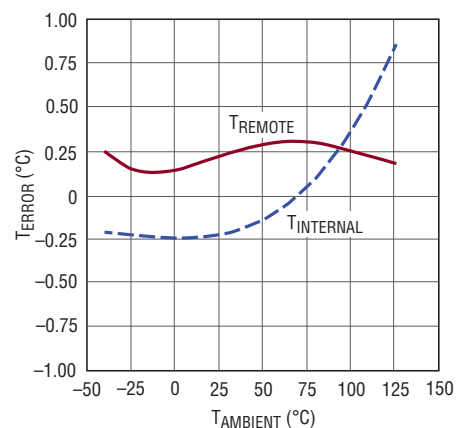
The LTC<sup>®</sup>2991 is used to monitor system temperatures, voltages and currents. Through the I<sup>2</sup>C serial interface, the eight monitors can individually measure supply voltages and can be paired for differential measurements of current sense resistors or temperature sensing transistors. Additional measurements include internal temperature and internal V<sub>CC</sub>. The internal 10ppm reference minimizes the number of supporting components and area required. Selectable address and configurable functionality give the LTC2991 flexibility to be incorporated in various systems needing temperature, voltage or current data. The LTC2991 fits well in systems needing submillivolt voltage resolution, 1% current measurement and 1°C temperature accuracy or any combination of the three.

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## TYPICAL APPLICATION



Temperature Total Unadjusted Error



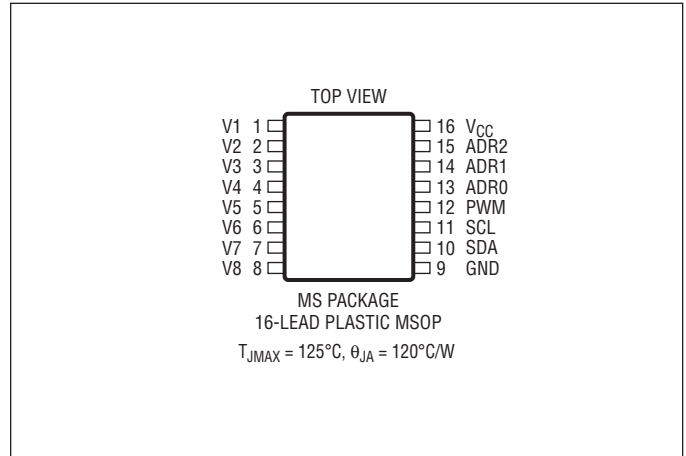
2991 TA01b

## ABSOLUTE MAXIMUM RATINGS

(Note 1)

|   |                              |
|---|------------------------------|
| Supply Voltage ( $V_{CC}$ )   | -0.3V to 6.0V                |
| Input Voltages V1, V2, V3, V4, V5, V6, V7, V8,<br>SCL, ADR0, ADR1, ADR2 | -0.3V to ( $V_{CC} + 0.3V$ ) |
| Output Voltage PWM  | -0.3V to ( $V_{CC} + 0.3V$ ) |
| Output Voltage SDA  | -0.3V to 6V                  |
| Operating Temperature Range   |                              |
| LTC2991C  | 0°C to 70°C                  |
| LTC2991I  | -40°C to 85°C                |
| Storage Temperature Range   | -65°C to 150°C               |
| Lead Temperature (Soldering, 10 sec)                                    |                              |
| MS Package  | 300°C                        |

## PIN CONFIGURATION



## ORDER INFORMATION

| LEAD FREE FINISH | TAPE AND REEL    | PART MARKING* | PACKAGE DESCRIPTION  | TEMPERATURE RANGE |
|------------------|------------------|---------------|----------------------|-------------------|
| LTC2991CMS#PBF   | LTC2991CMS#TRPBF | 2991          | 16-Lead Plastic MSOP | 0°C to 70°C       |
| LTC2991IMS#PBF   | LTC2991IMS#TRPBF | 2991          | 16-Lead Plastic MSOP | -40°C to 85°C     |

Consult LTC Marketing for parts specified with wider operating temperature ranges. \*The temperature grade is identified by a label on the shipping container.

For more information on lead free part marking, go to: <http://www.linear.com/leadfree/>

For more information on tape and reel specifications, go to: <http://www.linear.com/tapeandreel/>. Some packages are available in 500 unit reels through designated sales channels with #TRMPBF suffix.

## ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at  $T_A = 25^\circ\text{C}$ ,  $V_{CC} = 3.3V$ , unless otherwise noted.

| SYMBOL                      | PARAMETER   | CONDITIONS                                   | MIN   | TYP    | MAX   | UNITS |     |
|-----------------------------|---|--|-------|--------|-------|-------|-----|
| <b>General</b>              |   |  |       |        |       |       |     |
| $V_{CC}$                    | Input Supply Range  |  | ● 2.9 |        | 5.5   | V     |     |
| $I_{CC}$                    | Input Supply Current  | During Conversion, I <sup>2</sup> C Inactive | ●     | 1.1    | 1.5   | mA    |     |
| $I_{SD}$                    | Input Supply Current  | Shutdown Mode, I <sup>2</sup> C Inactive     | ●     | 1      | 6     | μA    |     |
| $V_{CC(UVL)}$               | Input Supply Undervoltage Lockout   |  | ● 1.3 | 2.0    | 2.6   | V     |     |
| <b>Measurement Accuracy</b> |   |  |       |        |       |       |     |
| $T_{INTERNAL(TUE)}$         | Internal Temperature Total Unadjusted Error                                       |  |       | ±1     | ±3.5  | °C    |     |
| $T_{RMT(TUE)}$              | Remote Diode Temperature Total Unadjusted Error                                   | $\eta = 1.004$                               | ●     | ±0.7   | ±1.5  | °C    |     |
| $V_{CC(TUE)}$               | $V_{CC}$ Voltage Total Unadjusted Error   | $2.9V \leq V_{CC} \leq 5.5V$                 | ●     | ±0.05  | ±0.25 | %     |     |
| $V_{N(TUE)}$                | V1 Through V8 Total Unadjusted Error  | $0V \leq V_{IN} \leq 4.9V$                   | ●     | ±0.05  | ±0.25 | %     |     |
| $V_{DIFF(TUE)}$             | Differential Voltage Total Unadjusted Error<br>V1 – V2, V3 – V4, V5 – V6, V7 – V8 | $-300mV \leq V_D \leq 300mV$                 | ●     | ±0.1   | ±0.75 | %     |     |
| $V_{DIFF(MAX)}$             | Full-Scale Differential Voltage   |  | ●     | -312.5 | 312.5 | mV    |     |
| $V_{OFFSET\_DIFF}$          | Differential Offset   | V1 through V8 = 0V                           | ●     | -12.5  | 0     | 12.5  | LSB |
| $V_{OFFSET\_SE}$            | Single-Ended Offset   | V1 through V8 = 0V                           | ●     | -6     | 0     | 6     | LSB |

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## ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at  $T_A = 25^\circ\text{C}$ ,  $V_{CC} = 3.3\text{V}$ , unless otherwise noted.

| SYMBOL  | PARAMETER  | CONDITIONS   |        | MIN                | TYP    | MAX                | UNITS              |
|---|--|--|--------|--------------------|--------|--------------------|--------------------|
| $V_{\text{DIFF(CMR)}}$                                | Differential Voltage Common Mode Range   |  | ●      | 0                  |        | $V_{CC}$           | V                  |
| $V_{\text{LSB(DIFF)}}$                                | Differential Voltage LSB Weight  |  |        |                    | 19.075 |                    | $\mu\text{V}$      |
| $V_{\text{LSB(SINGLE_ENDED)}}$                        | Single-Ended Voltage LSB Weight  |  |        |                    | 305.18 |                    | $\mu\text{V}$      |
| $V_{\text{LSB(TEMP)}}$                                | Temperature LSB Weight   | Celsius or Kelvin  |        |                    | 0.0625 |                    | Deg                |
| $V_{\text{LSB(DIODE_VOLTAGE)}}$                       | Diode Voltage LSB Weight   | Includes Series Resistance IR Drop   |        |                    | 38.15  |                    | $\mu\text{V}$      |
| $T_{\text{NOISE}}$                                    | Temperature Noise  | Celsius or Kelvin Filter Disengaged  |        |                    | 0.2    |                    | $^\circ\text{RMS}$ |
| $T_{\text{NOISE}}$                                    | Temperature Noise  | Celsius or Kelvin Filter Engaged   |        |                    | 0.07   |                    | $^\circ\text{RMS}$ |
| RES   | Resolution (No Missing Codes)  | (Note 2)   | ●      | 14                 |        |                    | Bits               |
| INL   | Integral Nonlinearity  | $2.9\text{V} \leq V_{CC} \leq 5.5\text{V}$ , $V_{\text{IN(CM)}} = 1.5\text{V}$<br>(Note 2)<br>Single-Ended<br>Differential | ●<br>● | -2<br>-2           |        | 2<br>2             | LSB<br>LSB         |
| $C_{\text{IN}}$                                       | V1 Through V8 Input Sampling Capacitance   | (Note 2)   |        |                    | 0.35   |                    | pF                 |
| $I_{\text{IN(AVG)}}$                                  | V1 Through V8 Input Average Sampling Current                                     | $(0 \leq V_N \leq 4.9\text{V})$ (Note 2)   |        |                    | 0.6    |                    | $\mu\text{A}$      |
| $I_{\text{DC\_LEAK(VIN)}}$                            | V1 Through V8 Input Leakage Current  | $(0 \leq V_N \leq V_{CC})$   | ●      | -10                |        | 10                 | nA                 |
| <b>PWM</b>  |  |  |        |                    |        |                    |                    |
| $F_{\text{PWM}}$                                      | PWM Period   |  | ●      | 0.9                |        | 1.2                | ms                 |
| $DC_{\text{PWM}}$                                     | Duty Cycle Range   |  | ●      | 0                  |        | 99.8               | %                  |
| $SCALE_{\text{PWM}}$                                  | 0% to 100% PWM Temperature Range   |  |        |                    | 32     |                    | Deg                |
| <b>Measurement Delay</b>                              |  |  |        |                    |        |                    |                    |
| $T_{\text{INTERNAL}}, T_{R1}, T_{R2}, T_{R3}, T_{R4}$ | Per Configured Temperature Measurement   |  | ●      | 37                 | 46     | 55                 | ms                 |
| V1, V2, V3, V4, V5, V6, V7, V8                        | Single-Ended Voltage Measurement   |  | ●      | 0.9                | 1.5    | 1.8                | ms                 |
| V1 – V2, V3 – V4, V5 – V6, V7 – V8                    | Differential Voltage Measurement   |  | ●      | 0.9                | 1.5    | 1.8                | ms                 |
| $V_{CC}$  | $V_{CC}$ Measurement   |  | ●      | 0.9                | 1.5    | 1.8                | ms                 |
| Max Delay   | Mode[4:0] = 11101, $T_{\text{INTERNAL}}, T_{R1}, T_{R2}, T_{R3}, T_{R4}, V_{CC}$ |  | ●      |                    |        | 277                | ms                 |
| <b>V1, V3, V5, V7 OUTPUT (Remote Diode Mode Only)</b> |  |  |        |                    |        |                    |                    |
| $I_{\text{OUT}}$                                      | Output Current   | Remote Diode Mode  | ●      |                    | 260    | 350                | $\mu\text{A}$      |
| $V_{\text{OUT}}$                                      | Output Voltage   |  | ●      | 0                  |        | $V_{CC}$           | V                  |
| <b>I<sup>2</sup>C Interface</b>                       |  |  |        |                    |        |                    |                    |
| $V_{\text{ADR(L)}}$                                   | ADR Input Low Threshold Voltage  | Falling  | ●      |                    |        | $0.3 \cdot V_{CC}$ | V                  |
| $V_{\text{ADR(H)}}$                                   | ADR Input High Threshold Voltage   | Rising   | ●      | $0.7 \cdot V_{CC}$ |        |                    | V                  |
| $V_{\text{OL1}}$                                      | SDA Low Level Maximum Voltage  | $I_O = -3\text{mA}$ , $V_{CC} 2.9\text{V}$ to $5.5\text{V}$  | ●      |                    |        | 0.4                | V                  |
| $V_{\text{IL}}$                                       | Maximum Low Level Input Voltage  | SDA and SCL Pins   | ●      |                    |        | $0.3 \cdot V_{CC}$ | V                  |
| $V_{\text{IH}}$                                       | Minimum High Level Input Voltage   | SDA and SCL Pins   | ●      | $0.7 \cdot V_{CC}$ |        |                    | V                  |
| $I_{\text{SDAI, SCLI}}$                               | SDA, SCL Input Current   | $0 < V_{\text{SDA}}, V_{\text{SCL}} < V_{CC}$  | ●      |                    |        | $\pm 1$            | $\mu\text{A}$      |
| $I_{\text{ADR(MAX)}}$                                 | Maximum ADR0, ADR1, ADR2 Input Current   | ADR0, ADR1 or ADR2 Tied to $V_{CC}$ or GND   | ●      |                    |        | $\pm 1$            | $\mu\text{A}$      |

## ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at  $T_A = 25^\circ\text{C}$ ,  $V_{CC} = 3.3\text{V}$ , unless otherwise noted.

| SYMBOL                                | PARAMETER  | CONDITIONS | MIN | TYP | MAX | UNITS         |
|---------------------------------------|--|------------|-----|-----|-----|---------------|
| <b>I<sup>2</sup>C Timing (Note 2)</b> |  |            |     |     |     |               |
| $f_{\text{SCL(MAX)}}$                 | Maximum SCL Clock Frequency                        |            | 400 |     |     | kHz           |
| $t_{\text{LOW}}$                      | Minimum SCL Low Period                             |            |     |     | 1.3 | $\mu\text{s}$ |
| $t_{\text{HIGH}}$                     | Minimum SCL High Period                            |            |     |     | 600 | ns            |
| $t_{\text{BUF(MIN)}}$                 | Minimum Bus Free Time Between Stop/Start Condition |            |     |     | 1.3 | $\mu\text{s}$ |
| $t_{\text{HD, STA(MIN)}}$             | Minimum Hold Time After (Repeated) Start Condition |            |     |     | 600 | ns            |
| $t_{\text{SU, STA(MIN)}}$             | Minimum Repeated Start Condition Set-Up Time       |            |     |     | 600 | ns            |
| $t_{\text{SU, STO(MIN)}}$             | Minimum Stop Condition Set-Up Time                 |            |     |     | 600 | ns            |
| $t_{\text{HD, DATI(MIN)}}$            | Minimum Data Hold Time Input                       |            |     |     | 0   | ns            |
| $t_{\text{HD, DATO(MIN)}}$            | Minimum Data Hold Time Output                      |            | 300 |     | 900 | ns            |
| $t_{\text{SU, DAT(MIN)}}$             | Minimum Data Set-Up Time Input                     |            |     |     | 100 | ns            |
| $t_{\text{SP(MAX)}}$                  | Maximum Suppressed Spike Pulse Width               |            | 50  |     | 250 | ns            |
| $C_X$                                 | SCL, SDA Input Capacitance                         |            |     |     | 10  | pF            |

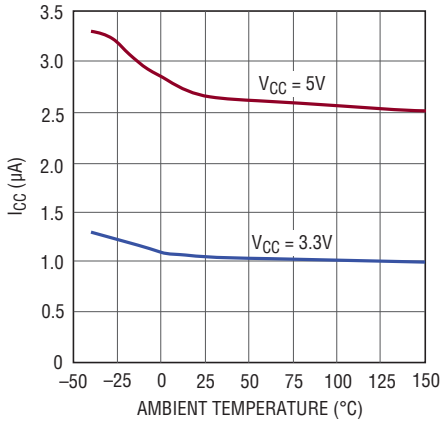
**Note 1:** Stresses beyond those listed under Absolute Maximum Ratings may cause permanent damage to the device. Exposure to any Absolute Maximum Rating condition for extended periods may affect device reliability and lifetime.

**Note 2:** Guaranteed by design and not subject to test.

**Note 3:** Integral nonlinearity is defined as the deviation of a code from a straight line passing through the actual endpoints of the transfer curve. The deviation is measured from the center of the quantization band.

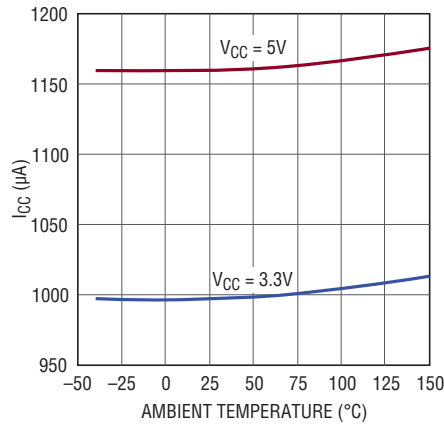
**TYPICAL PERFORMANCE CHARACTERISTICS**  $T_A = 25^\circ\text{C}$ ,  $V_{CC} = 3.3\text{V}$ , unless otherwise noted.

**Shutdown Current vs Temperature**



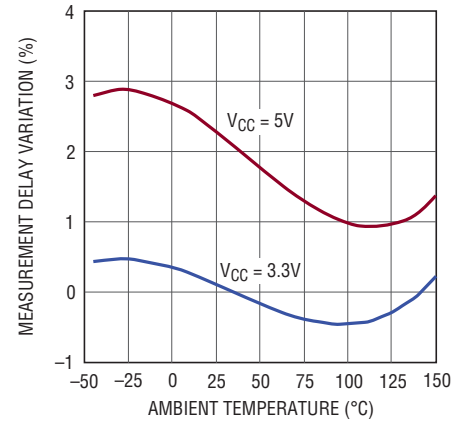
2991 G01

**Supply Current vs Temperature**



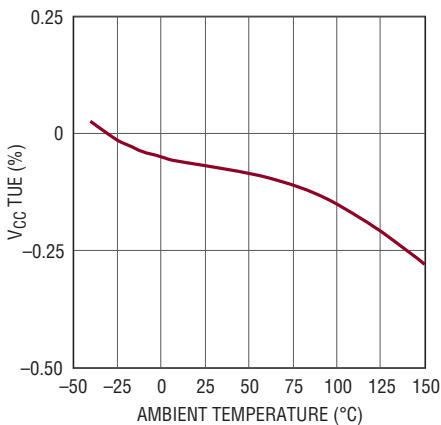
2991 G02

**Measurement Delay Variation vs T Normalized to 3.3V, 25°C**



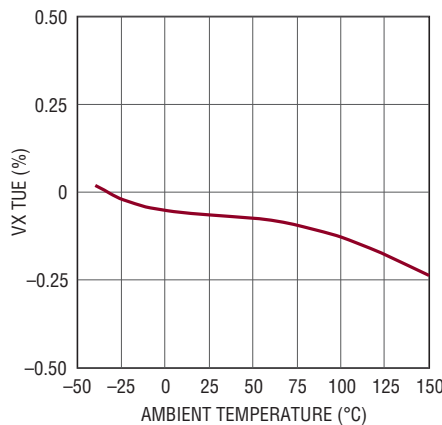
2991 G03

**$V_{CC}$  TUE**



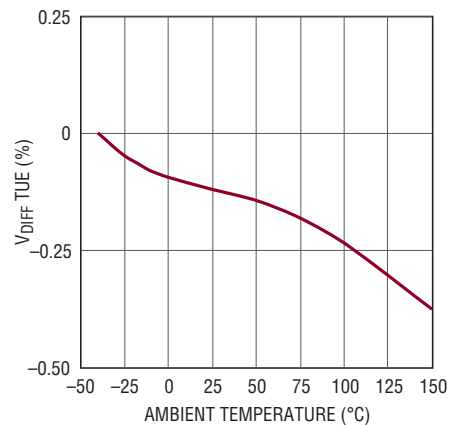
2991 G04

**Single-Ended VX TUE**



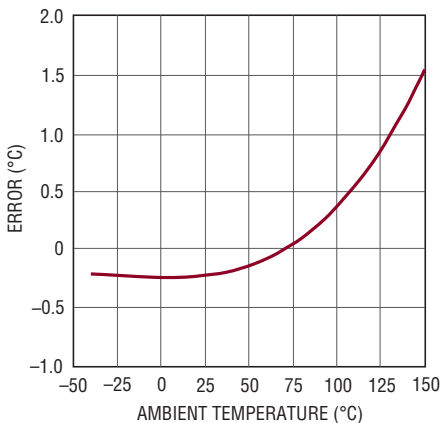
2991 G05

**Differential Voltage TUE**



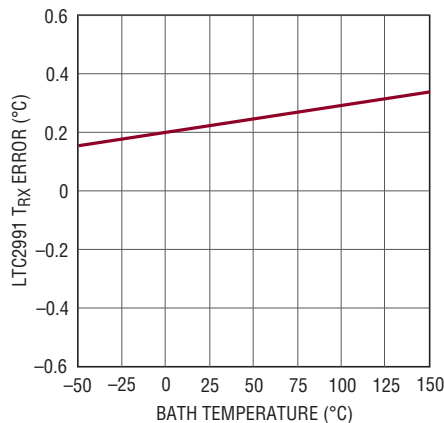
2991 G06

**$T_{INTERNAL}$  Error**



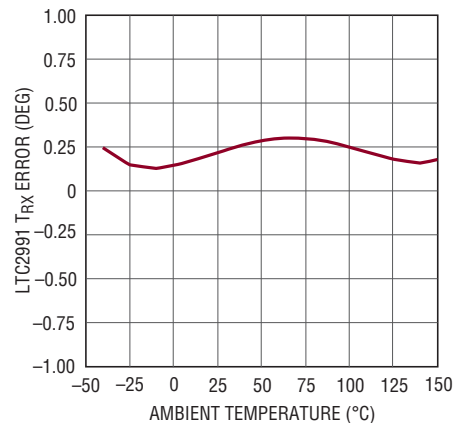
2991 G07

**Remote Diode Error with LTC2991 at 25°C**



2991 G08

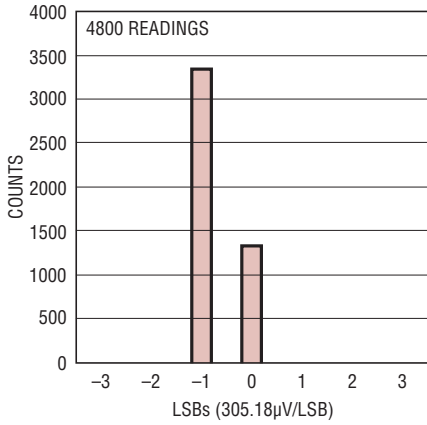
**Remote Diode Error with LTC2991 at Same Temperature as Diode**



2991 G09

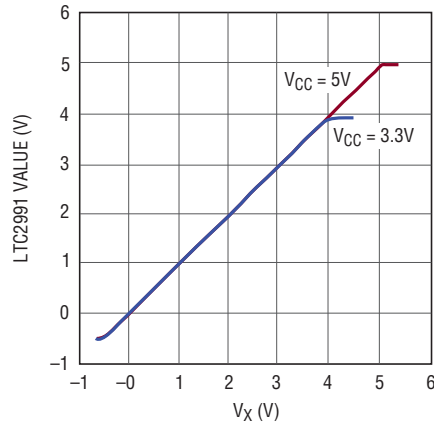
## TYPICAL PERFORMANCE CHARACTERISTICS $T_A = 25^\circ\text{C}$ , $V_{CC} = 3.3\text{V}$ , unless otherwise noted.

### Single-Ended Noise



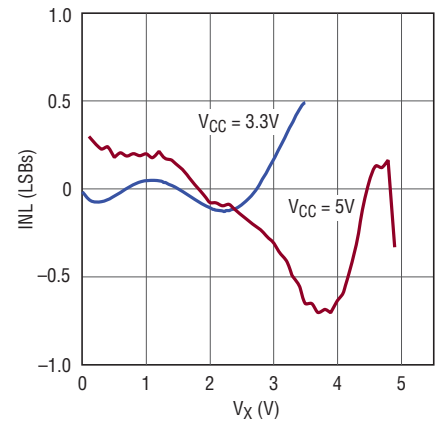
2991 G10

### Single-Ended Transfer Function



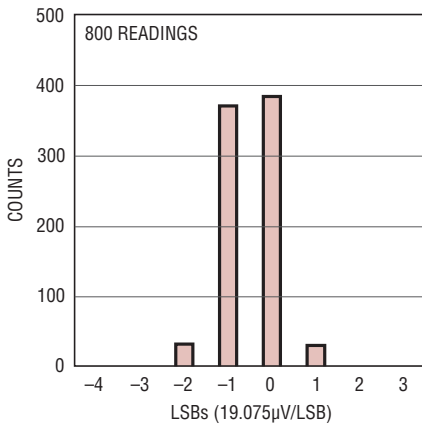
2991 G11

### Single-Ended INL



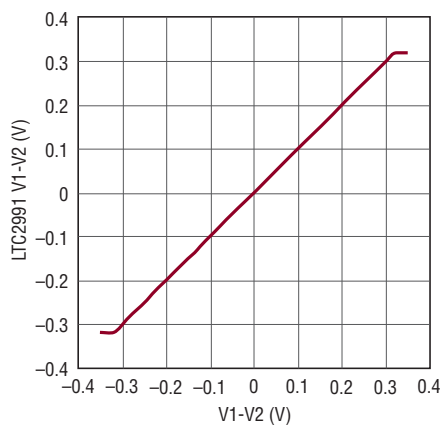
2991 G12

### LTC2991 Differential Noise



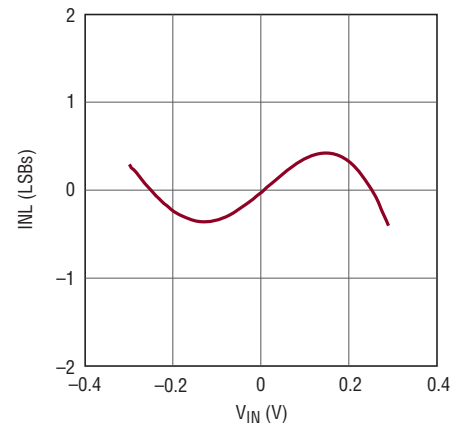
2991 G13

### Differential Transfer Function



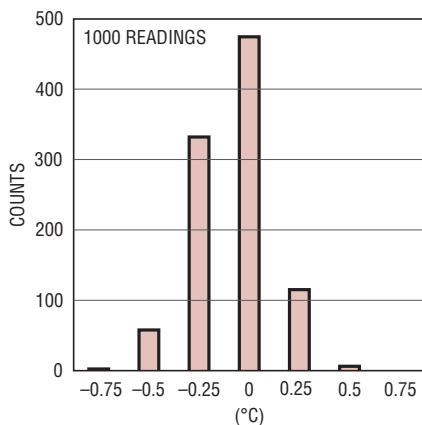
2991 G14

### Differential INL



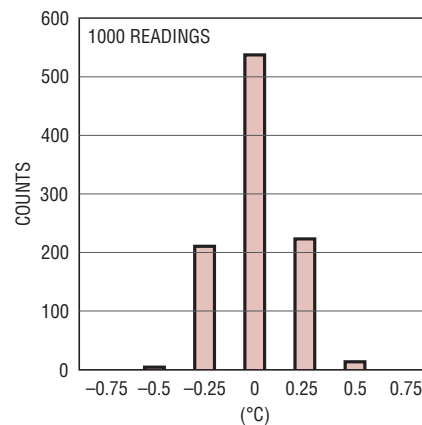
2991 G15

### INTERNAL Noise



2991 G16

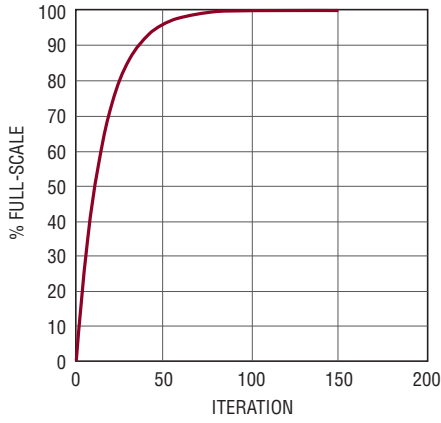
### Remote Diode Noise



2991 G17

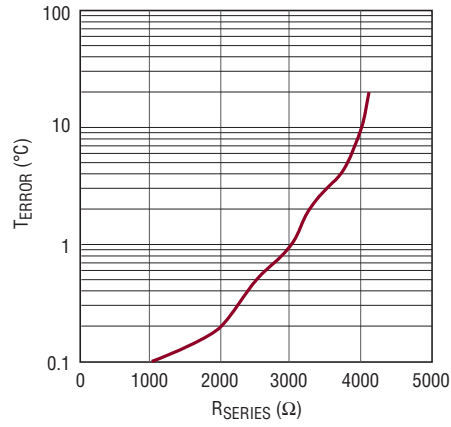
**TYPICAL PERFORMANCE CHARACTERISTICS**  $T_A = 25^\circ\text{C}$ ,  $V_{CC} = 3.3\text{V}$ , unless otherwise noted.

**Digital Filter Step Response**



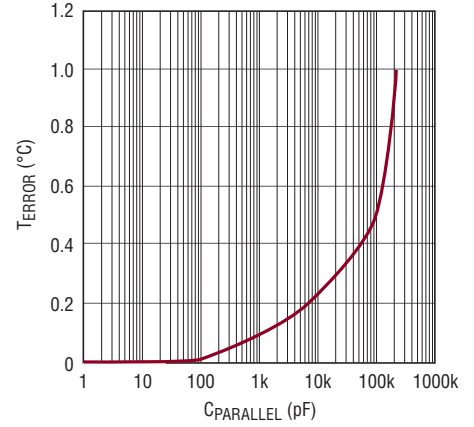
2991 G18

**TERROR VS R<sub>SERIES</sub>**



2991 G19

**TERROR VS C<sub>PARALLEL</sub>**



2991 G20

## PIN FUNCTIONS

**V1 (Pin 1):** First Monitor Input. This pin can be configured as a single-ended input (0V to 4.9V) or the positive input for a differential or remote diode temperature measurement (in combination with V2). Differential common mode range is 0V to  $V_{CC}$ ,  $\pm 300\text{mV}$  differential. When configured for remote diode temperature, this pin will source a current.

**V2 (Pin 2):** Second Monitor Input. This pin can be configured as a single-ended input (0V to 4.9V) or the negative input for a differential or remote diode temperature measurement (in combination with V1). Differential common mode range is 0V to  $V_{CC}$ ,  $\pm 300\text{mV}$  differential. When configured for remote diode temperature, this pin will have an internal termination, while the measurement is active.

**V3 (Pin 3):** Third Monitor Input. This pin can be configured as a single-ended input (0V to 4.9V) or the positive input for a differential or remote diode temperature measurement (in combination with V4). Differential common mode range is 0V to  $V_{CC}$ ,  $\pm 300\text{mV}$  differential. When configured for remote diode temperature, this pin will source a current.

**V4 (Pin 4):** Fourth Monitor Input. This pin can be configured as a single-ended input (0V to 4.9V) or the negative input for a differential or remote diode temperature measurement (in combination with V3). Differential common mode range is 0V to  $V_{CC}$ ,  $\pm 300\text{mV}$  differential. When configured for remote diode temperature, this pin will have an internal termination, while the measurement is active.

**V5 (Pin 5):** Fifth Monitor Input. This pin can be configured as a single-ended input (0V to 4.9V) or the positive input for a differential or remote diode temperature measurement (in combination with V6). Differential common mode range is 0V to  $V_{CC}$ ,  $\pm 300\text{mV}$  differential. When configured for remote diode temperature, this pin will source a current.

**V6 (Pin 6):** Sixth Monitor Input. This pin can be configured as a single-ended input (0V to 4.9V) or the negative input for a differential or remote diode temperature measurement (in combination with V5). Differential common mode range is 0V to  $V_{CC}$ ,  $\pm 300\text{mV}$  differential. When configured for remote diode temperature, this pin will have an internal termination, while the measurement is active.

**V7 (Pin 7):** Seventh Monitor Input. This pin can be configured as a single-ended input (0V to 4.9V) or the positive input for a differential or remote diode temperature measurement (in combination with V8). Differential common mode range is 0V to  $V_{CC}$ ,  $\pm 300\text{mV}$  differential. When configured for remote diode temperature, this pin will source a current.

**V8 (Pin 8):** Eighth Monitor Input. This pin can be configured as a single-ended input (0V to 4.9V) or the negative input for a differential or remote diode temperature measurement (in combination with V7). Differential common mode range is 0V to  $V_{CC}$ ,  $\pm 300\text{mV}$  differential. When configured for remote diode temperature, this pin will have an internal termination, while the measurement is active.

**GND (Pin 9):** Device Ground. Connect this pin through a low impedance connection to system ground.

**SDA (Pin 10):** Serial Bus Data Input and Output. In the transmitter mode (read), the conversion result is output through the SDA pin, while in the receiver mode (write), the device configuration bits are input through the SDA pin. At data input mode, the pin is high impedance; while at data output mode, it is an open-drain N-channel driver and, therefore, an external pull-up resistor or current source to  $V_{CC}$  is needed.

**SCL (Pin 11):** Serial Bus Clock Input of the I<sup>2</sup>C Interface. The LTC2991 can only act as a slave and the SCL pin only accepts external serial clock. The LTC2991 does not implement clock stretching.

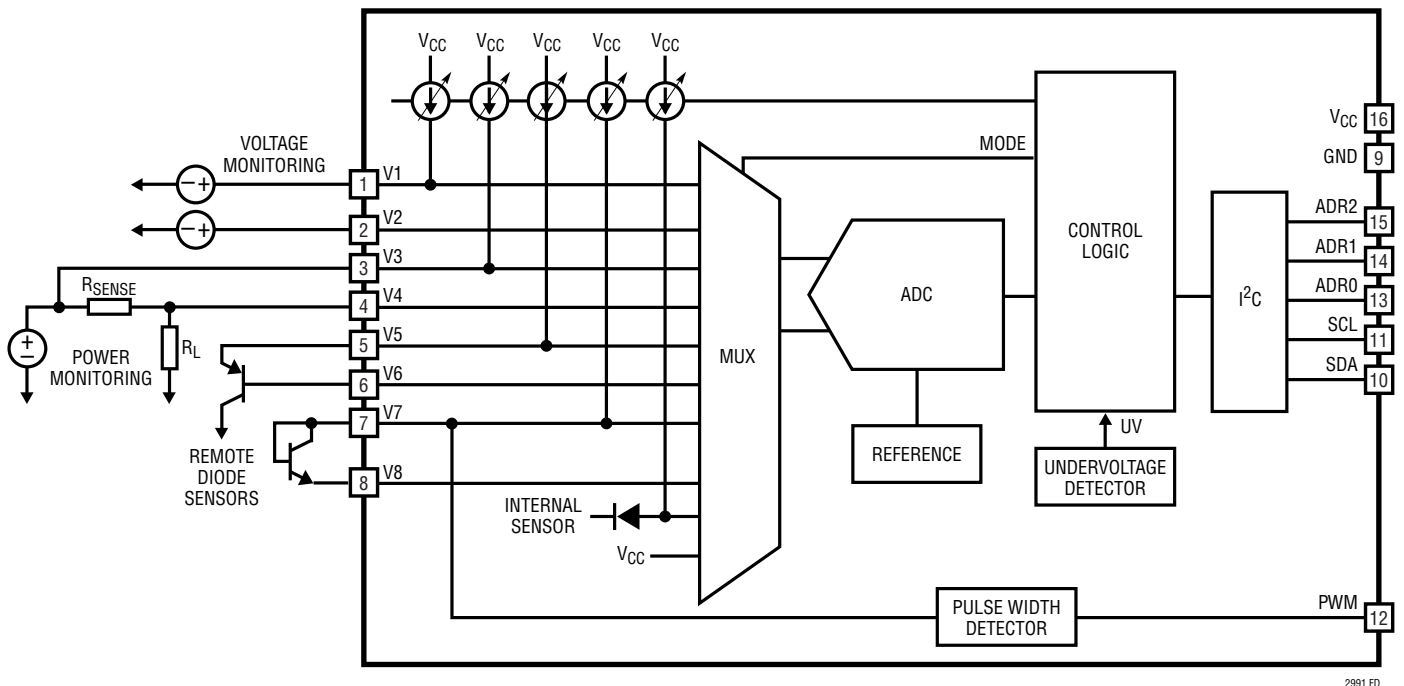
**PWM (Pin 12):** PWM Output. The PWM pin provides a CMOS output level with a duty cycle proportional to the remote diode temperature of the sensor connected to pins V7 and V8.

**ADR0, ADR1, ADR2 (Pins 13, 14, 15):** Serial Bus Address Control Input. The ADR pins are address control bits for the device I<sup>2</sup>C address. See Table 1.

**V<sub>CC</sub> (Pin 16):** Chip Power. Connect to 2.9V to 5.5V low noise supply. A 0.1 $\mu\text{F}$  decoupling capacitor to GND is required for this pin.

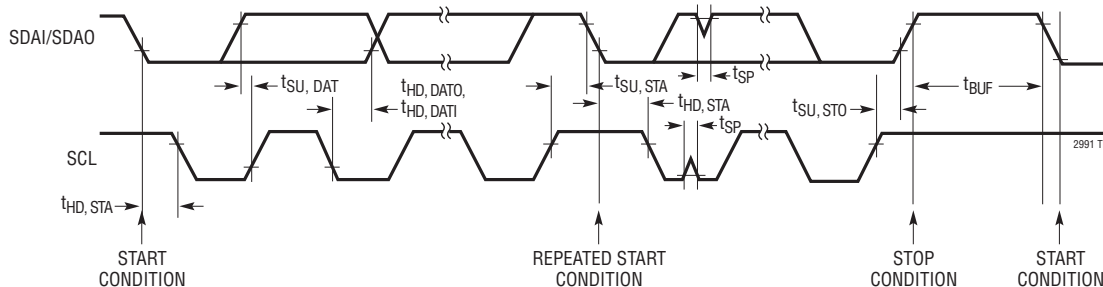


# FUNCTIONAL DIAGRAM



2991 FD

# TIMING DIAGRAM



2991 TD

## OPERATION

The LTC2991 monitors voltage, current, internal and remote temperatures. It can be configured through an I<sup>2</sup>C interface to measure many combinations of these parameters. Single or repeated measurements can be configured. Remote temperature measurements use transistors as temperature sensors, allowing the remote sensor to be a discrete NPN (ex. MMBT3904) or an embedded PNP device in a microprocessor or FPGA. The internal ADC reference minimizes the number of support components required.

The Functional Diagram displays the main functional components of the device. The input signals are selected with an input mux, controlled by the control logic block. The control logic block uses the mode bits in the control registers to manage the sequence and types of data acquisition. The control logic block also controls the current sources during remote temperature acquisition. The order of acquisitions is fixed: V1, V2, V3, V4, V5, V6, V7, V8, T<sub>INTERNAL</sub> then V<sub>CC</sub>. The ADC performs the necessary conversion(s) and supplies the data to the control logic for routing to the appropriate data register. The I<sup>2</sup>C interface supplies access to control, status and data registers. The ADR2, ADR1 and ADR0 pins select one of eight possible I<sup>2</sup>C addresses (see Table 1). The UVLO inhibits I<sup>2</sup>C communication below the specified threshold. During an undervoltage condition, the part is in a reset state, and the data and control registers are placed in the default state of 00h.

Remote diode measurements are conducted using multiple ADC conversions and source currents to compensate for sensor series resistance. The V2, V4, V6 or V8 terminals of the LTC2991 are terminated with a diode if that channel is configured for temperature measurements. It is acceptable to ground these pins, but increased noise may result on the temperature measurements. The LTC2991 is calibrated to yield the correct temperature for a remote diode with an ideality factor of 1.004. See the Applications Information section for compensation of sensor ideality factors other than the factory calibrated value of 1.004.

The LTC2991 communicates through an I<sup>2</sup>C serial interface. The serial interface provides access to control, status and data registers. I<sup>2</sup>C defines a 2-wire open-drain interface supporting multiple slave devices and masters on a single bus. The LTC2991 supports 100kbit/s in the standard mode and up to 400kbit/s in fast mode. The eight physical addresses supported are listed in Table 1. The I<sup>2</sup>C interface is used to trigger single conversions, or start repeated conversions by writing to a dedicated trigger register. The data registers contain a destructive read status bit (data valid), which is used in repeated mode to determine if the registers contents have been previously read. This bit is set when the register is updated with new data, and cleared when read.

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The basic LTC2991 application circuit is shown in Figure 1.

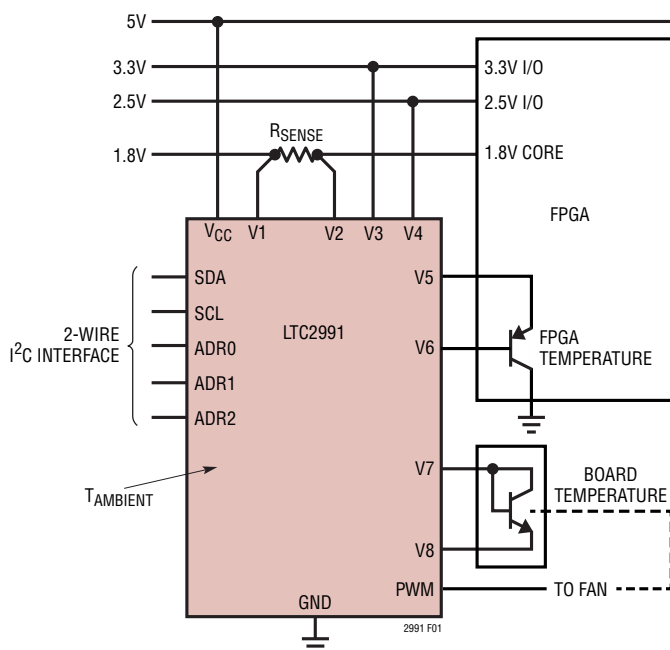


Figure 1.

### Power Up

The  $V_{CC}$  pin must exceed the undervoltage (UV) threshold of 2.5V to keep the LTC2991 out of power-on reset. Power-on reset will clear all of the data registers and the control registers.

### Temperature Measurements

The LTC2991 can measure internal temperature and up to four external diode or transistor sensors. During temperature conversion, current is sourced through the V1, V3, V5 or the V7 pin to forward bias the remote sensing diode. The change in sensor voltage per degree temperature change is hundreds of  $\mu\text{V}/^\circ\text{C}$ , so environmental noise must be kept to a minimum. Recommended shielding and PCB trace considerations are illustrated in Figure 2.

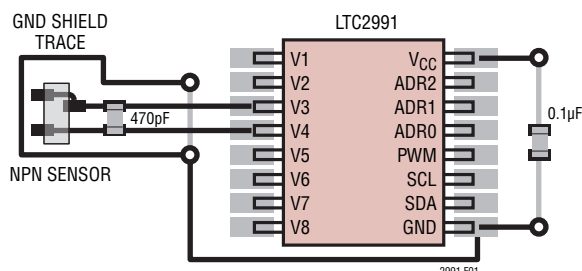


Figure 2. Recommended PCB Layout

The diode equation:

$$V_{BE} = \eta \cdot \frac{k \cdot T}{q} \cdot \ln\left(\frac{I_C}{I_S}\right) \quad (1)$$

can be solved for T, where T is Kelvin degrees,  $I_S$  is a process dependent factor on the order of  $1\text{E-}13$ ,  $\eta$  is the diode ideality factor, k is Boltzmann's constant and q is the electron charge.

$$T = \frac{V_{BE} \cdot q}{\eta \cdot k \cdot \ln\left(\frac{I_C}{I_S}\right)} \quad (2)$$

The LTC2991 makes differential measurements of diode voltage to calculate temperature. Proprietary techniques allow for cancellation of error due to series resistance.

### Ideality Factor Scaling

The LTC2991 is calibrated to yield the correct temperature for a remote diode with an ideality factor of 1.004. While this value is typical of target sensors, small deviations can yield significant temperature errors. The ideality factor of the diode sensor can be considered a temperature scaling factor. The temperature error for a 1% accurate ideality factor error is 1% of the Kelvin temperature. Thus, at  $25^\circ\text{C}$ , or 298K, a +1% accurate ideality factor error yields a +2.98 degree error. At  $85^\circ\text{C}$ , or 358K, a +1% error yields a 3.6 degree error. It is possible to scale the measured Kelvin or Celsius temperature measured using the LTC2991 with a sensor ideality factor other than 1.004, to the correct value. The scaling Equations (3) and (4), are simple, and can be implemented with sufficient precision using 16-bit fixed point math in a microprocessor or microcontroller.

Factory ideality calibration value:

$$\eta_{CAL} = 1.004$$

Actual sensor ideality value:

$$\eta_{ACT}$$

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Compensated Kelvin temperature:

$$T_{K\_COMP} = \frac{\eta_{CAL}}{\eta_{ACT}} \cdot T_{K\_MEAS} \quad (3)$$

Compensated Celsius temperature:

$$T_{C\_COMP} = \frac{\eta_{CAL}}{\eta_{ACT}} (T_{C\_MEAS} + 273.15) - 273.15 \quad (4)$$

A 16-bit unsigned number is capable of representing the ratio  $\eta_{CAL}/\eta_{ACT}$  in a range of 0.00003 to 1.99997, by multiplying the fractional ratio by  $2^{15}$ . The range of scaling encompasses every conceivable target sensor value. The ideality factor scaling granularity yields a worst-case temperature error of  $0.01^\circ$  at  $+125^\circ\text{C}$ . Multiplying this 16-bit unsigned number and the measured Kelvin (unsigned) temperature represented as a 16-bit number, yields a 32-bit unsigned result. To scale this number back to a 13-bit temperature (9-bit integer part, and a 4-bit fractional part), divide the number by  $2^{15}$ . Similarly, Celsius coded temperature values can be scaled using 16-bit fixed-point arithmetic, using Equation (4). In both cases, the scaled result will have a 9-bit integer (d[12:4]) and the four LSB's (d[3:0]) representing the 4-bit fractional part. To convert the corrected result to decimal, divide the final result by 24, or 16, as you would the register contents. If ideality factor scaling is implemented in the target application, it is beneficial to configure the LTC2991 for Kelvin coded results to limit the number of math operations required in the target processor.

$$T_{K\_COMP} = \frac{(\text{UNSIGNED}) \left( \frac{\eta_{CAL}}{\eta_{ACT}} 2^{15} \right) T_{K\_MEAS}}{2^{15}} \quad (5)$$

$$T_{C\_COMP} = \frac{(\text{UNSIGNED}) \left( \frac{\eta_{CAL}}{\eta_{ACT}} 2^{15} \right) (T_{C\_MEAS} + 273.15 \cdot 2^4)}{2^{15}} - 273.15 \cdot 2^4 \quad (6)$$

### Sampling Currents

Single-ended voltage measurements are directly sampled by the internal ADC. The average ADC input current is a function of the input applied voltage as follows:

$$I_{SAMPLE} = (V_{IN} - 1.49\text{V}) \cdot 0.17[\mu\text{A/V}]$$

Inputs with source resistance less than  $500\Omega$  will yield full-scale gain errors due to source impedance of  $< \frac{1}{2}$  LSB for 14-bit conversions. The nominal conversion time is 1.5ms for single-ended conversions.

### Current Measurements

The LTC2991 has the ability to perform 14-bit current measurements with the addition of a current sense resistor (see Figure 3).

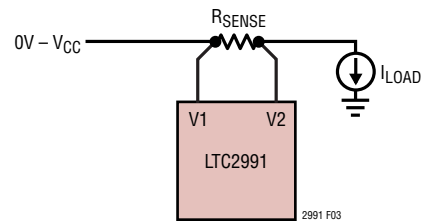


Figure 3. Simplified Current Sense Schematic

In order to achieve 13-bit current sensing a few details must be considered. Differential voltage or current measurements are directly sampled by the internal ADC. The average ADC input current for each leg of the differential input signal during a conversion is:

$$I_{SAMPLE} = (V_{IN} - 1.49\text{V}) \cdot 0.34[\mu\text{A/V}]$$

The maximum source impedance to yield 14-bit results with  $\frac{1}{2}$  LSB full-scale error is  $\sim 50\Omega$ .

In order to achieve 14-bit accuracy, 4-point, or Kelvin connected measurements of the sense resistor differential voltage are necessary.

In the case of current measurements, the external sense resistor is typically small, and determined by the full-scale input voltage of the LTC2991. The full-scale differential voltage is 0.300V. The external sense resistance, is then a function of the maximum measurable current, or  $R_{EXT\_MAX} = 0.300\text{V}/I_{MAX}$ . For example, if you wanted to measure a

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current range of  $\pm 5A$ , the external shunt resistance would equal  $0.300V/5A = 60m\Omega$ .

There exists a way to improve the sense resistor's precision using the LTC2991. The LTC2991 measures both differential voltage and remote temperature. It is therefore, possible to compensate for the absolute resistance tolerance of the sense resistor and the temperature coefficient of the sense resistor in software. The resistance would be measured by running a calibrated test current through the discrete resistor. The LTC2991 would measure both the differential voltage across this resistor and the resistor temperature. From this measurement,  $R_0$  and  $T_0$  in the following equation would be known. Using the two equations, the host microprocessor could compensate for both the absolute tolerance and the TCR.

$$R_T = R_0 \cdot [1 + \alpha(T - T_0)], \text{ where} \quad (7)$$

$$\alpha = 3930 \text{ ppm}/^\circ\text{C} \text{ for copper trace}$$

$$\alpha = \pm 2 \text{ to } \sim 200 \text{ ppm}/^\circ\text{C} \text{ for discrete R}$$

$$I = (V1 - V2)/R_T \quad (8)$$

### Device Configuration

The LTC2991 is configured by writing the channel control registers through the serial interface. Refer to Tables 5, 6 and 7 for control register bit definition. The device is capable of many application configurations including voltage, temperature and current measurements. It is possible to configure the device for single or repeated acquisitions. For repeated acquisitions, only the initial trigger is required, and new data is written over the old data. Acquisitions are frozen during serial read data transfers, to prevent the upper and lower data bytes for a particular measurement from becoming out of sync. Internally, both the upper and lower bytes are written at the same instant. Since serial data transfer timeout is not implemented, failure to terminate a read operation will yield an indefinitely frozen wait state. The device can also make single measurements, or with one trigger, all of the measurements for the configuration. When the device is configured for multiple measurements, the order of measurements is fixed. As each new data result is ready, the MSB of the corresponding data register is set, and the corresponding status register bit is set. These bits are cleared when the corresponding data register is addressed. The configuration register value at power-up yields the measurement of the internal tempera-

ture sensor and V1 through V8 as single-ended voltages, if triggered. The eight input pins V1 through V8 will be in a high impedance state, until configured otherwise, and a measurement triggered. Please note that when the device is configured for remote temperature measurements (using the control registers 0x06 and/or 0x07), the temperature data (Trx T) is stored in V1, V3, V5 and V7 respectively depending on the channel being used. Similarly, during this configuration the diode voltage (Trx Voltage) is stored in V2, V4, V6 and V8 registers.

### Data Format

The data registers are broken into 8-bit upper and lower bytes. Voltage and temperature conversions are 13-bits. The upper bits in the MSB registers provide status on the resulting conversions. These status bits are different for temperature and voltage conversions.

### Temperature

Temperature conversions are reported as Celsius or Kelvin results described in Tables 11 and 12, each with 0.0625 degree weighted LSBs. The format is controlled by the control registers. The temperature MSB result register most significant bit (Bit 7) is the DATA\_VALID bit, which indicates whether the current register contents have been accessed since the result was written to the register. This bit will be set when new data is written to the register, and cleared when accessed. The LTC2991 internal bias circuitry maintains this voltage above this level during normal operating conditions. Bit 4 through bit 0 of the MSB register are the conversion result bits D[12:8], in two's complement format. Note in Kelvin results, the result will always be positive. The LSB register contains temperature result bits D[7:0]. To convert the register contents to temperature, use the following equation:  $T = D[12:0]/16$ . See Table 16 for conversion value examples. Remote diode voltage is digitized at  $\sim 50\mu A$  of bias current. The ADC LSB value during these conversions is typically  $38.15\mu V$ . Voltages are only available for the remote diodes, not the internal sensor. This code repeats at a diode voltage of approximately 0.3125V (see Tables 13 and 14). The absolute temperature of the diode can be used to detect whether the diode is operating ( $\leq 0.3125V$  or  $\geq 0.3125V$ ). This mode is useful for testing small relative

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changes in temperature using the approximate relationship of  $-2.1\text{mV}/^\circ\text{C}$  of voltage dependence on temperature. With an LSB weight of  $38.15\mu\text{V}$  and a diode temperature relationship of  $-2.1\text{mV}/^\circ\text{C}$  this yields  $\sim 0.018$  degree resolution. For sensor applications involving heaters, the ability to sense small changes in temperature with low noise can yield significant power savings, allowing the heater power to be reduced. Table 16 has some conversion result examples for various diode voltages.

### Voltage/Current

Voltage results are reported in two respective registers, an MSB and LSB register. The Voltage MSB result register most significant bit (bit 7) is the DATA\_VALID bit, which indicates whether the current register contents have been accessed since the result was written to the register. This bit will be set when the register contents are new, and cleared when accessed. Bit 6 of the MSB register is the sign bit, bits 5 through 0 represent bits D[13:8] of the two's complement conversion result. The LSB register holds conversion bits D[7:0]. The LSB value is different for single-ended voltage measurements V1 through V8, and differential (current measurements) V1 – V2, V3 – V4, V5 – V6 and V7 – V8. Single-ended voltages are limited to positive values in the range 0V to 4.9V or  $V_{\text{CC}} + 0.2\text{V}$ , whichever is smaller. Differential voltages can have input values in the range of  $-0.300\text{V}$  to  $0.300\text{V}$ .

Use the following equations to convert the register values (see Table 16 for examples):

$$V_{\text{SINGLE\_ENDED}} = D[13:0] \cdot 305.18\mu\text{V}$$

$$V_{\text{DIFFERENTIAL}} = D[13:0] \cdot 19.075\mu\text{V}, \text{ if sign} = 0$$

$$V_{\text{DIFFERENTIAL}} = (\overline{D[13:0]} + 1) \cdot -19.075\mu\text{V}, \text{ if sign} = 1$$

$$\text{Current} = D[13:0] \cdot 19.075\mu\text{V}/R_{\text{SENSE}}, \text{ if sign} = 0$$

$$\text{Current} = (\overline{D[13:0]} + 1) \cdot -19.075\mu\text{V}/R_{\text{SENSE}}, \text{ if sign} = 1,$$

Where  $R_{\text{SENSE}}$  is the current sensing resistor, typically  $< 1\Omega$ .

### $V_{\text{CC}}$

The LTC2991 measures  $V_{\text{CC}}$ . To convert the contents of the  $V_{\text{CC}}$  register to voltage, use the following equation:  
 $V_{\text{CC}} = 2.5 + (D[13:0] \cdot 305.18\mu\text{V})$ .

### PWM Output

A 9-bit, 1kHz PWM output proportional to temperature  $V_7$  is available for controlling fans or heaters. PWM\_Threshold is a 9-bit value with an LSB weighting of one degree Kelvin. PWM\_Threshold is subtracted from  $V_7$  and a pulse width proportional to the difference is produced. Note that the PWM threshold is split among two registers, with PWM\_Threshold[8:1] in register 09h[7:0] and PWM\_Threshold[0] in register 08h[7]. Equation 9 shows the registers involved. The PWM frequency is  $\sim 1\text{kHz}$ . The PWM output can be disabled or inverted with the PWM enable and PWM invert bits in register 08h, respectively. Figure 9 illustrates the PWM transfer function. The equation for the duty cycle is:

$$\text{PWM\_DUTY\_CYCLE}(\%) = \frac{100 \cdot (\text{REG7} - \text{PWM} \cdot 16)}{512} \quad (9)$$

Where REG7 is bits [12:0] and  
 PWM is PWM Threshold bits [8:0]

A 50% duty cycle PWM signal would occur, for example, if the PWM threshold was set to 10h ( $16^\circ\text{C}$ ) and register 7 contained 200h ( $32^\circ\text{C}$ ). If channel 7 is configured for Kelvin temperatures, the PWM threshold must also be a Kelvin temperature. The registers are two's complement numbers. When calculating the duty cycle above for Celsius temperatures care should be taken to sign extend the register 7 and PWM threshold values. For temperatures below the PWM Threshold, the PWM output pin will be a constant logic level 0. For temperatures 32 degrees above

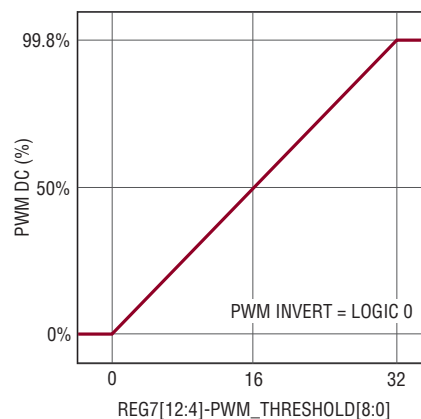


Figure 9. PWM Transfer Function

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the PWM Threshold, the PWM output pin will be a constant logic level 1. This relationship is opposite if the PWM invert bit is set. If the filter is enabled for the V7/V8 pair, the filtered result is routed to the PWM block; otherwise, the unfiltered version is used. The PWM CMOS output drive is intended to be buffered to drive large (>100pF) external capacitances or resistors <10k. A recommended noninverting buffer is a NC7SZ125 to increase the drive capability of the PWM signal.

### Digital Filter

Each conversion result can be filtered using an on-chip digital filter. The filter equation is:

$$\text{OUTPUT}[X] = (15 \cdot (\text{OUTPUT}[X - 1]) + \text{SAMPLE}[X]) / 16$$

where output[x] is the register value when enabled. The filter step response is illustrated in the Typical Performance Characteristics section. The filter can be seeded by triggering an unfiltered conversion of each configured measurement, then subsequently enabling the filter. This will cause the filter to converge instantaneously to the value of the initial unfiltered sample. The filter can be enabled or disabled for each channel pair and internal temperature measurements.  $V_{CC}$  measurements cannot be filtered.

### Digital Interface

The LTC2991 communicates with a bus master using a 2-wire interface compatible with the I<sup>2</sup>C Bus and the SMBus, an I<sup>2</sup>C extension for low power devices.

The LTC2991 is a read write slave device and supports SMBus bus read byte data and write byte data, read word data and write word data commands. The data formats for these commands are shown in Tables 3 through 15.

The connected devices can only pull the bus wires LOW and can never drive the bus HIGH. The bus wires are externally connected to a positive supply voltage via a current source or pull-up resistor. When the bus is free, both lines are HIGH. Data on the I<sup>2</sup>C bus can be transferred at rates of up to 100kbit/s in the standard mode and up to 400kbit/s in the fast mode. Each device on the I<sup>2</sup>C bus is recognized by a unique address stored in that device and can operate as either a transmitter or receiver, depending on the function of the device. In addition to transmitters and receivers, devices can also be considered as masters

or slaves when performing data transfers. A master is the device which initiates a data transfer on the bus and generates the clock signals to permit that transfer. At the same time any device addressed is considered a slave.

The LTC2991 can only be addressed as a slave. Once addressed, it can receive configuration bits or transmit the last conversion result. Therefore the serial clock line SCL is an input only and the data line SDA is bidirectional. The device supports the standard mode and the fast mode for data transfer speeds up to 400kbit/s. The Timing Diagram shows the definition of timing for fast/standard mode devices on the I<sup>2</sup>C bus. The internal state machine cannot update internal data registers during an I<sup>2</sup>C read operation. The state machine pauses until the I<sup>2</sup>C read is complete. It is therefore, important not to leave the LTC2991 in this state for long durations, or increased conversion latency will be experienced.

### START and STOP Conditions

When the bus is idle, both SCL and SDA must be high. A bus master signals the beginning of a transmission with a START condition by transitioning SDA from high to low while SCL is high. When the bus is in use, it stays busy if a repeated START (SR) is generated instead of a STOP condition. The repeated START (SR) conditions are functionally identical to the START (S). When the master has finished communicating with the slave, it issues a STOP condition by transitioning SDA from low to high while SCL is high. The bus is then free for another transmission.

### I<sup>2</sup>C Device Addressing

Eight distinct bus addresses are configurable using the ADR0, ADR1 and ADR2 pins. Table 1 shows the correspondence between ADR0, ADR1 and ADR2 pin states and addresses. There is also one global sync address available at EEh which provides an easy way to synchronize multiple LTC2991's on the same I<sup>2</sup>C bus. This allows write only access to all LTC2991's on the bus for simultaneous triggering.

### Acknowledge

The acknowledge signal is used for handshaking between the transmitter and the receiver to indicate that the last byte of data was received. The transmitter always releases the SDA line during the acknowledge clock pulse. When the

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slave is the receiver, it must pull down the SDA line so that it remains LOW during this pulse to acknowledge receipt of the data. If the slave fails to acknowledge by leaving SDA HIGH, then the master can abort the transmission by generating a STOP condition. After the master has received the last data bit from the slave, the master must pull down the SDA line during the next clock pulse to indicate receipt of the data. After the last byte has been received the master will leave the SDA line HIGH (not acknowledge) and issue a STOP condition to terminate the transmission.

### Write Protocol

The master begins communication with a START condition followed by the 7-bit slave address and the  $\overline{RW}$  bit set to zero. The addressed LTC2991 acknowledges the address and then the master sends a command byte which indicates which internal register the master wishes to write. The LTC2991 acknowledges the command byte and then latches the lower five bits of the command byte into its internal register address pointer. The master then delivers the data byte and the LTC2991 acknowledges once more and latches the data into its internal register. The transmission is ended when the master sends a STOP condition. If the master continues sending a second data byte, as in a write word command, the second data byte will be acknowledged by the LTC2991 and written to the next register in sequence, if this register has write access.

### Read Protocol

The master begins a read operation with a START condition followed by the 7-bit slave address and the  $\overline{RW}$  bit set to zero. The addressed LTC2991 acknowledges this and then the master sends a command byte which indicates which internal register the master wishes to read. The LTC2991 acknowledges this and then latches the lower five bits of the command byte into its internal register address pointer. The master then sends a repeated START condition followed by the same seven bit address with the  $\overline{RW}$

bit now set to one. The LTC2991 acknowledges and sends the contents of the requested register. The transmission is ended when the master sends a STOP condition. The register pointer is automatically incremented after each byte is read. If the master acknowledges the transmitted data byte, as in a read word command, the LTC2991 will send the contents of the next sequential register as the second data byte. The byte following register 1Dh is register 00h, or the status register.

### Control Registers

The control registers (Tables 5 through 8) determine the selected measurement mode of the device. The LTC2991 can be configured to measure voltages, currents and temperatures. These measurements can be single shot or repeated measurements. Temperatures can be set to report in Celsius or Kelvin temperature scales. The LTC2991 can be configured to run particular measurements, or all possible measurements per the configuration specified by the channel enable register (Table 4). The power-on default configuration of the control registers is 00h, which translates to a single-ended voltage measurement of the triggered channels. This mode prevents the application of remote diode test currents on pins V1, V3, V5 and V7, and remote diode terminations on pins V2, V4, V6 and V8 at power-up.

### Status Register

The status registers (Tables 3 and 4) report the status of a particular conversion result. When new data is written into a particular result register, the corresponding DATA\_VALID bit is set. When the register is addressed by the I<sup>2</sup>C interface, the status bit (as well as the DATA\_VALID bit in the respective register) is cleared. The host can then determine if the current available register data is new or stale. The busy bit, when high, indicates a single shot conversion is in progress. The busy bit is always high during repeated mode, after the initial conversion is triggered.

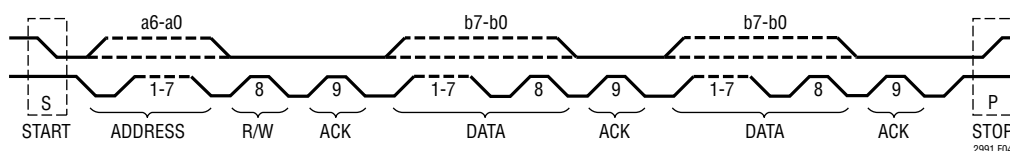


Figure 4. Data Transfer Over I<sup>2</sup>C or SMBus



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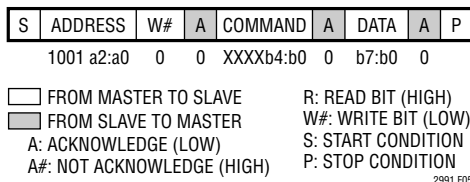


Figure 5. LTC2991 Serial Bus Write Byte Protocol

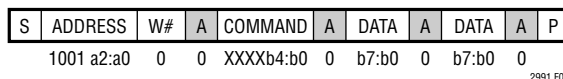


Figure 6. LTC2991 Serial Bus Repeated Write Byte Protocol

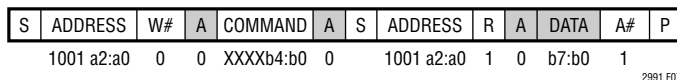


Figure 7. LTC2991 Serial Bus Read Byte Protocol

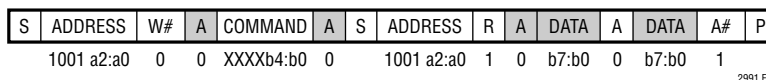


Figure 8. LTC2991 Serial Bus Repeated Read Byte Protocol

Table 1. I<sup>2</sup>C Base Address

| I <sup>2</sup> C BASE ADDRESS | ADR2                | ADR1 | ADR0 |
|-------------------------------|---------------------|------|------|
| 90h                           | 0                   | 0    | 0    |
| 92h                           | 0                   | 0    | 1    |
| 94h                           | 0                   | 1    | 0    |
| 96h                           | 0                   | 1    | 1    |
| 98h                           | 1                   | 0    | 0    |
| 9Ah                           | 1                   | 0    | 1    |
| 9Ch                           | 1                   | 1    | 0    |
| 9Eh                           | 1                   | 1    | 1    |
| Eh                            | Global Sync Address |      |      |

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Table 2. LTC2991 Register Address and Contents

| REGISTER ADDRESS* † | REGISTER NAME   | READ/WRITE | DESCRIPTION   |
|---------------------|---|------------|---|
| 00h                 | STATUS LOW  | R          | DATA_VALID Bits (V1 Through V8)   |
| 01h                 | CH EN, STAT. HI, TRIGGER**  | R/W        | CHANNEL ENABLE, V <sub>CC</sub> , T <sub>INTERNAL</sub> Conv. Status, Trigger |
| 02h                 | Reserved  | N/A        | Reserved  |
| 03h                 | Reserved  | N/A        | Reserved  |
| 04h                 | Reserved  | N/A        | Reserved  |
| 05h                 | Reserved  | N/A        | Reserved  |
| 06h                 | V1, V2 and V3, V4 CONTROL   | R/W        | V1, V2, V3 and V4 Control Register  |
| 07h                 | V5, V6 and V7, V8 CONTROL   | R/W        | V5, V6, V7 and V8 Control Register  |
| 08h                 | PWM_Threshold(LSB), V <sub>CC</sub> , T <sub>INTERNAL</sub> CONTROL | R/W        | PWM Threshold and T <sub>INTERNAL</sub> Control Register                      |
| 09h                 | PWM_Threshold(MSB)  | R/W        | PWM Threshold   |
| 0Ah                 | V1(MSB)   | R          | V1 or T <sub>R1</sub> T MSB   |
| 0Bh                 | V1(LSB)   | R          | V1 or T <sub>R1</sub> T LSB   |
| 0Ch                 | V2(MSB)   | R          | V2, V1 – V2, or T <sub>R1</sub> Voltage MSB                                   |
| 0Dh                 | V2(LSB)   | R          | V2, V1 – V2, or T <sub>R1</sub> Voltage LSB                                   |
| 0Eh                 | V3(MSB)   | R          | V3, or T <sub>R2</sub> T MSB  |
| 0Fh                 | V3(LSB)   | R          | V3, or T <sub>R2</sub> T LSB  |
| 10h                 | V4(MSB)   | R          | V4, V3 – V4, or T <sub>R2</sub> Voltage MSB                                   |
| 11h                 | V4(LSB)   | R          | V4, V3 – V4, or T <sub>R2</sub> Voltage LSB                                   |
| 12h                 | V5(MSB)   | R          | V5, or T <sub>R3</sub> T MSB  |
| 13h                 | V5(LSB)   | R          | V5, or T <sub>R3</sub> T LSB  |
| 14h                 | V6(MSB)   | R          | V6, V5 – V6, or T <sub>R3</sub> Voltage MSB                                   |
| 15h                 | V6(LSB)   | R          | V6, V5 – V6, or T <sub>R3</sub> Voltage LSB                                   |
| 16h                 | V7(MSB)   | R          | V7, or T <sub>R4</sub> T MSB  |
| 17h                 | V7(LSB)   | R          | V7, or T <sub>R4</sub> T LSB  |
| 18h                 | V8(MSB)   | R          | V8, V7 – V8, or T <sub>R4</sub> Voltage MSB                                   |
| 19h                 | V8(LSB)   | R          | V8, V7 – V8, or T <sub>R4</sub> Voltage LSB                                   |
| 1Ah                 | T <sub>INTERNAL</sub> (MSB)   | R          | T <sub>INTERNAL</sub> MSB   |
| 1Bh                 | T <sub>INTERNAL</sub> (LSB)   | R          | T <sub>INTERNAL</sub> LSB   |
| 1Ch                 | V <sub>CC</sub> (MSB)   | R          | V <sub>CC</sub> MSB   |
| 1Dh                 | V <sub>CC</sub> (LSB)   | R          | V <sub>CC</sub> LSB   |

\* Register address MSBs b7 to b5 are ignored.

\*\* Writing any value triggers a conversion.

† Power-on reset sets all registers to 00h.

## APPLICATIONS INFORMATION

**Table 3. STATUS LOW (00h) Register**

| BIT | NAME                  | OPERATION   |
|-----|-----------------------|---|
| b7  | V8, T4, V7 – V8 Ready | 1 = V8 Register Contains New Data, 0 = V8 Register Data Old |
| b6  | V7, T4, V7 – V8 Ready | 1 = V7 Register Contains New Data, 0 = V7 Register Data Old |
| b5  | V6, T3, V5 – V6 Ready | 1 = V6 Register Contains New Data, 0 = V6 Register Data Old |
| b4  | V5, T3, V5 – V6 Ready | 1 = V5 Register Contains New Data, 0 = V5 Register Data Old |
| b3  | V4, T2, V3 – V4 Ready | 1 = V4 Register Contains New Data, 0 = V4 Register Data Old |
| b2  | V3, T2, V3 – V4 Ready | 1 = V3 Register Contains New Data, 0 = V3 Register Data Old |
| b1  | V2, T1, V1 – V2 Ready | 1 = V2 Register Contains New Data, 0 = V2 Register Data Old |
| b0  | V1, T1, V1 – V2 Ready | 1 = V1 Register Contains New Data, 0 = V1 Register Data Old |

**Table 4. STATUS HIGH, CHANNEL ENABLE (01h) Register (Default 00h)**

| BIT | NAME                                | R/W | OPERATION   |
|-----|-------------------------------------|-----|---|
| b7  | V7 and V8, V7 – V8, $T_{R4}$ Enable | R/W | 1 = V7 and V8, or V7 – V8 or T4 Enabled<br>0 = V7 and V8, or V7 – V8 or T4 Disabled (Default)   |
| b6  | V5 and V6, V5 – V6, $T_{R3}$ Enable | R/W | 1 = V5 and V6, or V5 – V6 or T3 Enabled<br>0 = V5 and V6, or V5 – V6 or T3 Disabled (Default)   |
| b5  | V3 and V4, V3 – V4, $T_{R2}$ Enable | R/W | 1 = V3 and V4, or V3 – V4 or T2 Enabled<br>0 = V3 and V4, or V3 – V4 or T2 Disabled (Default)   |
| b4  | V1 and V2, V1 – V2, $T_{R1}$ Enable | R/W | 1 = V1 and V2, or V1 – V2 or T1 Enabled<br>0 = V1 and V2, or V1 – V2 or T1 Disabled (Default)   |
| b3  | $T_{INTERNAL}$ $V_{CC}$ Enable      | R/W | 1 = $T_{INTERNAL}$ and $V_{CC}$ Enabled<br>0 = $T_{INTERNAL}$ and $V_{CC}$ Disabled (Default)   |
| b2  | BUSY                                | R   | 1 = A Conversion Is in Process<br>0 = Sleep Mode (Default)                                      |
| b1  | $T_{INTERNAL}$                      | R   | 1 = $T_{INTERNAL}$ Register Contains New Data<br>0 = $T_{INTERNAL}$ Register Data Old (Default) |
| b0  | $V_{CC}$                            | R   | 1 = $V_{CC}$ Register Contains New Data<br>0 = $V_{CC}$ Register Data Old (Default)             |

**Table 5. V1, V2 and V3, V4 CONTROL (06h) Register (Default 00h)**

| BIT | NAME                  | OPERATION  |
|-----|-----------------------|--|
| b7  | V3, V4 Filt           | 1 = Filter Enabled, 0 = Filter Disabled for V3 and V4, V3 – V4 or T2 (Default)                   |
| b6  | $T_{R2}$ Kelvin       | 1 = Kelvin, 0 = Celsius for T2 (Default)   |
| b5  | V3, V4 Temperature    | 1 = Temperature, 0 = Voltage (Per b4 Setting) (Default)  |
| b4  | V3, V4 Differential 1 | 1 = Differential (V3 – V4) and V3 Single-Ended<br>0 = Single-Ended Voltage (V3 and V4) (Default) |
| b3  | V1, V2 Filt           | 1 = Filter Enabled, 0 = Filter Disabled for V1 and V2, V1 – V2 or T1 (Default)                   |
| b2  | $T_{R1}$ Kelvin       | 1 = Kelvin, 0 = Celsius for T1 (Default)   |
| b1  | V1, V2 Temperature    | 1 = Temperature, 0 = Voltage (Per b0 Setting) (Default)  |
| b0  | V1, V2 Differential   | 1 = Differential (V1 – V2) and V1 Single-Ended<br>0 = Single-Ended Voltage (V1 and V2) (Default) |

## APPLICATIONS INFORMATION

**Table 6. V5, V6 and V7, V8 CONTROL (07h) Register (Default 00h)**

| BIT | NAME                   | OPERATION  |
|-----|------------------------|--|
| b7  | V7, V8 Filt            | 1 = Filter Enabled, 0 = Filter Disabled for V7 and V8, V7 – V8 or T4 (Default)                   |
| b6  | T <sub>R4</sub> Kelvin | 1 = Kelvin, 0 = Celsius for T4 (Default)   |
| b5  | V7, V8 Temperature     | 1 = Temperature, 0 = Voltage (Per b4 Setting) (Default)  |
| b4  | V7, V8 Differential    | 1 = Differential (V7 – V8) and V7 Single-Ended<br>0 = Single-Ended Voltage (V7 and V8) (Default) |
| b3  | V5, V6 Filt            | 1 = Filter Enabled, 0 = Filter Disabled for V5 and V6, V5 – V6 or T3 (Default)                   |
| b2  | T <sub>R3</sub> Kelvin | 1 = Kelvin, 0 = Celsius for T3 (Default)   |
| b1  | V5, V6 Temperature     | 1 = Temperature, 0 = Voltage (Per b0 Setting) (Default)  |
| b0  | V5, V6 Differential    | 1 = Differential (V5 – V6) and V5 Single-Ended<br>0 = Single-Ended Voltage (V5 and V6) (Default) |

**Table 7. PWM, V<sub>CC</sub> and T<sub>INTERNAL</sub> CONTROL (08h) Register (Default 00h)**

| BIT | NAME                         | OPERATION   |
|-----|------------------------------|---|
| b7  | PWM[0]                       | PWM Threshold Least Significant Bit (Default = 0)   |
| b6  | PWM Invert*                  | 1 = PWM Inverted, 0 = PWM Noninverted (Default)   |
| b5  | PWM Enable**                 | 1 = PWM Enabled, 0 = PWM Disabled (Default)   |
| b4  | Repeated Acquisition         | 1 = Repeated Mode<br>0 = Single Shot (Default)  |
| b3  | T <sub>INTERNAL</sub> Filt   | 1 = Filter Enabled for T <sub>INTERNAL</sub><br>0 = Filter Disabled T <sub>INTERNAL</sub> (Default) |
| b2  | T <sub>INTERNAL</sub> Kelvin | 1 = Kelvin, 0 = Celsius for T <sub>INTERNAL</sub> (Default)   |
| b1  | Reserved                     | Reserved  |
| b0  | Reserved                     | Reserved  |

\* Noninverted would be an increasing duty cycle for an increasing temperature.

\*\* If disabled and noninverted, the PWM pin will be a logic level 0. If disabled and inverted, the PWM pin will be a logic level 1.

**Table 8. PWM Register Format (Default 00h)**

| Bit7 | Bit6 | Bit5 | Bit4 | Bit3 | Bit2 | Bit1 | Bit0 |
|------|------|------|------|------|------|------|------|
| D8   | D7   | D6   | D5   | D4   | D3   | D2   | D1   |

Note: D0 is located in the MSB of PWM, V<sub>CC</sub> and T<sub>INTERNAL</sub> CONTROL (08h) Register

**Table 9. Voltage/Current Measurement MSB Data Register Format**

| Bit7 | Bit6 | Bit5 | Bit4 | Bit3 | Bit2 | Bit1 | Bit0 |
|------|------|------|------|------|------|------|------|
| DV*  | Sign | D13  | D12  | D11  | D10  | D9   | D8   |

\*Data valid is set when a new result is written into the register. Data valid is cleared when this register is addressed (read) by the I<sup>2</sup>C interface.

**Table 10. Voltage/Current Measurement LSB Data Register Format**

| Bit7 | Bit6 | Bit5 | Bit4 | Bit3 | Bit2 | Bit1 | Bit0 |
|------|------|------|------|------|------|------|------|
| D7   | D6   | D5   | D4   | D3   | D2   | D1   | D0   |

## APPLICATIONS INFORMATION

**Table 11. Temperature Measurement MSB Data Register Format**

| Bit7 | Bit6 | Bit5 | Bit4 | Bit3 | Bit2 | Bit1 | Bit0 |
|------|------|------|------|------|------|------|------|
| DV*  | X    | X    | D12  | D11  | D10  | D9   | D8   |

\*Data valid is set when a new result is written into the register. Data valid is cleared when this register is addressed (read) by the I<sup>2</sup>C interface.

X Unused

**Table 12. Temperature Measurement LSB Data Register Format**

| Bit7 | Bit6 | Bit5 | Bit4 | Bit3 | Bit2 | Bit1 | Bit0 |
|------|------|------|------|------|------|------|------|
| D7   | D6   | D5   | D4   | D3   | D2   | D1   | D0   |

**Table 13. Diode Voltage Measurement MSB Data Register Format**

| Bit7 | Bit6 | Bit5 | Bit4 | Bit3 | Bit2 | Bit1 | Bit0 |
|------|------|------|------|------|------|------|------|
| DV*  | X    | X    | D12  | D11  | D10  | D9   | D8   |

\*Data valid is set when a new result is written into the register. Data valid is cleared when this register is addressed (read) by the I<sup>2</sup>C interface.

X Unused

**Table 14. Diode Voltage Measurement LSB Data Register Format**

| Bit7 | Bit6 | Bit5 | Bit4 | Bit3 | Bit2 | Bit1 | Bit0 |
|------|------|------|------|------|------|------|------|
| D7   | D6   | D5   | D4   | D3   | D2   | D1   | D0   |

**Table 15. PWM Threshold Register Format**

| Bit7 | Bit6 | Bit5 | Bit4 | Bit3 | Bit2 | Bit1 | Bit0 |
|------|------|------|------|------|------|------|------|
| D7   | D6   | D5   | D4   | D3   | D2   | D1   | D0   |

D7:D0 = PWM[8:1], bit 0 is located in the PWM, V<sub>CC</sub> and T<sub>INT</sub> CONTROL Register (Table 7)

**Table 16. Conversion Formats**

| VOLTAGE FORMATS   | SIGN | BINARY VALUE D[13:0] | VOLTAGE               |
|---|------|----------------------|-----------------------|
| Single-Ended<br>LSB = 305.18μV = 2.5/2 <sup>13</sup>                    | 0    | 11111111111111       | >5                    |
|   | 0    | 10110011001101       | 3.5000                |
|   | 0    | 01111111111111       | 2.5000                |
|   | 0    | 00000000000000       | 0.0000                |
|   | 1    | 11110000101001       | -0.3000               |
| Differential<br>LSB = 19.075μV = 2.5/2 <sup>17</sup>                    | 0    | 11110101101111       | 0.300                 |
|   | 0    | 10000010001111       | 0.159                 |
|   | 0    | 00000000000000       | 0.0000                |
|   | 1    | 01111101110001       | -0.159                |
|   | 1    | 00001010010001       | -0.300                |
| V <sub>CC</sub> = Result + 2.5V<br>LSB = 305.18μV = 2.5/2 <sup>13</sup> | 0    | 10110011001101       | V <sub>CC</sub> = 6.0 |
|   | 0    | 10000000000000       | V <sub>CC</sub> = 5.0 |
|   | 0    | 00001010001111       | V <sub>CC</sub> = 2.7 |

## APPLICATIONS INFORMATION

Table 16. Conversion Formats

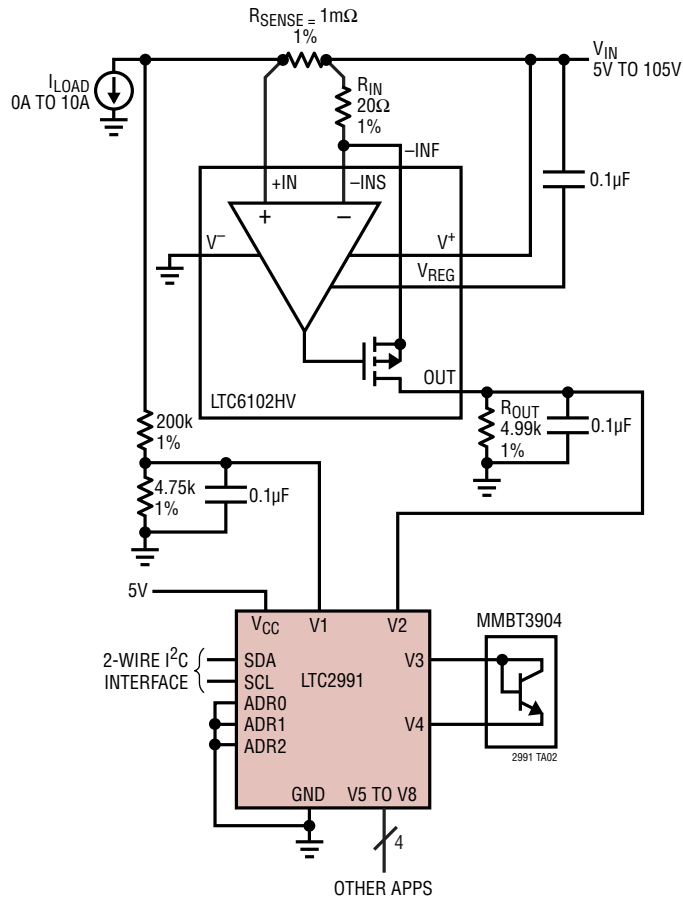
| TEMPERATURE FORMATS   | FORMAT  | BINARY VALUE D[12:0] | TEMPERATURE |
|---|---------|----------------------|-------------|
| Temperature Internal, T <sub>R1</sub> Through T <sub>R4</sub><br>LSB = 0.0625 Degrees | Celsius | 0011111010000        | 125.0000    |
|   | Celsius | 0000110010001        | 25.0625     |
|   | Celsius | 0000110010000        | 25.0000     |
|   | Celsius | 1110110000000        | -40.0000    |
|   | Kelvin  | 1100011100010        | 398.1250    |
|   | Kelvin  | 1000100010010        | 273.1250    |
|   | Kelvin  | 0111010010010        | 233.1250    |
|   | Kelvin  | 0010011010000        | 77.0000     |
| DIODE VOLTAGE FORMATS   | Sign    | Binary Value D[12:0] | Voltage     |
| Diode Voltage T <sub>R1</sub> Through T <sub>R4</sub><br>LSB = 38.15µV                | 0       | 0000000000000        | 0.0000      |
|   | 0       | 1111111111111        | 0.31249     |
|   | 0       | 0000000000000        | 0.31252     |
|   | 0       | 1111111111111        | 0.62501     |
|   | 0       | 0000000000000        | 0.62505     |
|   | 0       | 1001100110010        | 0.99999     |

Table 17. Recommended Transistors to Be Used as Temperature Sensors

| MANUFACTURER            | PART NUMBER | PACKAGE  |
|-------------------------|-------------|----------|
| Fairchild Semiconductor | MMBT3904    | SOT-23   |
| Fairchild Semiconductor | FMMT3904    | SOT-23   |
| Fairchild Semiconductor | 2N3904      | TO-92    |
| Central Semiconductor   | CMPT3904    | SOT-23   |
| Central Semiconductor   | CET3904E    | SOT-883L |
| Diodes, Inc.            | MMBT3904    | SOT-23   |
| On Semiconductor        | MMBT3904LT1 | SOT-23   |
| NXP                     | MMBT3904    | SOT-23   |
| Infineon                | MMBT3904    | SC-70    |
| Rohm                    | UMT3904     | SOT-23   |

# TYPICAL APPLICATIONS

## High Voltage/Current and Temperature Monitoring



ALL CAPACITORS ±20%

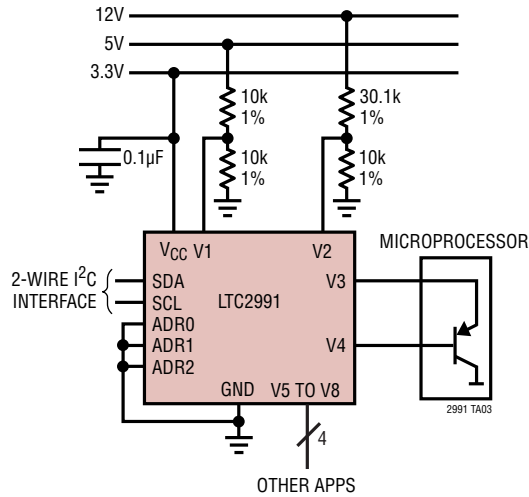
**VOLTAGE, CURRENT AND TEMPERATURE CONFIGURATION:**

CONTROL REGISTER: 0x06 0xA0

|                 |             |                     |
|-----------------|-------------|---------------------|
| $T_{AMBIENT}$   | REG 1A, 1B: | 0.0625°C/LSB        |
| $V_{LOAD}$      | REG 0A, 0B: | 13.2mV/LSB          |
| $V2(I_{LOAD})$  | REG 0C, 0D: | 1.223mA/LSB         |
| $T_{PROCESSOR}$ | REG 0E, 0F: | 0.0625°C/LSB        |
| $V_{CC}$        | REG 1C, 1D: | 2.5V + 305.18μV/LSB |

## TYPICAL APPLICATIONS

### Computer Voltage and Temperature Monitoring

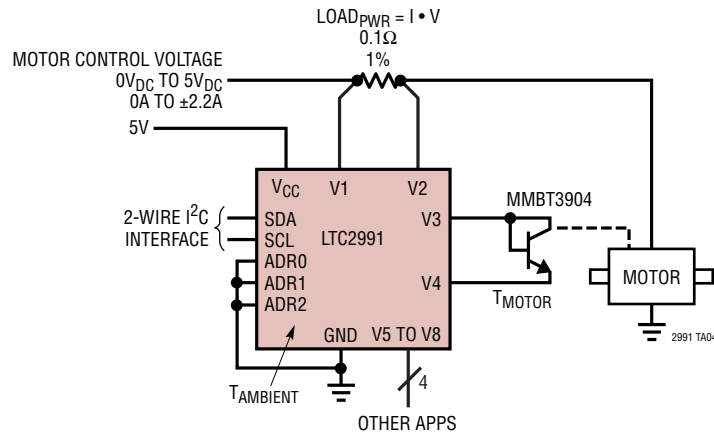


#### VOLTAGE AND TEMPERATURE CONFIGURATION

CONTROL REGISTER: 0x06 0x0A

|                        |             |                     |
|------------------------|-------------|---------------------|
| $T_{\text{AMBIENT}}$   | REG 1A, 1B: | 0.0625°C/LSB        |
| V1(+5)                 | REG 0A, 0B: | 610µV/LSB           |
| V2(+12)                | REG 0C, 0D: | 1.22mV/LSB          |
| $T_{\text{PROCESSOR}}$ | REG 0E, 0F: | 0.0625°C/LSB        |
| $V_{\text{CC}}$        | REG 1C, 1D: | 2.5V + 305.18µV/LSB |

### Motor Protection/Regulation



#### VOLTAGE, CURRENT AND TEMPERATURE CONFIGURATION:

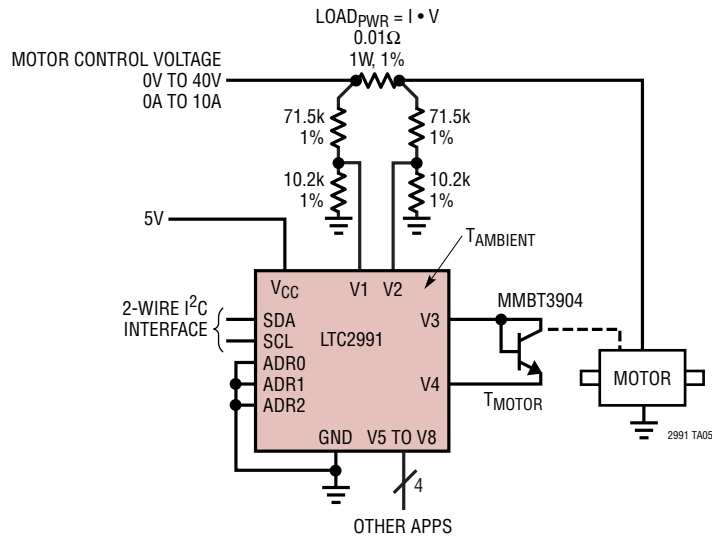
CONTROL REGISTER: 0x06: 0xA1

|                      |             |                     |
|----------------------|-------------|---------------------|
| $T_{\text{AMBIENT}}$ | REG 1A, 1B: | 0.0625°C/LSB        |
| $V_{\text{MOTOR}}$   | REG 0A, 0B: | 305.18µV/LSB        |
| $I_{\text{MOTOR}}$   | REG 0C, 0D: | 190.75µA/LSB        |
| $T_{\text{MOTOR}}$   | REG 1A, 1B: | 0.0625°C/LSB        |
| $V_{\text{CC}}$      | REG 1C, 1D: | 2.5V + 305.18µV/LSB |



# TYPICAL APPLICATIONS

## Large Motor Protection/Regulation

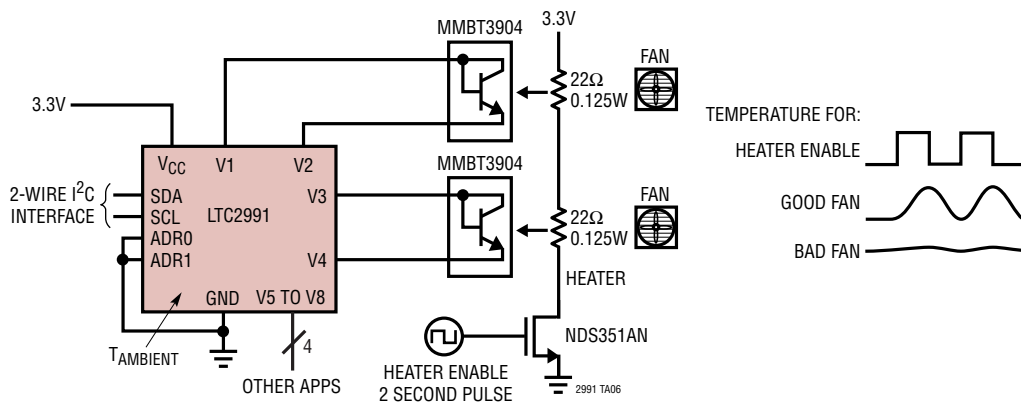


### VOLTAGE, CURRENT AND TEMPERATURE CONFIGURATION:

CONTROL REGISTER 06: 0xA1

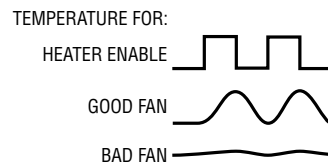
|                      |             |                     |
|----------------------|-------------|---------------------|
| T <sub>AMBIENT</sub> | REG 1A, 1B: | 0.0625°C/LSB        |
| V <sub>MOTOR</sub>   | REG 0A, 0B: | 2.44mV/LSB          |
| I <sub>MOTOR</sub>   | REG 0C, 0D: | 15.54mA/LSB         |
| T <sub>MOTOR</sub>   | REG 0E, 0F: | 0.0625°C/LSB        |
| V <sub>CC</sub>      | REG 1C, 1D: | 2.5V + 305.18µV/LSB |

## Fan/Air Filter/Temperature Alarm



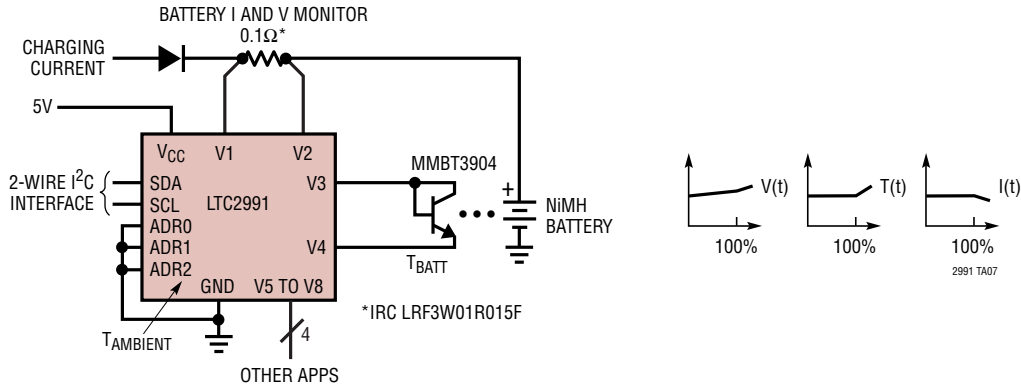
CONTROL REGISTER 0x06 = 0xA4

|                      |             |                     |
|----------------------|-------------|---------------------|
| T <sub>AMBIENT</sub> | REG 1A, 1B: | 0.0625°C/LSB        |
| T <sub>FAN1</sub>    | REG 0A, 0B: | 0.0625°C/LSB        |
| T <sub>FAN2</sub>    | REG 0C, 0D: | 0.0625°C/LSB        |
| V <sub>CC</sub>      | REG 1C, 1D: | 2.5V + 305.18µV/LSB |



## TYPICAL APPLICATIONS

### Battery Monitoring

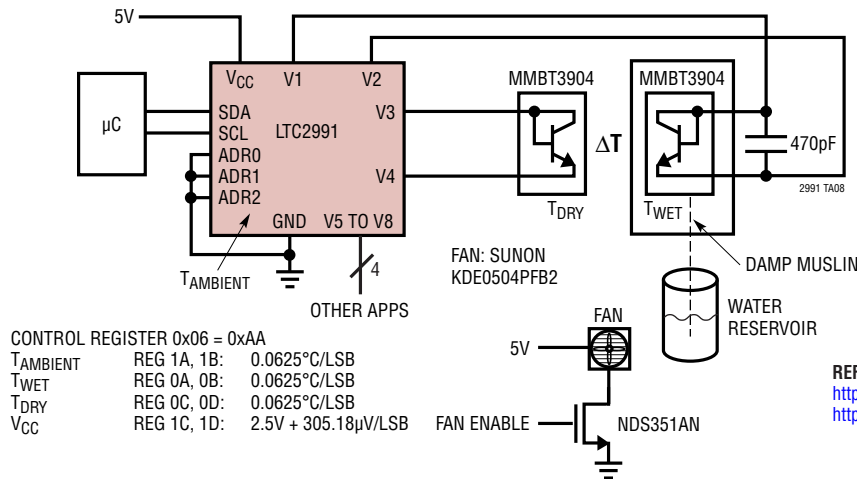


#### VOLTAGE AND TEMPERATURE CONFIGURATION:

CONTROL REGISTER: 0xA1

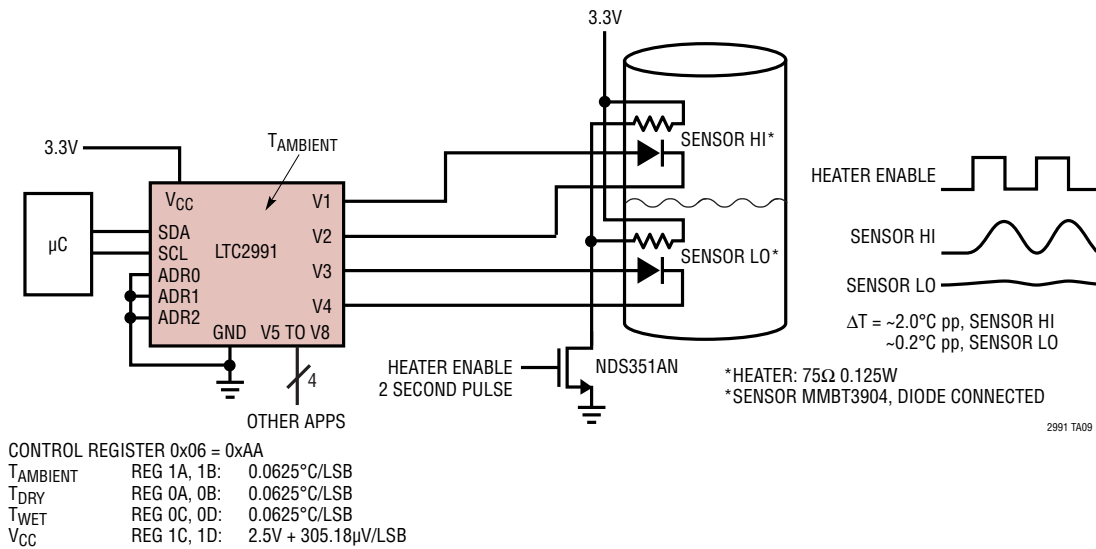
|                      |             |                     |
|----------------------|-------------|---------------------|
| T <sub>AMBIENT</sub> | REG 1A, 1B: | 0.0625°C/LSB        |
| V <sub>BAT</sub>     | REG 0A, 0B: | 305.18μV/LSB        |
| I <sub>BAT</sub>     | REG 0C, 0D: | 190.75μA/LSB        |
| T <sub>BAT</sub>     | REG 0E, 0F: | 0.0625°C/LSB        |
| V <sub>CC</sub>      | REG 1C, 1D: | 2.5V + 305.18μV/LSB |

### Wet Bulb Psychrometer

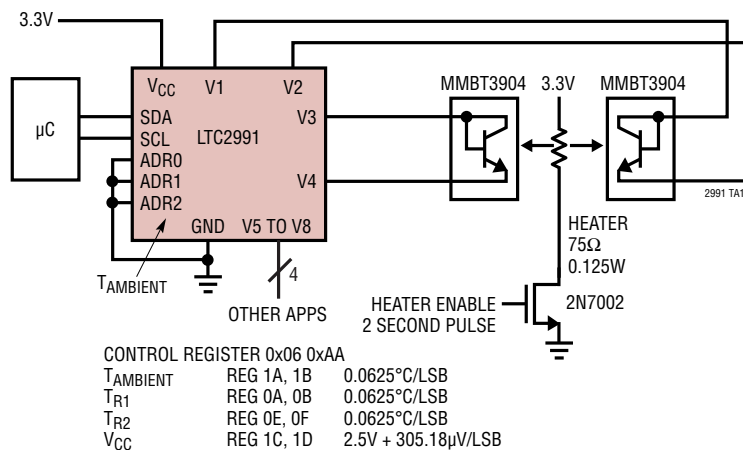


# TYPICAL APPLICATIONS

## Liquid Level Indicator

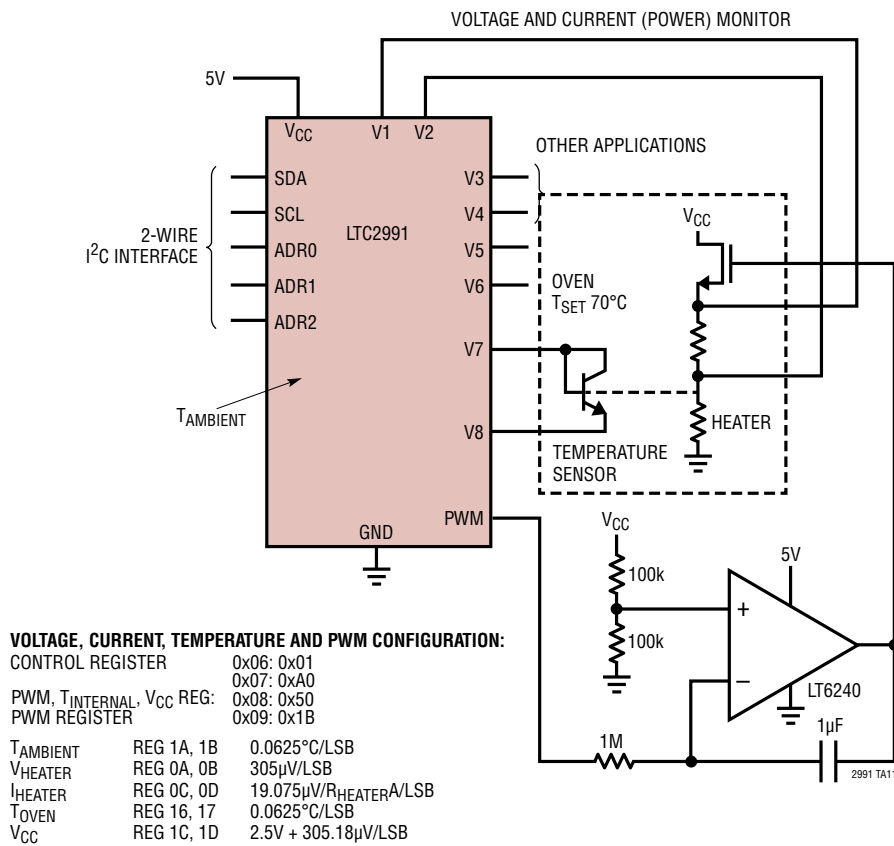


## Wind Direction/Instrumentation

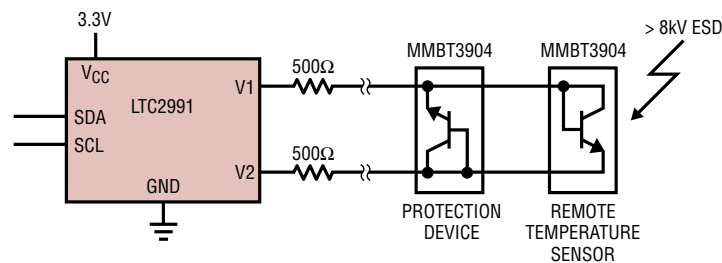


## TYPICAL APPLICATIONS

### Oven Control with Power Monitor



### Remote Temperature Sensing with Extended ESD Performance

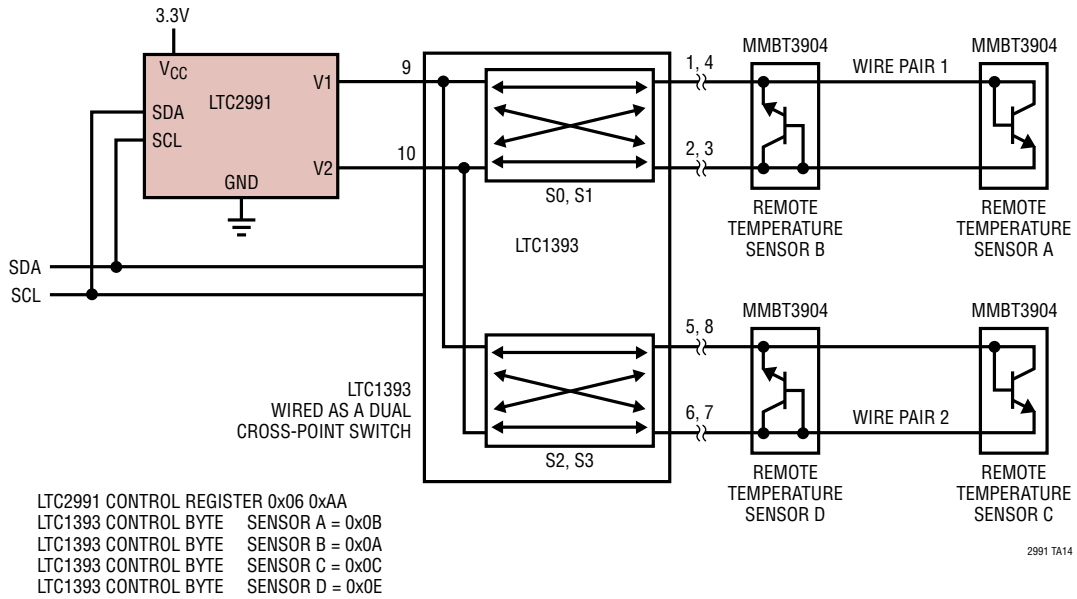


CONTROL REGISTER 0x06 = 0xAA  
 REMOTE TEMPERATURE SENSOR REG 0B, 0B: 0.0625 °C/LSB

2991 TA13

# TYPICAL APPLICATIONS

QUAD Remote Temperature Sensing with Two Wire Pairs Using One LTC2991 Channel



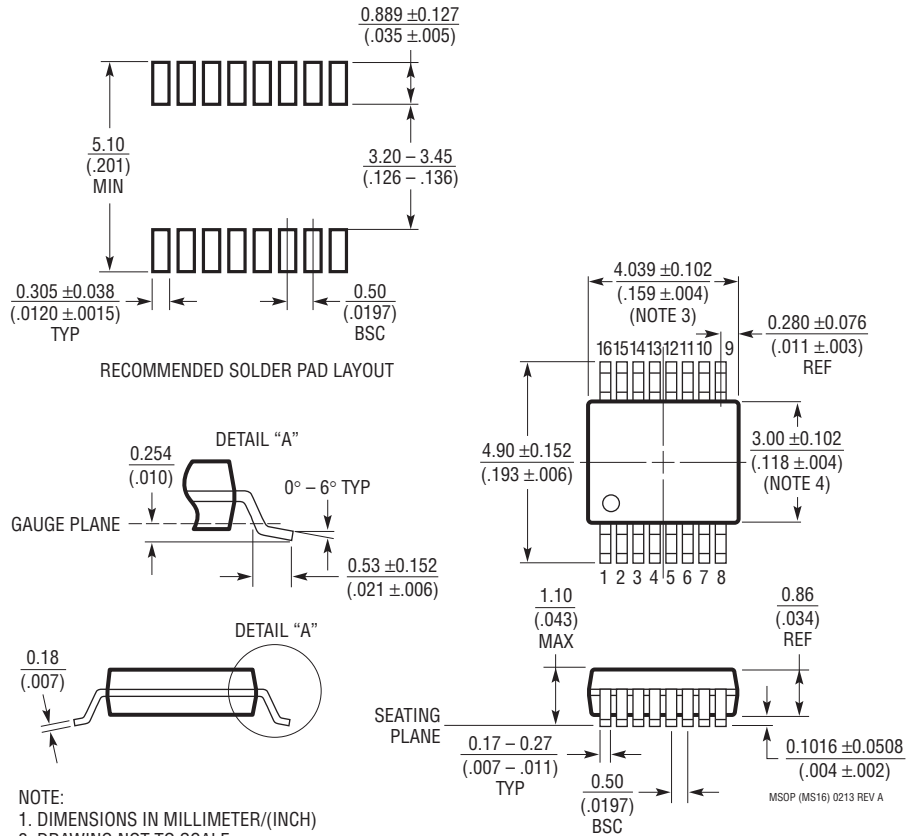
2991 TA14

LTC2291 REMOTE TEMPERATURE SENSOR REG 0B, 0B: 0.0625 °C/LSB

# PACKAGE DESCRIPTION

Please refer to <http://www.linear.com/product/Ltc2991#packaging> for the most recent package drawings.

## MS Package 16-Lead Plastic MSOP (Reference LTC DWG # 05-08-1669 Rev A)



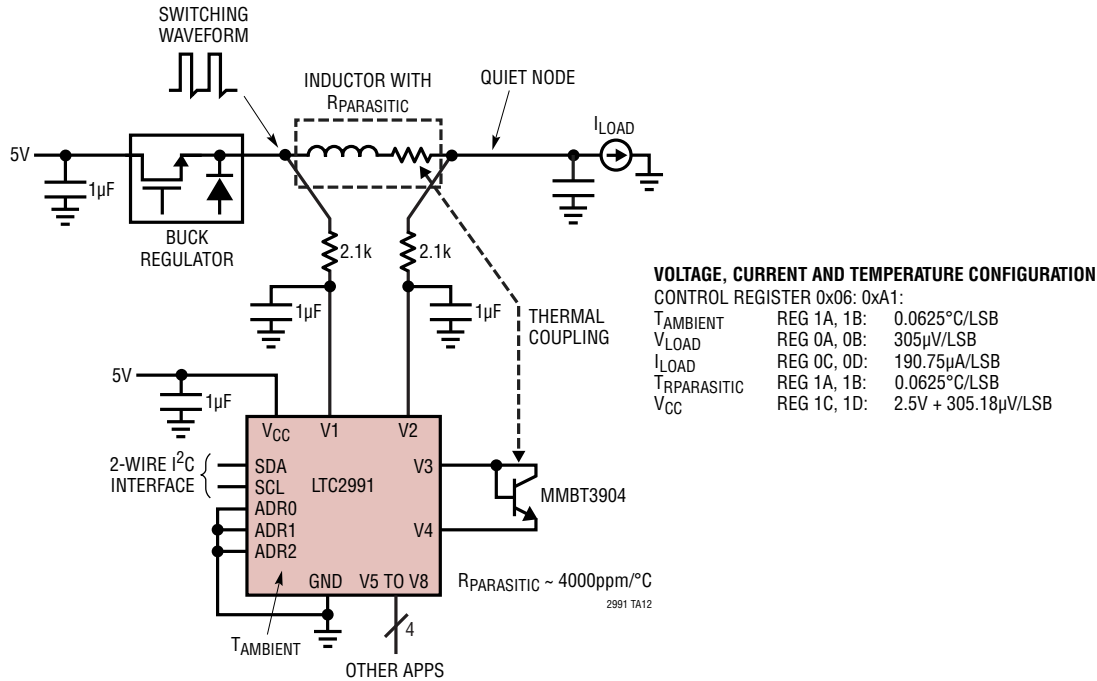
- NOTE:
1. DIMENSIONS IN MILLIMETER/(INCH)
  2. DRAWING NOT TO SCALE
  3. DIMENSION DOES NOT INCLUDE MOLD FLASH, PROTRUSIONS OR GATE BURRS.  
MOLD FLASH, PROTRUSIONS OR GATE BURRS SHALL NOT EXCEED 0.152mm (.006") PER SIDE
  4. DIMENSION DOES NOT INCLUDE INTERLEAD FLASH OR PROTRUSIONS.  
INTERLEAD FLASH OR PROTRUSIONS SHALL NOT EXCEED 0.152mm (.006") PER SIDE
  5. LEAD COPLANARITY (BOTTOM OF LEADS AFTER FORMING) SHALL BE 0.102mm (.004") MAX

## REVISION HISTORY

| REV | DATE  | DESCRIPTION  | PAGE NUMBER          |
|-----|-------|--|----------------------|
| A   | 10/11 | Corrected axis label on Figure 9.                                | 14                   |
|     |       | Inserted new text in I <sup>2</sup> C Device Addressing section. | 15                   |
|     |       | Inserted new row in Table 1.                                     | 17                   |
|     |       | Revised component values in Typical Application drawing TA05.    | 25                   |
| B   | 07/13 | Corrected diode voltage value.                                   | 13                   |
|     |       | Corrected V <sub>DIFFERENTIAL</sub> and current equations.       | 14                   |
| C   | 10/13 | Corrected slave address in Figures 5, 6, 7 and 8.                | 17                   |
| D   | 03/14 | Corrected LSB size to 19.075 $\mu$ V/LSB and 190.75 $\mu$ A/LSB. | 6, 24, 26,<br>28, 32 |
| E   | 08/15 | Added Single-Ended and Differential V <sub>OFFSET</sub> .        | 2                    |
|     |       | Inserted new text in Device Configuration.                       | 13                   |
|     |       | Updated MSOP Package Description to Rev A.                       | 30                   |
| F   | 10/15 | Correct serial bus protocol.                                     | 16                   |
|     |       | Correct Table 16.  | 22                   |

## TYPICAL APPLICATION

### Parasitic Resistance Voltage and Current Monitoring with Temperature Compensation



## RELATED PARTS

| PART NUMBER                       | DESCRIPTION   | COMMENTS  |
|-----------------------------------|---|---|
| <a href="#">LTC2990</a>           | Quad I <sup>2</sup> C Temperature, Voltage and Current Monitor                            | Remote and Internal Temperatures, 14-Bit Voltages and Current, Internal 10ppm/°C Reference  |
| <a href="#">LTC2997</a>           | Remote/Internal Temperature Sensor  | Temperature to Voltage with Integrated 1.8V Voltage Reference, ±1°C Accuracy  |
| <a href="#">LTC6102/LTC6102HV</a> | Precision Zero Drift Current Sense Amplifier  | 5V to 100V, 105V Absolute Maximum (LTC6102HV)   |
| <a href="#">LTC1392</a>           | Micropower Temperature, Power Supply and Differential Voltage Monitor                     | Complete Ambient Temperature Sensor Onboard   |
| <a href="#">LTC2970</a>           | Dual I <sup>2</sup> C Power Supply Monitor and Margining Controller                       | Integrated Reference and On-Chip Temperature Sensor Sequence, Trim, Margin and Supervise Eight Power Supplies   |
| <a href="#">LTC2977</a>           | Octal PMBus Power Supply Manager with EEPROM  | Integrated Reference and On-Chip Temperature Sensor and Fault Logging   |
| <a href="#">LTC2945</a>           | High Voltage I <sup>2</sup> C Power Monitor   | 0V to 80V Range, 12-Bit Voltage and Current. Measurement with 0.75% TUE I <sup>2</sup> C Interface Calculates 24-Bit Power Value, Stores Minimum and Maximum Values |
| <a href="#">LTC2487</a>           | 16-Bit 2-, 4-Channel Delta Sigma ADC with PGA, Easy Drive™ and I <sup>2</sup> C Interface | Internal Temperature Sensor   |
| <a href="#">LM134</a>             | Constant Current Source and Temperature Sensor  | Can Be Used as Linear Temperature Sensor  |
| <a href="#">LTC2983</a>           | Multi-Sensor High Accuracy Digital Temperature Measurement System                         | 0.1°C Accuracy, Directly Digitize RTDs, Thermocouples, Thermistors and Diodes, 20 Flexible Inputs   |



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