PRACTICAL DESIGN TECHNIQUES FOR SENSOR SIGNAL CONDITIONING

1. Introduction
2. Bridge Circuits
3. Amplifiers for Signal Conditioning
4. Strain, Force, Pressure, and Flow Measurements
5. High Impedance Sensors
6. Position and Motion Sensors
7. Temperature Sensors
8. ADCs for Signal Conditioning
9. Smart Sensors
10. Hardware Design Techniques
APPLICATIONS OF TEMPERATURE SENSORS

- Monitoring
  - Portable Equipment
  - CPU Temperature
  - Battery Temperature
  - Ambient Temperature

- Compensation
  - Oscillator Drift in Cellular Phones
  - Thermocouple Cold-Junction Compensation

- Control
  - Battery Charging
  - Process Control
## TYPES OF TEMPERATURE SENSORS

<table>
<thead>
<tr>
<th>THERMOCOUPLE</th>
<th>RTD</th>
<th>THERMISTOR</th>
<th>SEMICONDUCTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Widest Range:</td>
<td>Range:</td>
<td>Range:</td>
<td>Range:</td>
</tr>
<tr>
<td>–184ºC to +2300ºC</td>
<td>–200ºC to +850ºC</td>
<td>0ºC to +100ºC</td>
<td>–55ºC to +150ºC</td>
</tr>
<tr>
<td>High Accuracy and</td>
<td>Fair Linearity</td>
<td>Poor Linearity</td>
<td>Linearity: 1ºC</td>
</tr>
<tr>
<td>Repeatability</td>
<td></td>
<td></td>
<td>Accuracy: 1ºC</td>
</tr>
<tr>
<td>Needs Cold Junction</td>
<td>Requires</td>
<td>Requires</td>
<td>Requires</td>
</tr>
<tr>
<td>Compensation</td>
<td>Excitation</td>
<td>Excitation</td>
<td>Excitation</td>
</tr>
<tr>
<td>Low-Voltage Output</td>
<td>Low Cost</td>
<td>High Sensitivity</td>
<td>10mV/K, 20mV/K,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>or 1µA/K Typical Output</td>
</tr>
</tbody>
</table>
# COMMON THERMOCOUPLES

<table>
<thead>
<tr>
<th>JUNCTION MATERIALS</th>
<th>TYPICAL USEFUL RANGE (°C)</th>
<th>NOMINAL SENSITIVITY (µV/°C)</th>
<th>ANSI DESIGNATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinum (6%)/Rhodium-</td>
<td>38 to 1800</td>
<td>7.7</td>
<td>B</td>
</tr>
<tr>
<td>Platinum (30%)/Rhodium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten (5%)/Rhenium -</td>
<td>0 to 2300</td>
<td>16</td>
<td>C</td>
</tr>
<tr>
<td>Tungsten (26%)/Rhenium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromel - Constantan</td>
<td>0 to 982</td>
<td>76</td>
<td>E</td>
</tr>
<tr>
<td>Iron - Constantan</td>
<td>0 to 760</td>
<td>55</td>
<td>J</td>
</tr>
<tr>
<td>Chromel - Alumel</td>
<td>–184 to 1260</td>
<td>39</td>
<td>K</td>
</tr>
<tr>
<td>Platinum (13%)/Rhodium-</td>
<td>0 to 1593</td>
<td>11.7</td>
<td>R</td>
</tr>
<tr>
<td>Platinum (10%)/Rhodium-</td>
<td>0 to 1538</td>
<td>10.4</td>
<td>S</td>
</tr>
<tr>
<td>Platinum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platinum (10%)/Rhodium-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platinum (13%)/Rhodium-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromium - Alumel</td>
<td>–184 to 400</td>
<td>45</td>
<td>T</td>
</tr>
</tbody>
</table>
THERMOCOUPLE OUTPUT VOLTAGES FOR TYPE J, K, AND S THERMOCOUPLES
THERMOCOUPLE SEEBECK COEFFICIENT
VERSUS TEMPERATURE

SEEBECK COEFFICIENT - \( \mu \text{V/ } ^\circ \text{C} \)

TEMPERATURE (°C)

TYPE J

TYPE K

TYPE S
THERMOCOUPLE BASICS

A. THERMOELECTRIC VOLTAGE

Metal A

\[ V_1 \rightarrow T_1 \rightarrow \text{Thermoelectric EMF} \rightarrow T_2 \rightarrow V_2 \]

Metal B

\[ R = \text{Total Circuit Resistance} \]

\[ I = \frac{(V_1 - V_2)}{R} \]

B. THERMOCOUPLE

Metal A

\[ V_1 \rightarrow T_1 \rightarrow R \rightarrow T_2 \rightarrow V_2 \]

Metal B

\[ R = \text{Total Circuit Resistance} \]

\[ I = \frac{(V_1 - V_2)}{R} \]

C. THERMOCOUPLE MEASUREMENT

Metal A

\[ V_1 \rightarrow T_1 \rightarrow V_2 \rightarrow T_2 \rightarrow V_2 \]

Metal B

\[ V = V_1 - V_2, \text{ If } T_3 = T_4 \]

D. THERMOCOUPLE MEASUREMENT

Copper

\[ V \]

Copper

\[ V = V_1 - V_2, \text{ If } T_3 = T_4 \]
CLASSICAL COLD-JUNCTION COMPENSATION USING AN ICE-POINT (0°C) REFERENCE JUNCTION

METAL A

T1 → V1

METAL B

V1 – V(0°C)

ICE BATH

V(0°C)

T2

0°C
USING A TEMPERATURE SENSOR FOR COLD-JUNCTIONCOMPENSATION

V(COMP) = f(T2)

V(OUT) = V(T1) – V(T2) + V(COMP)

IF V(COMP) = V(T2) – V(0°C), THEN

V(OUT) = V(T1) – V(0°C)
TERMINATING THERMOCOUPLE LEADS DIRECTLY TO AN ISOTHERMAL BLOCK

TEMP SENSOR

T2

METAL A

T1

V1

METAL B

ISOTHERMAL BLOCK

TEMPERATURE COMPENSATION CIRCUIT

COPPER

V(OUT) = V1 - V(0°C)

COPPER

COPPER
USING A TEMPERATURE SENSOR FOR COLD-JUNCTION COMPENSATION (TMP35)

- **TMP35**
- **R1* 24.9kΩ**
- **R2* 102Ω**
- **R3* 1.24MΩ**
- **R4* 4.99kΩ**
- **R5* 1.21MΩ**
- **R6 100kΩ**
- **P1 50kΩ**
- **OP193**
- **0.1µF**
- **VOUT 0.1 - 2.6V**
- **10mV/°C**
- **3.3V TO 5.5V**

**TYPE K THERMO COUPLE**

0 °C < T < 250 °C

**CHROMEL**

**ALUMEL**

**ISOTHERMAL BLOCK**

**COLD JUNCTION**

**Cu**

* USE 1% RESISTORS
AD594/AD595 MONOLITHIC THERMOCOUPLE AMPLIFIERS WITH COLD-JUNCTION COMPENSATION

TYPE J: AD594
TYPE K: AD595

THERMOCOUPLE

AD594/AD595

0.1 µF

4.7 kΩ

+5 V

BROKEN THERMOCOUPLE ALARM

10 mV/°C

OVERLOAD DETECT

G

+A

ICE POINT COMP

+TC

-TC

V_{OUT}

G

G

+
AD77XX ADC USED WITH TMP35 TEMPERATURE SENSOR FOR CJC

3V OR 5V (DEPENDING ON ADC)

G=1 TO 128

AD77XX SERIES (16-22 BITS)

TO MICROCONTROLLER
RESISTANCE TEMPERATURE DETECTORs (RTD)

- Platinum (Pt) the Most Common
- 100Ω, 1000Ω Standard Values
- Typical TC = 0.385% / °C,
  
  0.385Ω / °C for 100Ω Pt RTD
- Good Linearity - Better than Thermocouple,
  Easily Compensated
A 100Ω Pt RTD WITH 100 FEET OF 30-GAUGE LEAD WIRES

RESISTANCE TC OF COPPER = 0.40%/°C @ 20°C

RESISTANCE TC OF Pt RTD = 0.385%/°C @ 20°C
FOUR-WIRE OR KELVIN CONNECTION TO Pt RTD FOR ACCURATE MEASUREMENTS

- Force lead
- Force lead
- R_{LEAD}
- 100\Omega
- Pt RTD
- Sense lead
- Sense lead
- I
- To high-Z in-amp or ADC
INTERFACING A Pt RTD TO A HIGH RESOLUTION ADC

- **R_{REF} 6.25kΩ**
- **400μA**
- **100Ω Pt RTD**
- **V_{REF}**
- **MUX**
- **G=1 TO 128**
- **ΣΔ ADC**
- **PGA**
- **CONTROL REGISTER**
- **OUTPUT REGISTER**
- **SERIAL INTERFACE**
- **AD77XX SERIES (16-22 BITS)**
- **TO MICROCONTROLLER**

3V OR 5V (DEPENDING ON ADC)
CONDITIONING THE PLATINUM RTD USING THE ADT70

1kΩ Pt RTD

1kΩ REF RES

0.1μF

+5V

ADT70

2.5V REFERENCE

MATCHED 1mA SOURCES

INST AMP

GND REF

R_G = 50kΩ

SHUT DOWN

OUT = 5mV/ °C

-1V TO -5V

Note: Some Pins Omitted for Clarity
RESISTANCE CHARACTERISTICS OF A 10kΩ NTC THERMISTOR

ALPHA THERMISTOR, INCORPORATED
RESISTANCE/TEMPERATURE CURVE 'A'
10 kΩ THERMISTOR, #13A1002-C3

Nominal Value @ 25 °C
TEMPERATURE COEFFICIENT OF 10kΩ NTC THERMISTOR

THERMISTOR TEMPERATURE COEFFICIENT
ppm/ °C

TEMPERATURE - °C

ALPHA THERMISTOR, INCORPORATED
RESISTANCE/TEMPERATURE CURVE 'A'
10 kΩ THERMISTOR, #13A1002-C3
LINEARIZATION OF NTC THERMISTOR USING A 5.17kΩ SHUNT RESISTOR

RESISTANCE (kΩ)

TEMPERATURE - °C

THERMISTOR

PARALLEL COMBINATION
LINEARIZED THERMISTOR AMPLIFIER

10kΩ NTC THERMISTOR

226µA

5.17kΩ LINEARIZATION RESISTOR

[V_{OUT} \approx 0.994V \text{ @ } T = 0°C\]

[V_{OUT} \approx 0.294V \text{ @ } T = 70°C\]

\[\Delta V_{OUT}/\Delta T \approx -10mV/°C\]

AMPLIFIER OR ADC

LINEARITY \approx \pm 2°C, \ 0°C TO +70°C
BASIC RELATIONSHIPS FOR SEMICONDUCTOR TEMPERATURE SENSORS

\[ V_{BE} = \frac{kT}{q} \ln \left( \frac{I_C}{I_S} \right) \]

\[ V_N = \frac{kT}{q} \ln \left( \frac{I_C}{N \cdot I_S} \right) \]

\[ \Delta V_{BE} = V_{BE} - V_N = \frac{kT}{q} \ln(N) \]

INDEPENDENT OF \( I_C, I_S \)
CLASSIC BANDGAP TEMPERATURE SENSOR

\[ \Delta V_{BE} = V_{BE} - V_N = \frac{kT}{q} \ln(N) \]

\[ V_{PTAT} = 2 \frac{R_1}{R_2} \frac{kT}{q} \ln(N) \]

\[ V_{BANDGAP} = 1.205V \]

"BROKAW CELL"
CURRENT OUTPUT SENSORS: AD592, TMP17

- 1µA/K Scale Factor
- Nominal Output Current @ +25°C: 298.2µA
- Operation from 4V to 30V
- ±0.5°C Max Error @ 25°C, ±1.0°C Error Over Temp,
  ±0.1°C Typical Nonlinearity (AD592CN)
- ±2.5°C Max Error @ 25°C, ±3.5°C Error Over Temp,
  ±0.5°C Typical Nonlinearity (TMP17F)
- AD592 Specified from –25°C to +105°C
- TMP17 Specified from –40°C to +105°C
RATIOMETRIC VOLTAGE OUTPUT SENSORS

VOUT = \( \frac{V_S}{3.3V} \times \left( 0.25V + 28\text{mV/°C} \times TA \right) \)

AD22103

VOUT

REFERENCE

ADC

INPUT

GND

R(T)

I(VS)

VOUT

VS = +3.3V

0.1μF
ABSOLUTE VOLTAGE OUTPUT SENSORS WITH SHUTDOWN

- **V_{OUT}:**
  - TMP35, 250mV @ 25°C, 10mV/°C (+10°C to +125°C)
  - TMP36, 750mV @ 25°C, 10mV/°C (−40°C to +125°C)
  - TMP37, 500mV @ 25°C, 20mV/°C ( +5°C to +100°C)

- ±2°C Error Over Temp (Typical), ±0.5°C Non-Linearity (Typical)
- Specified −40°C to +125°C
- 50µA Quiescent Current, 0.5µA in Shutdown Mode

+V_s = 2.7V TO 5.5V

0.1µF

SOT-23-5

ALSO
SO-8
OR TO-92
ADT45/ADT50 ABSOLUTE VOLTAGE OUTPUT SENSORS

- $V_{OUT}$:
  - ADT45, 250mV @ 25°C, 10mV/°C Scale Factor
  - ADT50, 750mV @ 25°C, 10mV/°C Scale Factor
- ±2°C Error Over Temp (Typical), ±0.5°C Non-Linearity (Typical)
- Specified –40°C to +125°C
- 60µA Quiescent Current

$V_S = 2.7V$ TO 12V

SOT-23
THERMAL RESPONSE IN FORCED AIR FOR SOT-23-3

SOT-23-3 SOLDERED TO 0.338" x 0.307" Cu PCB
V+ = 2.7V TO 5V
NO LOAD

AIR VELOCITY - LFPM

TIME CONSTANT - SECONDS

0 100 200 300 400 500 600 700

0 5 10 15 20 25 30 35
DIGITAL OUTPUT SENSORS: TMP03/04

+V_S = 4.5 TO 7V

REFERENCE VOLTAGE

CLOCK (1MHz)

TEMP SENSOR VPTAT

SIGMA-DELTA ADC

OUTPUT (TMP04)

OUTPUT (TMP03)

GND

TMP03/TMP04
TMP03/TMP04 OUTPUT FORMAT

T1 Nominal Pulse Width = 10ms
±1.5°C Error Over Temp, ±0.5°C Non-Linearity (Typical)
Specified -40°C to +100°C
Nominal T1/T2 @ 0°C = 60%
Nominal Frequency @ +25°C = 35Hz
6.5mW Power Consumption @ 5V
TO-92, SO-8, or TSSOP Packages

\[
\text{TEMPERATURE (°C)} = 235 - \left( \frac{400 \times T1}{T2} \right)
\]

\[
\text{TEMPERATURE (°F)} = 455 - \left( \frac{720 \times T1}{T2} \right)
\]
INTERFACING TMP04 TO A MICROCONTROLLER

TMP04 OUT

OSCILLATOR

CPU

TIMER CONTROL

+5V

XTAL

0.1µF

GND

V+

P1.0

80C51 MICROCONTROLLER

NOTE: ADDITIONAL PINS OMITTED FOR CLARITY

TIMER 0

TIMER 1
MONITORING HIGH POWER MICROPROCESSOR OR DSP WITH TMP04

FAST MICROPROCESSOR, DSP, ETC., IN PGA PACKAGE

PGA SOCKET

PC BOARD

TMP04 IN SURFACE MOUNT PACKAGE
ADT05 THERMOSTATIC SWITCH

- ±2°C Setpoint Accuracy
- 4°C Preset Hysteresis
- Specified Operating Range: –40°C to +150°C
- Power Dissipation: 200µW @ 3.3V

+S = 2.7V TO 7V

R_PULL-UP
OUT

0.1µF

SOT-23-5
TMP01 PROGRAMMABLE SETPOINT CONTROLLER

VREF 2.5V

TEMPERATURE SENSOR AND VOLTAGE REFERENCE

TEMPERATURE SENSOR AND VOLTAGE REFERENCE

WINDOW COMPARATOR

HYSTERESIS GENERATOR

R1

SET HIGH

R2

SET LOW

R3

GND

V+

OVER

UNDER

VPTAT
TMP01 SETPOINT CONTROLLER KEY FEATURES

- $V_C$: 4.5 to 13.2V
- Temperature Output: VPTAT, +5mV/K
- Nominal 1.49V Output @ 25°C
- ±1°C Typical Accuracy Over Temperature
- Specified Operating Range: –55°C to + 125°C
- Resistor-Programmable Hysteresis
- Resistor-Programmable Setpoints
- Precision 2.5V ±8mV Reference
- 400μA Quiescent Current, 1μA in Shutdown
- Packages: 8-Pin Dip, 8-Pin SOIC, 8-Pin TO-99
- Other Setpoint Controllers:
  - Dual Setpoint Controllers: ADT21/ADT22
    (3V Versions of TMP01 with Internal Hysteresis)
  - Quad Setpoint Controller: ADT14
AD7816 10-BIT DIGITAL TEMPERATURE SENSOR WITH SERIAL INTERFACE

+V_{DD} = 2.7V TO 5.5V

AD7816

TEMP SENSOR

MUX

2.5V REF

OVER TEMP REGISTER

CLOCK

10-BIT CHARGE REDISTRIBUTION SAR ADC

A > B

OUTPUT REGISTER

CONTROL REGISTER

D_{IN/OUT}

SCLK

RD/WR

OTI

AGND

CONVST

7.36
AD7817 10-BIT MUXED INPUT ADC WITH TEMP SENSOR

- REF\textsubscript{IN}
- +V\textsubscript{DD} = 2.7V TO 5.5V
- \text{MUX}
- \text{TEMP Sensor}
- \text{2.5V REF}
- \text{OVER TEMP REGISTER}
- \text{A > B}
- \text{CLOCK}
- \text{10-BIT CHARGE REDISTRIBUTION SAR ADC}
- \text{OUTPUT REGISTER}
- \text{CONTROL REGISTER}
- \text{AGND}
- \text{DGND}
- \text{BUSY}
- \text{CONVST}
- \text{OTI}
- \text{D\textsubscript{OUT}}
- \text{SCLK}
- \text{RD/WR}
- \text{D\textsubscript{IN}}
- \text{CS}

V\text{IN1}, V\text{IN2}, V\text{IN3}, V\text{IN4}
AD7816/7817/7818 - SERIES TEMP SENSOR
10-BIT ADCs WITH SERIAL INTERFACE

- 10-Bit ADC with 9µs Conversion Time
- Flexible Serial Interface (Intel 8051, Motorola SPI™ and QSPI™, National MICROWIRE™)
- On-Chip Temperature Sensor: –55°C to +125°C
- Temperature Accuracy: ± 2°C from –40°C to +85°C
- On-Chip Voltage Reference: 2.5V ±1%
- +2.7V to +5.5V Power Supply
- 4µW Power Dissipation at 10Hz Sampling Rate
- Auto Power Down after Conversion
- Over-Temp Interrupt Output
- Four Single-Ended Analog Input Channels: AD7817
- One Single-Ended Analog Input Channel: AD7818
- AD7416/7417/7418: Similar, but have I²C Compatible Interface
ADM1021 MICROPROCESSOR TEMPERATURE MONITOR
INPUT SIGNAL CONDITIONING CIRCUITS

\[ V_{DD} = +3 \text{V TO } +5.5 \text{V} \]

\[ \Delta V_{BE} = \frac{kT}{q} \ln N \]

\[ V_{OUT} = G \cdot \frac{kT}{q} \ln N \]

\[ I \rightarrow N \times I \rightarrow I_{BIAS} \rightarrow \text{Oscillator} \]

\[ \mu \text{P Remote Sensing Transistor} \]

\[ \text{SPNP} \]

\[ C \]

\[ D^- \]

\[ V_{DD} = +3 \text{V TO } +5.5 \text{V} \]
ADM1021 KEY SPECIFICATIONS

- On-Chip and Remote Temperature Sensing
- 1°C Accuracy for On-Chip Sensor
- 3°C Accuracy for Remote Sensor
- Programmable Over / Under Temperature Limits
- 2-Wire SMBus Serial Interface
- 70µA Max Operating Current
- 3µA Standby Current
- +3V to +5.5V Supplies
- 16-Pin QSOP Package