Resistance Temperature Detector (RTD)

Ishanya[1]

[1]Indian Institute of Science Education and Research Bhopal, Bhopal 462 066
Madhya Pradesh, India

Contact: ishanya21@iiserb.ac.in

November 18, 2024

Introduction

- Temperature measurement is essential in industrial applications and research.
- RTDs provide reliable, precise, and linear response to temperature changes.
- The presentation focuses on designing an affordable RTD-based temperature sensing system using ESP32 microcontroller.
- The system includes signal conditioning and real-time temperature display on OLED screen.

Working Principle of RTD

When the temperature of a metal increases, the resistance to the flow of electricity increases as well. An electrical current is passed through the sensor, the resistance element is used to measure the resistance of the current being passed through it. Mathematically, the resistance variation with temperature can be expressed as:

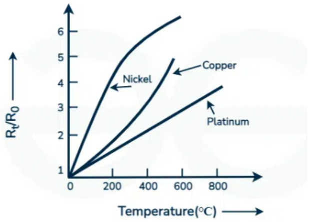
$$R_T = R_0 \left[1 + \alpha(T - T_0) + \beta(T - T_0)^2 + \dots\right],$$

$$R_T = R_0 \left[1 + \alpha(T - T_0)\right]$$

- R_T: Resistance at temperature T
- R_0: Resistance at reference temperature T_0
- α: Temperature coefficient ($\Omega/°\mathrm{C}$)

Platinum for RTDs

- Platinum has a stable and linear temperature coefficient of resistance (TCR) of approximately 0.00385 per °C.
- Maintains its resistance stability over a wide temperature range from -200°C to 850°C.
- It is chemically inert and resistant to corrosion and oxidation.
- It has high electrical resistivity, allowing for sensitive temperature measurements.



Components and Software Requirements

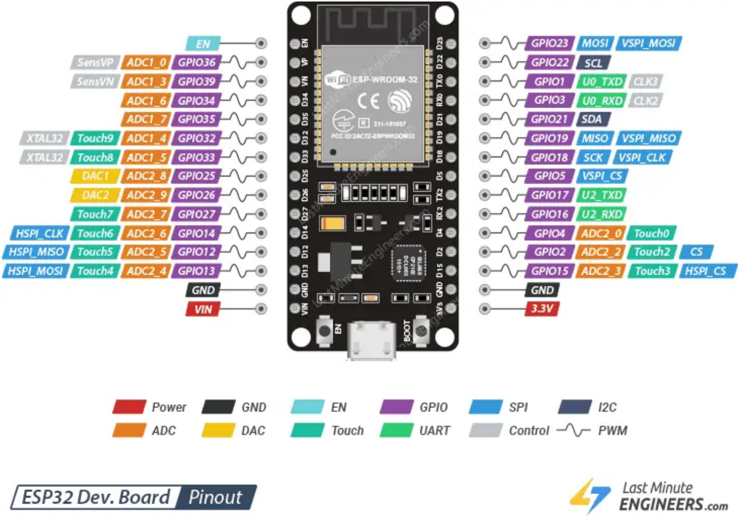
Hardware:

- **RTD Sensor**
- **ESP32 Microcontroller-WROOM:** For data acquisition and processing.
- **SSD1306 0.96 inch I2C OLED Display:** For real-time temperature display.
- **Potentiometer:** Simulates the RTD for initial testing.
- **Resistors and Wires**

Software Requirements:

- **Arduino IDE:** For ESP32 programming.
- **Libraries:** Adafruit GFX, Adafruit SSD1306 for display and ADC interface.

ESP32 Pinout



RTD Sensor Fabrication Steps(Done by PhD)

- **Substrate Preparation:** Start with a silicon (Si) wafer as the substrate.
- **Coating of Sacrificial Layer:** Apply a Poly-methyl methacrylate (PMMA) layer to act as the sacrificial material.
- **Deposition of Chromium (Cr) Layer:** Deposit a Cr layer over PMMA using sputtering for etch resistance.
- **Lithographic Patterning:** Use lithography to define geometry on the Cr layer.
- **Etching of PMMA Layer:** Selectively etch exposed PMMA with chemical etchants to shape the structure.
- **Deposition of Functional Layers:** Deposit functional material (Platinum in this case) over the patterned structure.
- **Lift-Off Process:** Dissolve the PMMA layer using acetone, leaving the desired patterned materials.
- **Final Cleaning and Testing:** Clean the device to remove residues and test for functionality.

ESP32 ADC Resolution

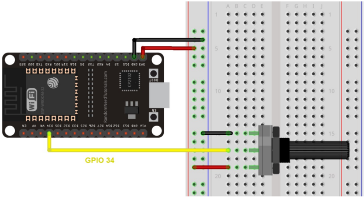
- **Built-in ADC:** The ESP32 features a 12-bit ADC with a resolution of $2^{12} = 4096$ levels.
- **Voltage Range:** Operates from 0V to 3.3V.
- **M**inimum detectable voltage change is:

$$\text{LSB} = \frac{\text{Reference Voltage}}{2^{12}} = \frac{3.3\ \text{V}}{4096} \approx 0.8\,\text{mV}$$

- **Limitations:** Actual performance may vary due to:
  - Non-linearity in ADC response, requiring calibration.
  - Electrical noise, especially during Wi-Fi/Bluetooth operations.
  - High input impedance affecting accuracy for high-impedance sources.
  - Variations in reference voltage stability.

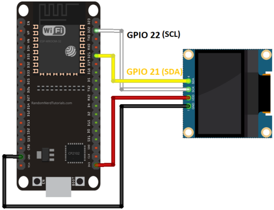
Circuit Design: Voltage Measurement

- Two methods explored for measuring RTD resistance:
  - **Voltage Divider**
  - **Wheatstone Bridge**
- A potentiometer was used for initial testing to simulate RTD performance.
- Key ESP32 connections:
  - **D34 (GPIO34):** Analog input for voltage measurement.
  - **3.3V Pin:** Provides excitation voltage for ADC.
  - **GND Pin:** Ground connection for the circuit.



Voltage Measurement Circuit using ESP32-WROOM

I2C OLED and ESP32-WROOM Interfacing

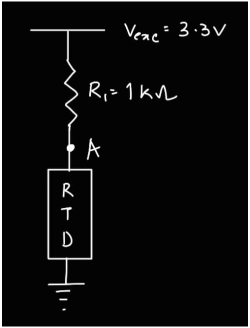


- Demonstrates how an OLED display is connected to the ESP32.
- Uses the I2C communication protocol for interfacing:
  - **SDA (GPIO21)**: Data line for I2C communication.
  - **SCL (GPIO22)**: Clock line for I2C communication.
- Useful for real-time data visualization in applications like sensor monitoring.

Voltager Divider Method-RTD

- Converts RTD resistance changes into voltage using the formula:

$$V_A = \frac{R_{RTD}}{R_{RTD} + R_1} \cdot V_{exc}$$



Voltage Divider Circuit. The the voltage is measured across the RTD

Voltage Divider Method-RTD

Assuming the nominal resistance of the RTD at $0°C$ is $1000\,\Omega$ and it increases by $4\,\Omega/°C$, the resistance at a temperature of $0.2°C$ becomes:

$$R_{RTD} = 1000 + (4 \times 0.2) = 1000.8\,\Omega$$

The voltage at node A for $R_1 = 1000\,\Omega$ is calculated as:

$$V_A = \frac{1000.8}{1000.8 + 1000} \cdot 3.3 \approx 1.65033\,\mathrm{V}$$

For a temperature increase of $0.2°C$, the voltage changes from:

$$V_A(0°C) = \frac{1000}{1000 + 1000} \cdot 3.3 = 1.65\,\mathrm{V}$$

to:

$$V_A(0.2°C) \approx 1.65033\,\mathrm{V}$$

The change in voltage is:

$$\Delta V_A = 1.65033 - 1.65 = 0.00033\,\mathrm{V}\,(330\,\mu\mathrm{V})$$

Limitations of the Voltage Divider

- **Sensitivity to V_{exc}:** Variations in the excitation voltage can lead to inaccurate measurements.
- **Non-linearity in RTD Characteristics:** The approach does not account for the RTD's non-linear behavior over a wide temperature range.
- **Component Stability:** Accuracy is affected by the tolerance and stability of the fixed resistor R_1.
- **ADC Resolution:** Requires a high-resolution ADC to detect small voltage changes effectively.
- **Noise Susceptibility:** Noise in the circuit can affect the precision of the measurements.

Wheatstone Bridge Implementation

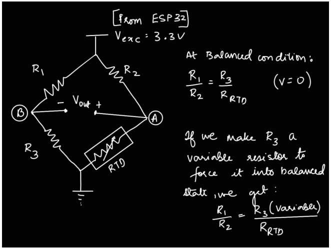


Figure: Wheatstone Bridge for RTD Measurement

A Wheatstone Bridge offers a more sensitive approach to measuring small resistance changes, as it operates on a differential voltage measurement. In a bridge configuration, the voltage difference between the two branches is measured, which can effectively amplify small variations in the RTD resistance, improving the signal-to-noise ratio and it a better implementation compared to a Voltage Divider implementation.

Balanced Bridge and Temperature Imbalance

Balanced Bridge at Reference Temperature:

- The condition for balance is $V_{out} = V_A - V_B = 0$, with $R_1 = R_2$ and $R_3 = R_4$ at the reference temperature.

Imbalance due to Temperature Change:

- The resistance of the RTD (R_{RTD}) changes with temperature, leading to a non-zero output voltage (V_{out}) which is proportional to the temperature variation.

$$R_{RTD}(T) = R_0\,(1 + \alpha T)$$

At 0°C:

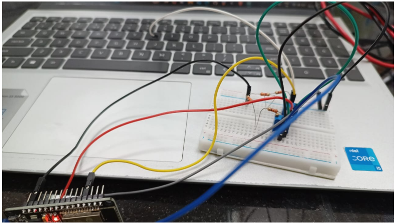
$$R_{RTD} = 1000 + (4 \times 0.2) = 1000.8\,\Omega$$

$$V_A = \frac{1000.8}{1000.8 + 1000} \times 3.3 \approx 1.6503\,\text{V}$$

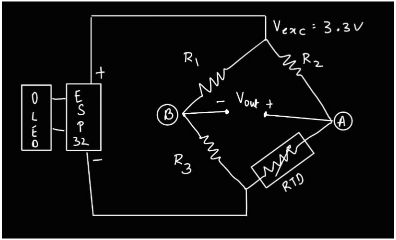
$$V_B = \frac{1000}{1000 + 1000} \times 3.3 = 1.65\,\text{V}$$

$$V_{out} = V_A - V_B = 1.6503 - 1.65 = 0.0003\,\text{V} = 300\,\mu\text{V}$$

Wheatstone Bridge Implementation



Wheatstone Bridge-RTd



Circuit for Wheatstone Bridge-RTD

This small voltage change ($V_{out} = 300\,\mu$V) can be measured using the ESP32's analog-to-digital converter (ADC). The Wheatstone Bridge offers higher sensitivity compared to the simple voltage divider method, but it is sensitive to noise and non-linearity.

Readout Circuit and Verification

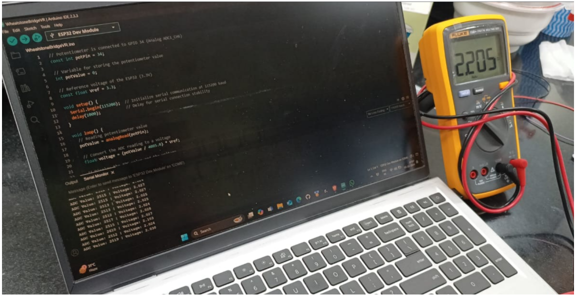


Figure: Readout Circuit Verification for Wheatstone Bridge Implementation

The ESP32 and voltmeter readout circuit show a consistent 0.2V difference.

Limitations of the Wheatstone Bridge for RTD Applications

While the Wheatstone bridge approach reduces the ADC requirements, it has some disadvantages:

- The bridge output is dependent on the value of the resistors employed. Therefore, three precision resistors are required to achieve accurate measurements.
- The bridge circuit can also be affected by power supply noise, which may impact the final measurements.
- The complexity of wiring and connections in the Wheatstone bridge makes it prone to errors from contact resistance and other environmental factors.

Improvement: RTD Sensor Measurement Using a 22-bit Delta-Sigma Converter

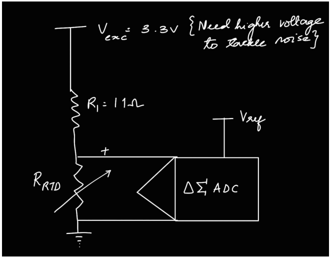


Figure: Delta-Sigma Converter for RTD Measurement

While the Wheatstone bridge implementation is more accurate than the Voltage-Divider implementation, the accuracy can be further improved by using a higher-resolution analog-to-digital converter (ADC), such as a 22-bit Delta-Sigma (ΔΣ) ADC.

Delta-Sigma Converter: Principle and Benefits

A $\Delta\Sigma$ ADC works by oversampling the input signal (sampling at a rate much higher than the Nyquist rate) and applying a noise-shaping filter to push quantization noise to higher frequencies, which can be filtered out. This results in higher effective resolution, particularly for low-level analog signals such as those produced by RTDs.
By using a 22-bit $\Delta\Sigma$ ADC, we can improve the resolution of the voltage measurement, enabling finer detection of small changes in the RTD's resistance and the resulting voltage output.

Resolution Calculation

Let's compare the resolution of a 12-bit ADC and a 22-bit $\Delta\Sigma$ ADC. We know the excitation voltage is $V_{exc} = 3.3\,\mathrm{V}$, and the output voltage change for a small temperature change of 0.2°C is approximately $\Delta V_{out} = 300\,\mu\mathrm{V}$.

$$\text{Resolution}_{\text{12-bit}} = \frac{V_{exc}}{2^{12}} = \frac{3.3}{4096} \approx 0.000805\,\mathrm{V} = 805\,\mu\mathrm{V}$$

This means the smallest voltage change that can be detected by a 12-bit ADC is approximately 805 μV, which is much larger than the 300 μV change observed for a 0.2°C temperature variation.

Resolution Calculation (Continued)

The resolution of a 22-bit $\Delta\Sigma$ ADC is calculated as:

$$\text{Resolution}_{\text{22-bit}} = \frac{V_{exc}}{2^{22}} = \frac{3.3}{4194304} \approx 0.000000787\,\text{V} = 0.787\,\mu\text{V}$$

With a 22-bit ADC, the resolution is 0.787 μV, which is significantly finer than the 300 μV voltage change from the 0.2°C temperature variation. This allows for much more sensitive detection of small temperature changes.

Noise Considerations and Solutions

When using a 22-bit $\Delta\Sigma$ ADC, the resolution is extremely fine, which can make the system sensitive to noise. Even small fluctuations in noise could be detected as temperature changes. Some solutions to mitigate the effects of noise:

- **Averaging Multiple Samples:** Instead of relying on a single sample from the ADC, multiple readings can be taken and averaged over time. This helps smooth out any short-term noise or fluctuations in the signal.
- **Use of a Low-Pass Filter:** A low-pass filter can be implemented in the signal processing chain to filter out high-frequency noise components.
- **Use of Higher Excitation Voltage:** Increasing the excitation voltage V_{exc} can increase the output signal strength, making it easier to detect small temperature-induced changes.

Use of Higher Excitation Voltage

If the excitation voltage is increased to 5 V, the resolution for a 22-bit ADC changes as follows:

$$\text{Resolution}_{\text{22-bit}} = \frac{5}{2^{22}} = \frac{5}{4194304} \approx 1.192\,\mu\text{V}$$

With a resolution of 1.192 μV, the system becomes more robust to noise compared to the previous 0.787 μV resolution. This makes it easier to detect the 300 μV voltage change caused by a 0.2°C temperature variation.

The built-in 12-bit ADC of the ESP32 provides a theoretical resolution of 0.8 mV per step. However, for applications requiring high precision, such as RTD temperature measurements, it may be necessary to use an external, high-resolution ADC to achieve more stable and accurate results.

Conclusion

Voltage Divider Method:

- Simple and cost-effective approach for measuring RTD resistance.
- Sensitive to variations in excitation voltage and RTD non-linearities.
- Prone to noise interference, which can degrade the measurement quality.

Wheatstone Bridge Method:

- Improves sensitivity by using differential voltage measurement.
- Requires precision resistors and is susceptible to environmental factors and power supply noise.

Delta-Sigma ADC Integration:

- Enhances precision with oversampling and noise shaping.
- Achieves resolutions finer than those of the ESP32's 12-bit ADC.

Comparison Summary

Feature	Voltage Divider	Wheatstone Bridge	22-bit $\Delta\Sigma$ ADC
Sensitivity	Low	Moderate	High
Noise Tolerance	Poor	Moderate	High (with noise shaping)
Hardware Complexity	Minimal	Moderate	High
Resolution (300 µV Change)	Marginal	Good	Excellent
Limitations	Non-linearities, noise	Precision resistors, noise	Noise sensitivity, complexity

- The RTD sensor provides accurate temperature measurements for various applications.
- The ESP32 microcontroller enables efficient data acquisition and processing.
- Real-time display of temperature on an OLED screen ensures easy monitoring.
- The system can be further optimized for better precision and portability.

Resources and Codes

All relevant resources and code implementations for the RTD project can be accessed at the following link:
Google Drive: RTD Resources and Codes

References

1. "ESP32 Pinout Diagram," ElectronicsHub. [Online]. Available: https://www.electronicshub.org/esp32-pinout/
2. "ESP32 ADC - Analog Read in Arduino IDE," Random Nerd Tutorials. [Online]. Available: https://randomnerdtutorials.com/esp32-adc-analog-read-arduino-ide/
3. "Voltage Measurement Using Arduino," Instructables. [Online]. Available: https://www.instructables.com/Voltage-Measurement-Using-Arduino/
4. "Introduction to RTD Signal Conditioning Circuits," All About Circuits. [Online]. Available: https://www.allaboutcircuits.com/technical-articles/introduction-to-rtd-signal-conditioning-circuits-voltage-di
5. "Resistance-temperature characteristics of RTD," GeeksforGeeks. [Online]. Available: https://www.geeksforgeeks.org/rtd/