Resistance Temperature Detector (RTD)

A
Project Report
Submitted in Fulfillment of the Requirements
for the
Completion of the course
ECS611: Introduction to MEMS

by

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1 Introduction

Resistance Temperature Detectors (RTDs) are widely used for temperature measurement due to reliability, precision, and linear response to temperature changes. This project focuses on designing a simple and affordable RTD-based temperature sensing system using the ESP32 microcontroller.

The system is built around an RTD sensor whose resistance varies with temperature. To ensure accurate readings, a signal conditioning circuit is used to be used to better amplify and process the RTD's output. The ESP32 microcontroller handles data acquisition and displays the measured temperature in real-time on a OLED screen. For initial testing, a potentiometer is used to simulate the RTD's behavior and validate the system's functionality before integrating the actual sensor.

2 Working Principle Of RTD

Working Principle of RTD

The working principle of a Resistance Temperature Detector (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:

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

where:

- R_T is the resistance at temperature T.
- R_0 is the resistance at a reference temperature T_0 (commonly $0°C$).
- α and β are temperature coefficients specific to the metal used in the RTD element.

For practical applications, the higher-order terms (β, etc.) are often negligible within a limited temperature range, simplifying the equation to:

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

In operation, the RTD is placed in contact with the object or medium whose temperature is to be measured. A precise current is passed through the RTD, and the voltage drop across it is measured. Using Ohm's law ($R = V/I$), the resistance is calculated, and the corresponding temperature is determined from the resistance-temperature relationship.

An RTD is a passive device. External electronic devices are used to measure the resistance of the sensor by passing a small electrical current through the sensor to generate a voltage. Typically 1 mA or less measuring current, 5 mA maximum without the risk of self-heating.

RTDs typically use platinum. Platinum remains stable over a wide operating temperature range, typically from $-200°C$ to $850°C$. It exhibits high linearity, with its resistance changing predictably with temperature, ensuring accurate measurements.platinum offers exceptional stability and repeatability over time, with minimal drift in resistance values, making it reliable for long-term use. Its low susceptibility to corrosion enhances its durability, even in harsh environments. The high resistivity of platinum allows for the creation of smaller sensors without sacrificing sensitivity.

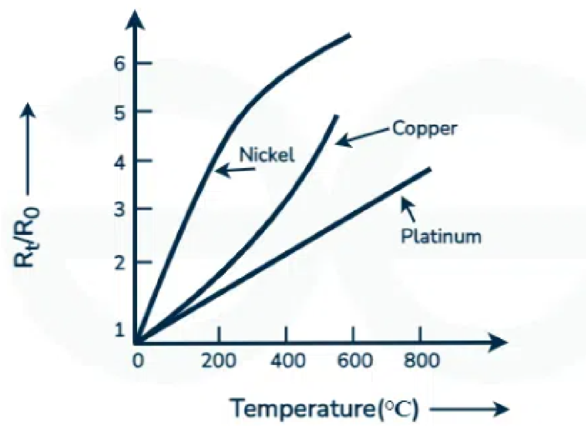

Figure 1: Resistance-temperature characteristics of Ni, Cu and Pt[22].

When the RTD is subjected to a change in temperature, its resistance varies accordingly. This change is detected using a voltage divider, Wheatstone bridge circuit, or by the use of Sigma-Delta Convertor.

3 Components

3.1 Hardware Components

- **RTD Sensor:** RTD Sensor made in the lab for accurate temperature sensing.
- **Potentiometer:** Simulates the RTD resistance during initial testing.
- **ESP32 Microcontroller-WROOM:** For data acquisition, processing, and display.
- **Resistors:** Used for signal conditioning and stabilization.
- **SSD1306 0.96 inch I2C OLED Display:** Displays the temperature in real-time.
- **Power Supply:** USB power or a 3.3V power source for the circuit.
- **Wires and Breadboard:** For circuit assembly and testing.

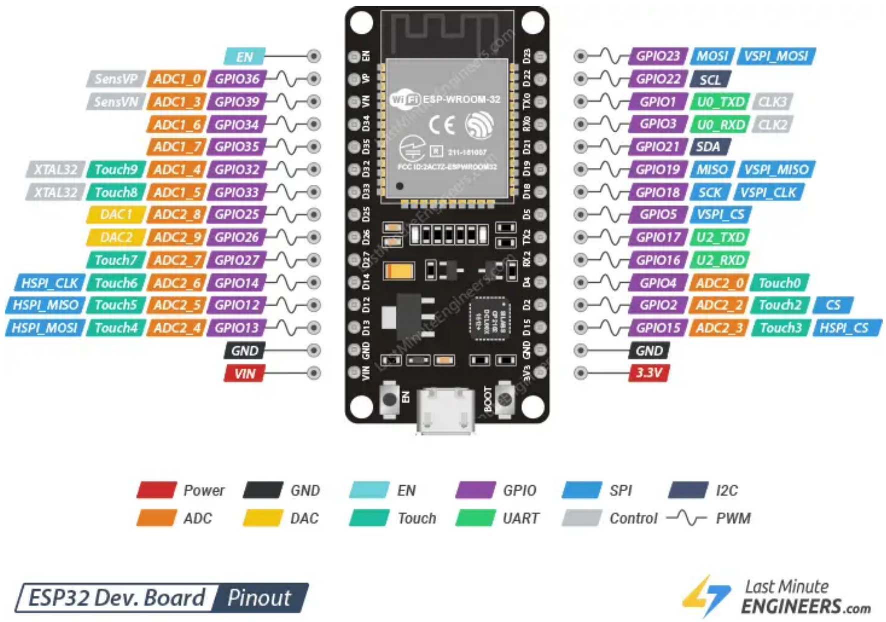

Figure 2: Pinout diagram of the ESP32 WROOM module

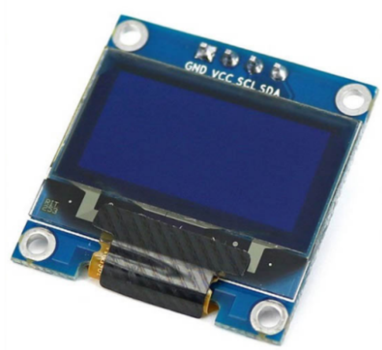

Figure 3: 0.96 Inch I2C OLED Display

3.2 Software Requirements

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

ESP32 ADC Resolution

The ESP32 features built-in Analog-to-Digital Converters (ADCs) with a maximum resolution of 12 bits. This means the input voltage range is divided into $2^{12} = 4096$ discrete levels.

Voltage Range and ADC Resolution

The ESP32 ADC typically operates over a voltage range from 0V to 3.3V. Given a 12-bit ADC, the minimum detectable voltage change, also known as the Least Significant Bit (LSB), is calculated as:

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

Configurable Resolution

The ESP32's ADC can be configured for lower resolutions, such as 9-bit, 10-bit, or 11-bit, depending on the application's need for faster sampling or reduced precision requirements. However, 12-bit is the maximum resolution.

Limitations of the Built-in ADC

While the 12-bit resolution provides a theoretical step size of 0.8 mV, the actual performance of the ESP32's ADC may be affected by several factors:

- **Non-linearity**: The ADC readings may not be perfectly linear across the full voltage range, which may require calibration.
- **Noise**: Electrical noise can affect ADC performance, especially when Wi-Fi or Bluetooth are used simultaneously.
- **Input Impedance**: The ADC has a relatively high input impedance, so the accuracy may degrade if the signal source impedance is too high.
- **Reference Voltage Stability**: Variations in the ESP32's power supply voltage can affect ADC accuracy.

4 RTD Sensor Fabrication Steps

These steps are provided just for information(I have not fabricated the device)

Substrate Preparation:

The fabrication begins with a silicon (Si) wafer, which serves as the substrate.

Coating of Sacrificial Layer:

A thin layer of Poly-methyl methacrylate) (PMMA) is coated on the silicon substrate. This acts as the sacrificial layer for the process.

Deposition of Chromium (Cr) Layer:

A chromium layer is deposited over the PMMA using techniques such as sputtering. Chromium serves as an etch-resistant material for patterning.

Lithographic Patterning:

The chromium layer is patterned using e-beam lithography process to define the desired geometry on the surface.

Etching of PMMA Layer:

After patterning, the exposed PMMA layer is selectively etched using a suitable chemical etchant. This step ensures that the chromium layer above the PMMA remains intact, while the sacrificial material is removed in the patterned areas.

Deposition of Functional Layers:

A functional material (e.g., for sensor or MEMS applications) is deposited over the patterned structure. This material could be a metal, semiconductor, or dielectric, depending on the sensor's application. **Platinum** was the metal used in this case.

Lift-Off Process:

The PMMA sacrificial layer is dissolved or lifted off using a solvent such as acetone, leaving the chromium layer and the deposited functional material in the desired pattern.

Final Cleaning and Testing:

The sensor structure is cleaned thoroughly to remove any residual materials and then subjected to testing and characterization.

5 Circuit Design

Explored two methods for measuring the resistance variations in an RTD sensor: the **Voltage Divider** and the **Wheatstone Bridge**. A potentiometer is used in place of the sensor to mimic its performance for the preliminary framework. The ciruit connection is made according to the pin-out of ESP 32. The pins of OLED are connected to ESP 32 as specified in the pinout. The following pins are used in the measurement setup:

- **D34 (GPIO34)**: This pin is used as the analog input to measure the voltage. In this setup, it is connected to the external voltage source whose signal we wish to measure.
- **3.3V Pin**: The ESP32 provides a 3.3V excitation voltage, which can be used as the reference voltage for the ADC.

- **GND Pin**: This is the ground pin, which is connected to the ground of the external circuit.

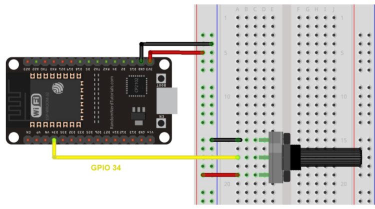

Figure 4: Voltage Measurement Circuit using ESP32-WROOM

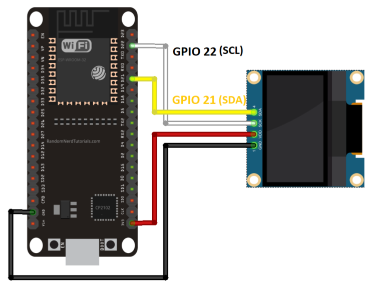

Figure 5: I2C OLED and ESP32-WROOM interfacing

5.1 Using a Voltage Divider for RTD Measurement

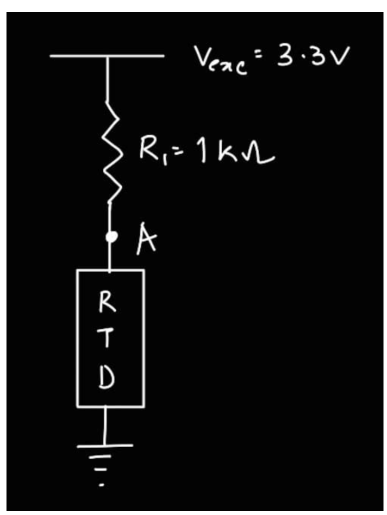

Figure 6: Voltage Divider for RTD Measurement

A simple and effective approach to measure the resistance variations of an RTD is by utilizing a **resistive voltage divider** circuit. We measure at A and Ground parallelly across the RTD.

The basic principle behind a voltage divider is to convert the RTD's resistance changes into a corresponding voltage signal, which can then be measured by the microcontroller.

The ESP32 provides an excitation voltage of $V_{exc} = 3.3\,\mathrm{V}$. The output voltage at node A can be expressed as:

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

where:

- R_{RTD}: Resistance of the RTD (or the equivalent resistance of the potentiometer in our case).
- $R_1 = 1000\Omega$: Fixed resistor in the voltage divider circuit
- $V_{exc} = 3.3\,\mathrm{V}$: Excitation voltage.

Assuming the nominal resistance of the RTD at 0°C is $1000\,\Omega$ and it increases by $4\,\Omega/°\mathrm{C}$, 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:

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

to:

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

The change in voltage is:

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

To resolve this voltage change, the analog-to-digital converter (ADC) must have a resolution capable of detecting $330\,\mu\mathrm{V}$ within the range of $3.3\,\mathrm{V}$. The noise-free counts required are:

$$\text{Noise-Free Counts} = \frac{3.3}{330 \times 10^{-6}} \approx 10000$$

This corresponds to a noise-free resolution of:

$$\log_2(10000) \approx 13.29\,\text{bits}$$

With modern delta-sigma ($\Delta\Sigma$) ADCs, achieving a resolution of 14 bits or higher is feasible. Thus, the voltage divider circuit can effectively be used for RTD measurements when paired with a suitable ADC. We will see in further section how a sigma-delta converter can be used for an RTD.

Limitations of the Voltage Divider

While the voltage divider approach is simple and cost-effective, it is sensitive to variations in V_{exc} and non-linearities in the RTD characteristics. Furthermore, the accuracy of this method depends on the stability and tolerance of R_1 and the ADC's ability to resolve small voltage changes. We also need to take care of how the noise affects the readout circuit.

5.2 Wheatstone Bridge Implementation

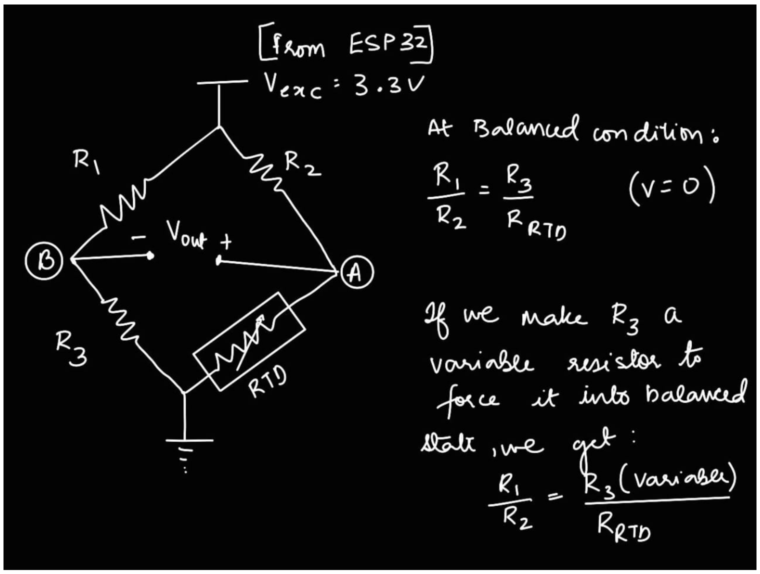

Figure 7: Wheatstone Bridge for RTD Measurement

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.

Balanced Bridge at Reference Temperature:

When the Wheatstone Bridge is balanced, the voltage difference across the bridge (V_{out}) is zero i.e., $V_{out} = V_A - V_B = 0.$. This occurs when the resistances of R_1, R_2, and R_3 are chosen such that the bridge is in a balanced state. The resistance of R_4 (the RTD) is also at its reference value at a known temperature, usually $0°C$ or $25°C$. The balanced condition is given by:

$$V_{out} = 0 \quad \text{when} \quad R_1 = R_2 \quad \text{and} \quad R_3 = R_4$$

Imbalance due to Temperature Change:

When the resistance of the RTD (R_{RTD}) changes, the bridge becomes unbalanced, producing a nonzero output voltage (V_{out}), which is proportional to the change in resistance of the RTD and can be used to calculate temperature variations.

$$R_RTD(T) = R_0\,(1 + \alpha T)$$

At 0°C, the resistance of the RTD is $1000\,\Omega$. As the temperature increases, the resistance of the RTD increases by $4\,\Omega/C$, so at 0.2°C, the RTD resistance is $R_{RTD} = 1000 + (4 \times 0.2) = 1000.8\,\Omega$.

The voltage at node A (V_A) is calculated as:

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

Substituting $R_{RTD} = 1000.8\,\Omega$, $R_1 = 1000\,\Omega$, and $V_{exc} = 3.3\,\text{V}$, we get:

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

The voltage at node B (V_B) is calculated as:

$$V_B = \frac{R_3}{R_3 + R_2} \times V_{exc} = \frac{1000}{1000 + 1000} \times 3.3 = 1.65\,\text{V}$$

The output voltage (V_{out}) is:

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

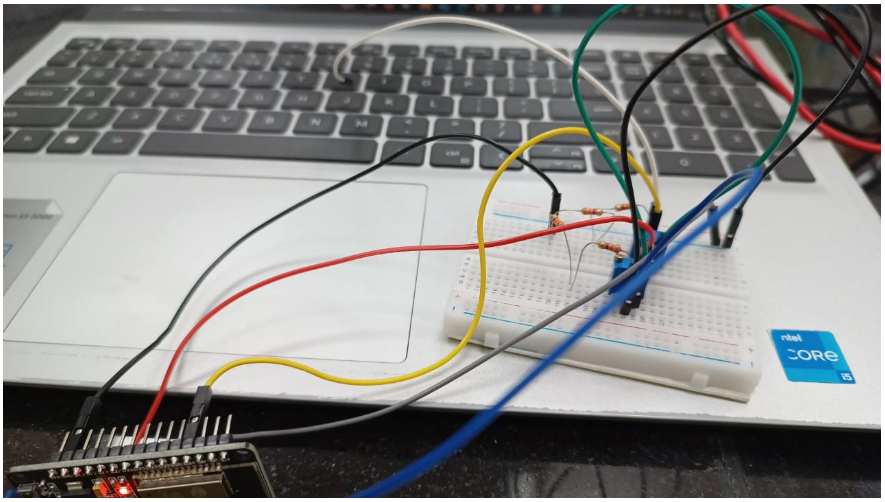

Figure 8: Wheatstone Bridge implementation

This small voltage change can be measured using the ESP32's analog-to-digital converter (ADC), providing a direct measurement of temperature variation but it is not tolerant to noise and non-linearity. The Wheatstone bridge offers higher sensitivity compared to the simple voltage divider method. This measuremnts can be improved even more by the use of Sigma-Delta Converters.

The ESP 32 and the voltmeter readout circuit verification have a consistent 0.2V difference.

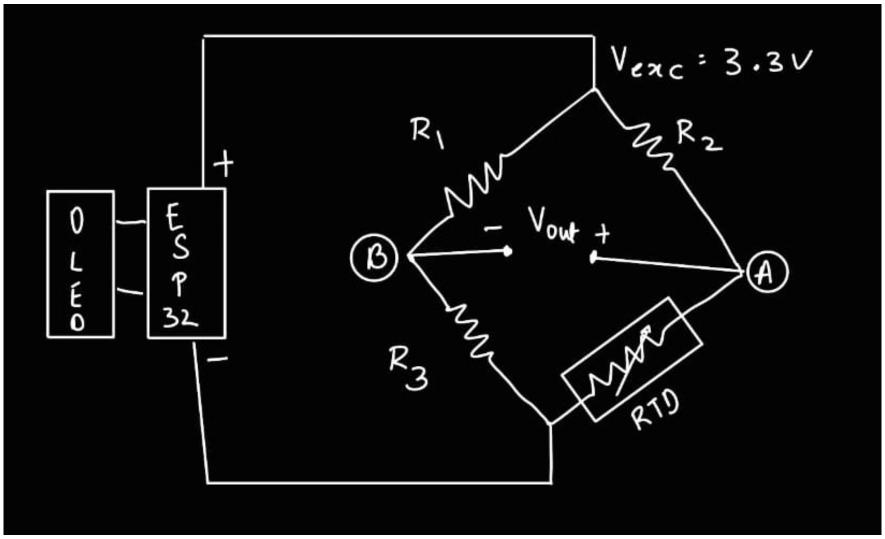

Figure 9: Wheatstone Bridge for RTD Measurement

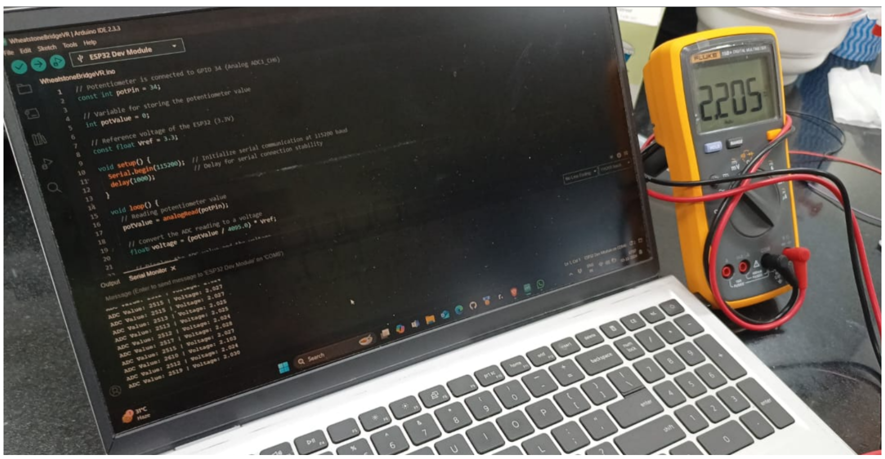

Figure 10: Readout Circuit Verification for Wheatstone Bridge Implementation

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.

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

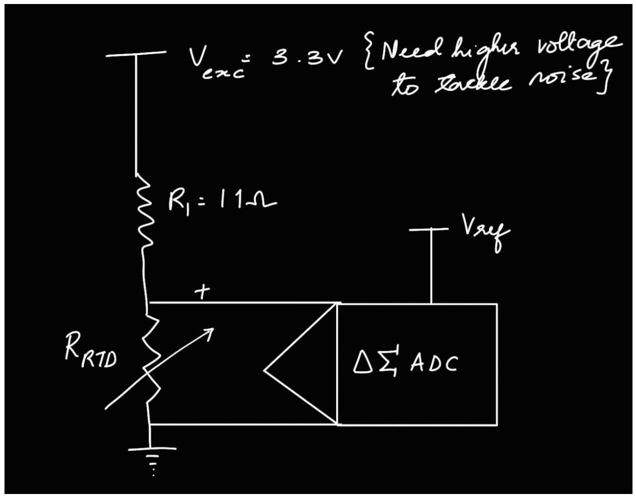

Figure 11: Delta-Sigma Converter for RTD Measurement

While the Wheatstone bridge setup provides a precise measurement of RTD resistance, the measurement accuracy can be further improved by using a higher-resolution analog-to-digital converter (ADC), such as a 22-bit Delta-Sigma ($\Delta\Sigma$) ADC. A $\Delta\Sigma$ ADC provides high-resolution digital output by oversampling and applying noise shaping techniques. This method is particularly suitable for measuring small voltage changes, such as those generated by RTDs, enabling highly precise temperature measurements.

In the previous Wheatstone bridge setup, we observed that a temperature change of 0.2°C led to a voltage change of approximately 300 μV. To resolve such small changes more accurately, we need a higher-resolution ADC than the 12-bit ADC provided by the ESP32. A 22-bit $\Delta\Sigma$ ADC offers significantly higher resolution, allowing for more precise measurements of the small voltage variations produced by the RTD.

6.1 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.

6.2 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 $V_{exc} = 3.3\,\text{V}$, and the output voltage change for a small temperature change of 0.2°C is approximately $\Delta V_{out} = 300\,\mu\text{V}$.

6.2.1 12-bit ADC Resolution

The resolution of a 12-bit ADC can be calculated as:

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

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.

6.2.2 22-bit ADC Resolution

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.But 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. By averaging many measurements, random noise tends to cancel out, while the actual signal (i.e., temperature-induced changes) remains constant. This approach improves the accuracy of the measurement, making it more robust to noise.

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. A low-pass filter allows the slow-changing signal (temperature-induced voltage change) to pass through while attenuating high-frequency noise. This helps to clean up the signal and makes it easier to detect temperature variations without interference from noise.

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. While increasing the excitation voltage will make the ADC resolution more relevant, the RTD characteristics must be carefully considered to avoid exceeding the maximum voltage limits of the ADC. Also, the RTD's behavior might change at higher excitation voltages. 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.

7 Conclusion

Voltage Divider Method: The voltage divider is a simple and cost-effective approach for measuring RTD resistance. However, it is sensitive to variations in excitation voltage (V_{exc}) and RTD non-linearities. The accuracy of this method is highly dependent on the tolerance of R_1 and the ADC's ability to resolve small voltage changes. Additionally, it is prone to noise interference, which can degrade the measurement quality.

Wheatstone Bridge Method: The Wheatstone bridge improves sensitivity by using differential voltage measurement to amplify small variations in RTD resistance. At the reference temperature, the bridge is balanced ($R_1 = R_2$ and $R_3 = R_4$), resulting in zero output voltage ($V_{\text{out}} = 0$). When the RTD resistance changes, the bridge becomes unbalanced, producing an output voltage proportional to the resistance change. For example, at 0.2°C, the RTD resistance ($R_{\text{RTD}} = 1000.8\,\Omega$) creates $V_{\text{out}} = 300\,\mu\text{V}$, which is measurable by the ESP32 ADC. While this method enhances signal-to-noise ratio compared to the voltage divider, it requires precision resistors and is susceptible to environmental factors and power supply noise.

Delta-Sigma ADC Integration: The integration of a high-resolution 22-bit $\Delta\Sigma$ ADC significantly enhances the precision of RTD measurements. By oversampling and applying noise shaping, $\Delta\Sigma$ ADCs achieve resolutions much finer than those of the ESP32's 12-bit ADC. For instance:

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

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

This allows precise detection of small RTD-induced voltage changes, such as $300\,\mu$V for $0.2°$C. However, the increased resolution also amplifies noise sensitivity. Strategies to mitigate noise include averaging multiple samples, applying low-pass filtering, and increasing V_{exc} (e.g., $V_{exc} = 5\,$V improves resolution to $1.192\,\mu$V).

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 Wheatstone bridge improves sensitivity and noise immunity compared to the voltage divider, while a 22-bit $\Delta\Sigma$ ADC delivers unmatched precision. Combining the Wheatstone bridge with a $\Delta\Sigma$ ADC results in a high-performance RTD measurement system capable of robust and accurate temperature sensing in noisy environments.

8 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

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