Department of Electronic and Telecommunication Engineering

University of Moratuwa, Sri Lanka

**EN3533 - ELECTRONIC INSTRUMENTATION**

# *Instrumentation Amplifier for Thermo-couple*

## Group Members


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# Contents

## 0.1 *Introduction*

In this project, we have designed an ***Instrumentation amplifier*** specifically tailored for thermocouple applications. The report provides a comprehensive overview, including basic information about thermocouples and instrumentation amplifiers. It outlines the meticulous design process, encompassing component selection, amplifier configuration, and testing procedures employed to achieve accurate amplification of thermoelectric signals. The report also includes detailed schematics, PCB layouts, and insights into the amplifier selection process, offering readers a holistic understanding of the project.

### 0.1.1 Thermocouples and applications

Thermocouples are temperature sensors widely used in various industrial, scientific, and commercial applications due to their reliability and simplicity. Operating principle of thermocouples based on the Seebeck effect, where a temperature difference between two dissimilar metals generates a voltage proportional to the temperature change. The subtopic covers different types of thermocouples, such as **K-type, J-type,** and **T-type**, each suited for specific temperature ranges and environments.

Real-world applications of thermocouples are explored, ranging from industrial processes and HVAC systems to aerospace and scientific research. Detailed examples illustrate how thermocouples are utilized in diverse settings, showcasing their adaptability and effectiveness in measuring temperatures under varying conditions.

### 0.1.2 Introduction to Instrumentation amplifiers

Instrumentation amplifiers (In-amps) are specialized operational amplifiers (op-amps) designed to amplify small signals with high precision and accuracy, particularly in noisy environments. Unlike general-purpose op-amps, instrumentation amplifiers are specifically engineered for applications where signal integrity is critical, such as in sensor measurements and data acquisition systems.

What sets instrumentation amplifiers apart is their ability to provide high input impedance, high common-mode rejection ratio (CMRR), and low output impedance. These characteristics make them ideal for amplifying weak signals while rejecting common-mode noise, ensuring that the amplified output accurately represents the desired signal.

Instrumentation amplifiers typically consist of multiple operational amplifiers and precision resistors configured in specific ways to achieve high performance. They offer differential inputs, allowing the amplification of the voltage difference between two input signals. In-amps are commonly used in various fields, including industrial automation, medical instrumentation, and scientific research, where accurate measurement of small signals is crucial.

### 0.1.3 Need for an INAMP in thermo-couple applications

In thermocouple-based applications, accurate temperature measurement is paramount. Thermocouples generate small voltage signals proportional to temperature changes, which are susceptible to interference and noise. Instrumentation amplifiers play a crucial role by precisely amplifying these weak signals while **rejecting common-mode noise**. Their **high input impedance** and excellent **common-mode rejection** properties ensure the fidelity of temperature readings, making them indispensable in thermocouple circuits. By enhancing signal integrity, instrumentation amplifiers enable reliable and precise temperature measurements, making them essential components in thermocouple-based systems used across various industries and scientific research.

## 0.2 *Thermo-couple Specifications*

### 0.2.1 Operating Principles and Parameters

A thermocouple is a device made by two different wires joined at one end, called junction end or measuring end. The two wires are called thermoelements or legs of the thermocouple: the two thermoelements are distnguished as positive and negative ones. The other end of the thermocouple is called tail end or reference end (Figure1). The junction end is immersed in the enviroment whose temperature T2 has to be measured, which can be for instance the temperature of a furnace at about 500°C, while the tail end is held at a different temperature T1, e.g. at ambient temperature.

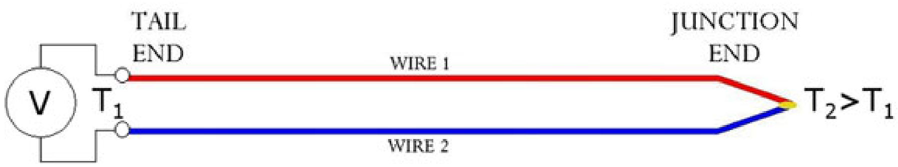


Figure 1: Schematic drawing of a thermo-couple

Because of the temperature difference between junction end and tail end a voltage difference can be measured between the two thermoelements at the tail end: so the thermocouple is a ***temperature-voltage transducer***.

However, it can be understood that the Emf depends on both T1 and T2: as T1 and T2 can change indipendently, a monotonic Emf vs T2 relationship cannot be defined if the tail end temperature is not constant. For this reason the tail end is mantained in an ice bath made by crushed ice and water in a Dewar flask: this produces a reference temperature of 0°C. All the voltage versus temperature relationships for thermocouples are referenced to 0°C. In a thermo-couple, measuring end is called as **Hot junction** and the tail end (reference junction) is called as **Cold junction**.

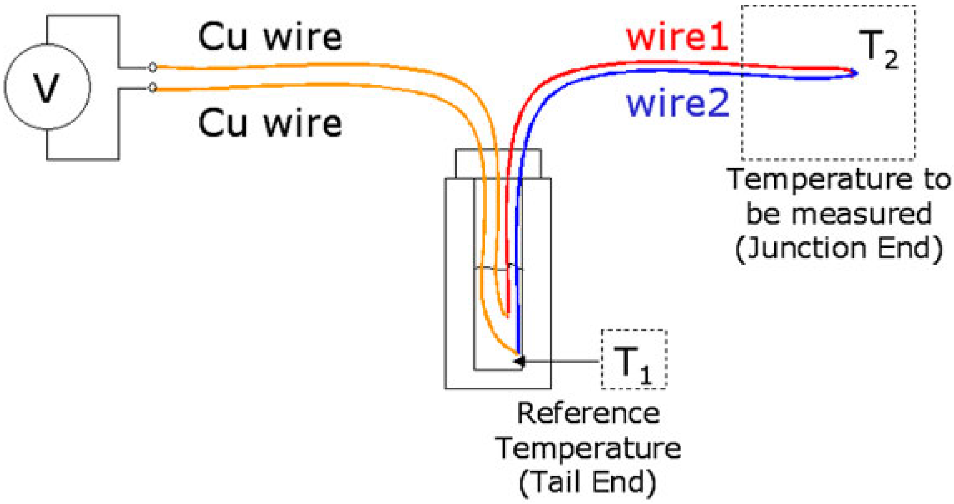


Figure 2: Thermo-couple with Cold junction

### 0.2.2 Output voltage of a thermo-couple

Induced voltage **E** due to temperature at hot junction $\theta$ have the following relationship,

$$E(\theta) = A\theta + B\theta^2 + C\theta^3 + \ldots$$

However, usually coefficients of higher order terms are very small.

In practice, we can get the voltage value at each temperature using temperature - voltage tables. Usually these tables are defined when the cold junction (Reference junction) is at **0**°C.

**K°C**

**TABLE 9** ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

Thermoelectric Voltage in Millivolts

| °C | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | °C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -270 | -6.458 | | | | | | | | | | | -270 |
| -260 | -6.441 | -6.444 | -6.446 | -6.448 | -6.450 | -6.452 | -6.453 | -6.455 | -6.456 | -6.457 | -6.458 | -260 |
| -250 | -6.404 | -6.408 | -6.413 | -6.417 | -6.421 | -6.425 | -6.429 | -6.432 | -6.435 | -6.438 | -6.441 | -250 |
| -240 | -6.344 | -6.351 | -6.358 | -6.364 | -6.370 | -6.377 | -6.382 | -6.388 | -6.393 | -6.399 | -6.404 | -240 |
| -230 | -6.262 | -6.271 | -6.280 | -6.289 | -6.297 | -6.306 | -6.314 | -6.322 | -6.329 | -6.337 | -6.344 | -230 |
| -220 | -6.158 | -6.170 | -6.181 | -6.192 | -6.202 | -6.213 | -6.223 | -6.233 | -6.243 | -6.252 | -6.262 | -220 |
| -210 | -6.035 | -6.048 | -6.061 | -6.074 | -6.087 | -6.099 | -6.111 | -6.123 | -6.135 | -6.147 | -6.158 | -210 |
| -200 | -5.891 | -5.907 | -5.922 | -5.936 | -5.951 | -5.965 | -5.980 | -5.994 | -6.007 | -6.021 | -6.035 | -200 |
| -190 | -5.730 | -5.747 | -5.763 | -5.780 | -5.797 | -5.813 | -5.829 | -5.845 | -5.861 | -5.876 | -5.891 | -190 |
| -180 | -5.550 | -5.569 | -5.588 | -5.606 | -5.624 | -5.642 | -5.660 | -5.678 | -5.695 | -5.713 | -5.730 | -180 |
| -170 | -5.354 | -5.374 | -5.395 | -5.415 | -5.435 | -5.454 | -5.474 | -5.493 | -5.512 | -5.531 | -5.550 | -170 |
| -160 | -5.141 | -5.163 | -5.185 | -5.207 | -5.228 | -5.250 | -5.271 | -5.292 | -5.313 | -5.333 | -5.354 | -160 |
| -150 | -4.913 | -4.936 | -4.960 | -4.983 | -5.006 | -5.029 | -5.052 | -5.074 | -5.097 | -5.119 | -5.141 | -150 |
| -140 | -4.669 | -4.694 | -4.719 | -4.744 | -4.768 | -4.793 | -4.817 | -4.841 | -4.865 | -4.889 | -4.913 | -140 |
| -130 | -4.411 | -4.437 | -4.463 | -4.490 | -4.516 | -4.542 | -4.567 | -4.593 | -4.618 | -4.644 | -4.669 | -130 |
| -120 | -4.138 | -4.166 | -4.194 | -4.221 | -4.249 | -4.276 | -4.303 | -4.330 | -4.357 | -4.384 | -4.411 | -120 |
| -110 | -3.852 | -3.882 | -3.911 | -3.939 | -3.968 | -3.997 | -4.025 | -4.054 | -4.082 | -4.110 | -4.138 | -110 |
| -100 | -3.554 | -3.584 | -3.614 | -3.645 | -3.675 | -3.705 | -3.734 | -3.764 | -3.794 | -3.823 | -3.852 | -100 |
| -90 | -3.243 | -3.274 | -3.306 | -3.337 | -3.368 | -3.400 | -3.431 | -3.462 | -3.492 | -3.523 | -3.554 | -90 |
| -80 | -2.920 | -2.953 | -2.986 | -3.018 | -3.050 | -3.083 | -3.115 | -3.147 | -3.179 | -3.211 | -3.243 | -80 |
| -70 | -2.587 | -2.620 | -2.654 | -2.688 | -2.721 | -2.755 | -2.788 | -2.821 | -2.854 | -2.887 | -2.920 | -70 |
| -60 | -2.243 | -2.278 | -2.312 | -2.347 | -2.382 | -2.416 | -2.450 | -2.485 | -2.519 | -2.553 | -2.587 | -60 |
| -50 | -1.889 | -1.925 | -1.961 | -1.996 | -2.032 | -2.067 | -2.103 | -2.138 | -2.173 | -2.208 | -2.243 | -50 |
| -40 | -1.527 | -1.564 | -1.600 | -1.637 | -1.673 | -1.709 | -1.745 | -1.782 | -1.818 | -1.854 | -1.889 | -40 |
| -30 | -1.156 | -1.194 | -1.231 | -1.268 | -1.305 | -1.343 | -1.380 | -1.417 | -1.453 | -1.490 | -1.527 | -30 |
| -20 | -0.778 | -0.816 | -0.854 | -0.892 | -0.930 | -0.968 | -1.006 | -1.043 | -1.081 | -1.119 | -1.156 | -20 |
| -10 | -0.392 | -0.431 | -0.470 | -0.508 | -0.547 | -0.586 | -0.624 | -0.663 | -0.701 | -0.739 | -0.778 | -10 |
| 0 | 0.000 | -0.039 | -0.079 | -0.118 | -0.157 | -0.197 | -0.236 | -0.275 | -0.314 | -0.353 | -0.392 | 0 |
| 0 | 0.000 | 0.039 | 0.079 | 0.119 | 0.158 | 0.198 | 0.238 | 0.277 | 0.317 | 0.357 | 0.397 | 0 |
| 10 | 0.397 | 0.437 | 0.477 | 0.517 | 0.557 | 0.597 | 0.637 | 0.677 | 0.718 | 0.758 | 0.798 | 10 |
| 20 | 0.798 | 0.838 | 0.879 | 0.919 | 0.960 | 1.000 | 1.041 | 1.081 | 1.122 | 1.163 | 1.203 | 20 |
| 30 | 1.203 | 1.244 | 1.285 | 1.326 | 1.366 | 1.407 | 1.448 | 1.489 | 1.530 | 1.571 | 1.612 | 30 |
| 40 | 1.612 | 1.653 | 1.694 | 1.735 | 1.776 | 1.817 | 1.858 | 1.899 | 1.941 | 1.982 | 2.023 | 40 |

Figure 3: Temperature Vs Voltage table of a K type thermo-couple

### 0.2.3 Selection of a thermo-couple

For our design, we have selected **K Type thermo-couple** due to its wide range of temperatures. One of the major advantage of K type thermocouple over other thermocouple's is it can function in rugged environmental condition & in various atmospheres. Two wires of K type thermocouple are made from Alumel and Chromel alloys.

Another major importance is output voltage of K type thermocouple is almost linear with the temperature. **(Linearity)**

**Specifications of K type thermo-couple**

- Temperature Range - 0 to 1300°C (Can be used for negative temperatures also)
- Output voltage - 0 to 55 mV
- Sensitivity - Approximately $41\mu V/$°C

## 0.3 *Instrumentation Amplifiers*

Instrumentation amplifiers (Referred as **IN-AMP**) are specialized operational amplifiers that play a pivotal role in enhancing the accuracy and reliability of thermocouple measurements. By precisely amplifying weak thermoelectric signals while rejecting common-mode noise, these amplifiers ensure the fidelity of temperature data.

### 0.3.1 Operation of IN-AMPS

Three operational amplifiers (Op-Amps) and a number of precisely arranged resistors are needed to operate an instrumentation amplifier in order to produce the required amplification characteristics. An IN-AMP typically has three stages in its configuration:

- **Differential Amplifier Stage:** Two inputs receive the input signal differently. An initial differential amplifier that amplifies the voltage difference between these inputs is typically used in the first stage.

- **Buffer Stages:** After the differential amplifier are two buffer amplifiers, which are frequently constructed using operational amplifiers. Gain adjustment, low output impedance, and high input impedance are all made possible by these buffers. Additionally, they improve the overall performance by enabling the isolation of the gain-setting resistors from the source impedance.

- **Gain Control:** External precision resistors are usually used to set the gain of the IN-AMP and can be adjusted based on the needs of the application.

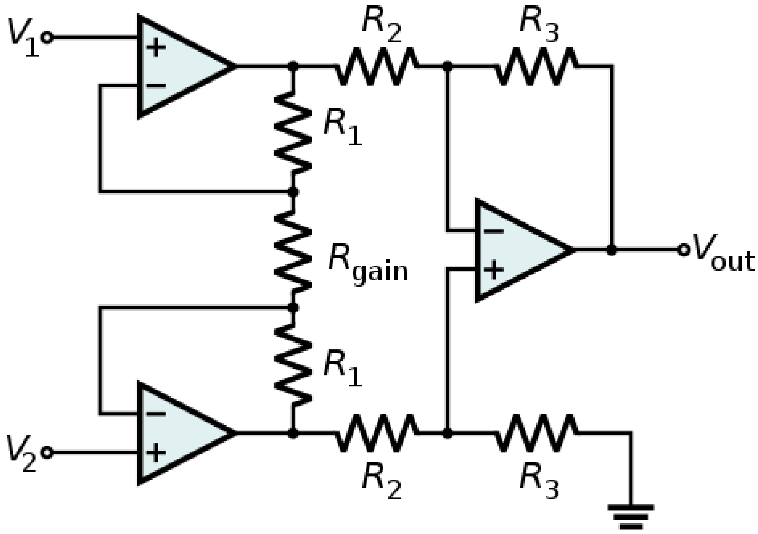


Figure 4: Basic Instrumentation amplifier

Since operational amplifiers normally have very high input impedance, two OP-amps at the input provides very high input impedance. Output voltage is given by ,

$$V_{out} = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2}$$

By adjusting the $R_{gain}$ properly, we can control the gain of the instrumentation amplifier.

### 0.3.2 Signal Conditioning using IN-AMP

Signal conditioning using instrumentation amplifiers (IN-AMPS) is a crucial aspect in various fields where precise signal manipulation is necessary to enhance the accuracy of measurements or sensor data.

- **Amplification and Gain Control**

  With their high differential gain and ability to precisely magnify the difference between two input signals, IN-AMPS are invaluable tools for amplifying weak signals. The simplicity of gain control, which is accomplished by using external resistors, is their main feature. Because of its adaptability, amplification can be customized to meet the needs of individual applications, guaranteeing accurate and regulated signal enhancement.

- **Noise Rejection**

  The remarkable ability of IN-AMPS to reject common-mode noise is a crucial component. They are excellent at reducing noise or interference that is equally present on both inputs while enhancing the differences between the input signals. This ability to reject noise is essential in applications where the signal of interest is frequently overshadowed by background noise.

- **Filtering and Conditioning**

  IN-AMPS can be easily combined with other circuitry to offer conditioning and filtering of signals. By combining resistors, capacitors, and filters, they effectively cut out undesirable frequencies and modify the circuit response to fit the particular requirements of the application.

- **High Input Impedance**

  Because of their high input impedance and low current consumption, IN-AMPS shield the signal source from loading effects. This quality guarantees precise measurements, which is critical in many applications where accuracy is critical.

- **Precision Measurements**

  IN-AMPS are essential for sensor data acquisition applications like strain gauges, temperature, pressure, and bio-signal monitoring. They precisely boost these tiny sensor signals, improving measurement accuracy and dependability.

- **Data Acquisition Systems**

  Before analog-to-digital conversion, signals gathered from a variety of sensors are conditioned by IN-AMPS, which are essential parts of data acquisition systems. Their involvement affects the dependability and quality of the collected data by guaranteeing the optimization of signals for precise and accurate digital representation.

### 0.3.3 Design requirements

In order to make our thermocouple measurement system effective and competitive, we looked at existing temperature controllers in the market. By understanding their features, we established specific design needs for our project. These requirements act as our project's foundation, guiding us to create a system that meets user expectations and industry standards. We mainly referred the ***Omoron temperature controllers datasheets*** to get an idea for design requirements.

Required Specifications for Instrumentation Amplifier

| Parameter | Value |
|---|---|
| Gain | ≈200(132) |
| CMMR | 100dB |
| Input impedance | ≈36 MΩ |
| Bandwidth | 1 Hz |
| Output voltage range | 0-5V |

Figure 5: Requirements for the IN-AMP

### 0.3.4 Selection of a IN-AMP for the design

For the selection of an instrumentation amplifier (IN-AMP) for our design project, each of our group members individually researched and identified several op-amp ICs. The ICs we considered for our project include the AD8495, AMP04, and INA821. To determine the best IC for our instrumentation amplifier, we established specific criteria and assigned marks to each IC based on those criteria. The table below summarizes the marks obtained by each IC.

## Selection criteria

1. Input voltage range
2. Output voltage range
3. Gain
4. Input Impedance
5. CMRR
6. Bandwidth

| | AD8495 | AMP04 | INA821 |
|---|---|---|---|
| Input voltage range | -Vs-0.2 to +Vs-1.6 | -Vs+3 to +Vs-3 | -Vs+2 to +Vs-2 |
| | **9** | **6** | **7** |
| Output voltage range | -Vs+0.025 to +Vs-0.1 | -Vs to +Vs | -Vs+0.15 to +Vs-0.15 |
| | 9 | 10 | 8 |
| Gain | 122.4 | 0 to 1000 | 0 to 10000 |
| | **8** | **9** | **9** |
| Input Impedance | 10 GΩ | 4 GΩ | 5 GΩ |
| | **9** | **6** | **7** |
| CMRR | 100 dB | Depends on gain<br>Min=80 , Max=105 | 112 dB |
| | **8** | **7** | **9** |
| Bandwidth | 25kHz | 700 kHz | 100 kHz |
| | **7** | **9** | **8** |
| Total Marks | 50 | 47 | 48 |

Figure 6: Selection criteria for IN-AMP selection

## Grounding and Shielding recommendations

In order to select the best IC for our design, we also considered the grounding and shielding recommendations given in the datasheet of each IC. By adhering to these guidelines, we can confidently anticipate optimal performance, minimal interference, and overall reliability in our final design.

| **Criterion** | ***AD8495*** | ***AMP04*** | ***INA821*** |
|---|---|---|---|
| **Grounding** | Given properly with diagrams, Single ground is suffient at input to avoid ground loops. | Not properly mentioned | Provided proper component placement. But no much detail about grounding practices. |
| **Shielding** | Ground planes and power planes have been used in layouts. | Recommends to use shielded cables at input , twisted pairs | Recommends to keep proper trace spaces |
| **Recommend Layouts** | Evaluation board for the IC are available by same manufacturer. It can be used as reference. | Not given | Provided recommend layout practices and component placement guidline |
| **Marks** | **9** | **5** | **8** |

Table 1: Selection criteria for IN-AMP selection

By considering the Marks allocated in the selection Matrix and the best grounding and shielding methods given in the datasheets, **AD8495** is the selected best Instrumentation amplifier for our thermocouple application.

## 0.4 *Design Process*

In the Design Process section, we outline the systematic approach undertaken to create our thermocouple measurement system. Above established guidelines and considering the specific requirements of the selected thermocouple and instrumentation amplifier, this phase focused on meticulous schematic design and precise PCB layout. By adhering to these guidelines, our team ensured the integration of key components for accurate and reliable temperature measurements. For the Schematic and PCB design, we used **Altium PCB designer** software.

### 0.4.1 Schematic Design

In the schematic design, our focus was on translating theoretical concepts into a practical and functional circuit. Guided by the unique requirements of our selected thermocouple and instrumentation amplifier.

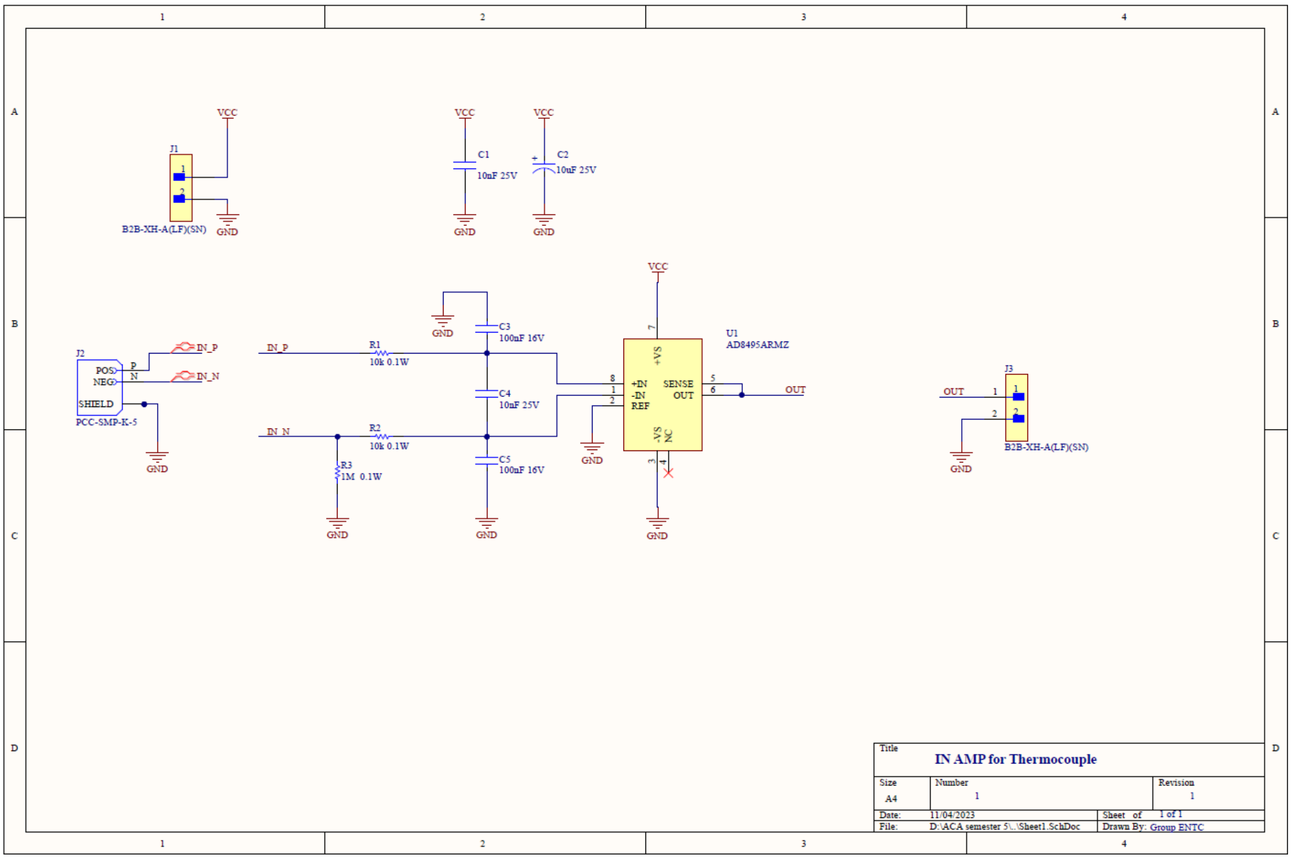


Figure 7: Schematic design for the IN-AMP

#### Component description and Signal flow

- **J1** - Power connector (JST 2 pin connector)
- **J2** - Thermo-couple connector with ground connection for shielding
- **J3** - Output connector (JST 2 pin connector)

Nets assigned for **J3** input pins are defined as **Differential inputs** to ensure the both PCB tracks of positive and negative input are equal length.

In **AD8495** instrumentation amplifier data sheet, they have provided the recommend schematic for basic applications of the IC.

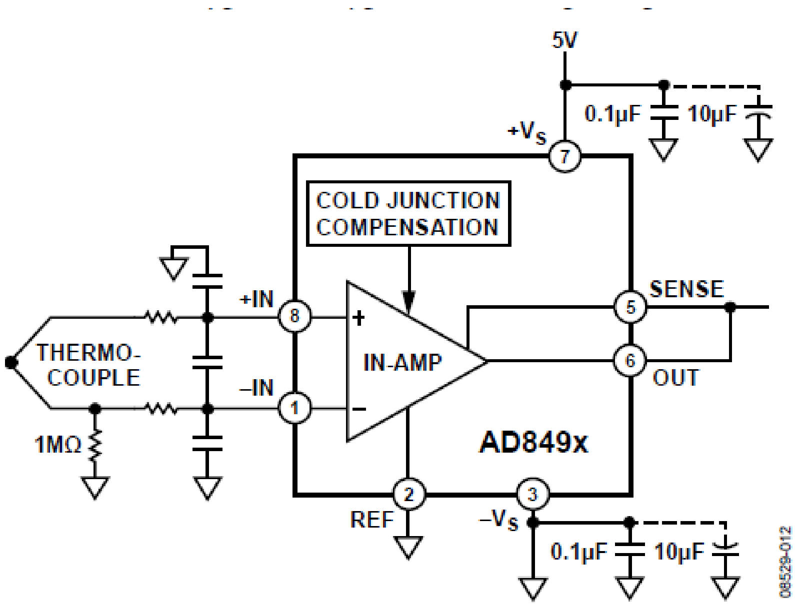


Figure 8: Basic connection given in data sheet of AD8495 IC

**C1** and **C2** are coupling capacitors to clean power supply voltage at **+Vs** pin of AD8495. **R1,R2,C3,C4** and **C5** at the input perform a filtering operation to filter out the common mode and differential mode noise at the input.

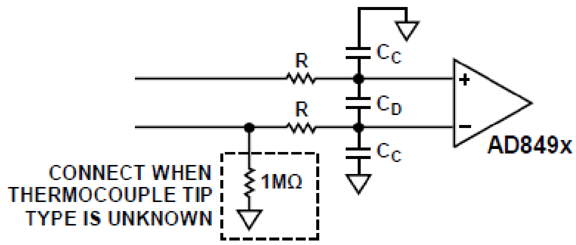


Figure 9: Filters at the input

When we set $R1 = R2 = R$ and $C3 = C5 = C_c$ and $C4 = C_D$ , filter frequencies are given by ,

$$f_{DIFF} = \frac{1}{2\pi R(2C_D + C_c)}$$

and ,

$$f_{CM} = \frac{1}{2\pi RC_c}$$

where $C_D \geq 10C_c$ .

**R3** is a $1M\Omega$ resistor which is connected to negative input of the thermo-couple connector and ground. It helps to detect any thermo-couple breakdown condition by putting the output to rail high in an open thermocouple condition.

Output voltage of the circuit has a sensitivity of **5mV/°C** and it is given by,

$$V_{OUT} = (T_{MJ} \times 5mV/°\text{C}) + V_{REF}$$

where $T_{MJ}$ is the measuring junction temperature in Celsius and $V_{REF}$ is the voltage at Reference pin of AD8495. We have grounded the reference pin.

### Internal structure of AD8495

AD8495 includes a 3 op amp configuration described in the section Instrumentation Amplifiers with temperature sensing unit for cold junction compensation. $R_G$, gain adjustment resistor is fixed internally as in the block diagram, so it has a **fixed gain of 122dB**.

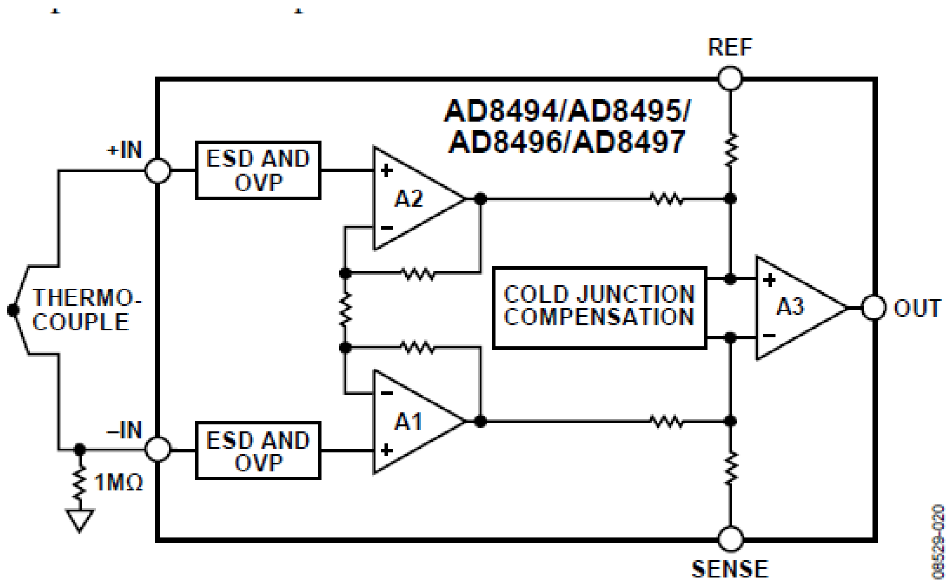


Figure 10: Block diagram of AD8495

### 0.4.2 PCB Design

In the PCB Design section, we outline the meticulous process of translating our circuit schematic into a physical, manufacturable board. Guided by the principles of signal integrity, noise reduction, and shielding techniques. We have designed a **two layer PCB** of **22mm** $\times$ **33mm** in dimension.

- Top layer - Power lines ($V_{CC}$, width = 20mil ) and signal tracks (Width = 10mil).
- Bottom layer - Ground

Connecting the whole bottom layer to ground minimizes loop areas and reduces EMI between signal tracks.

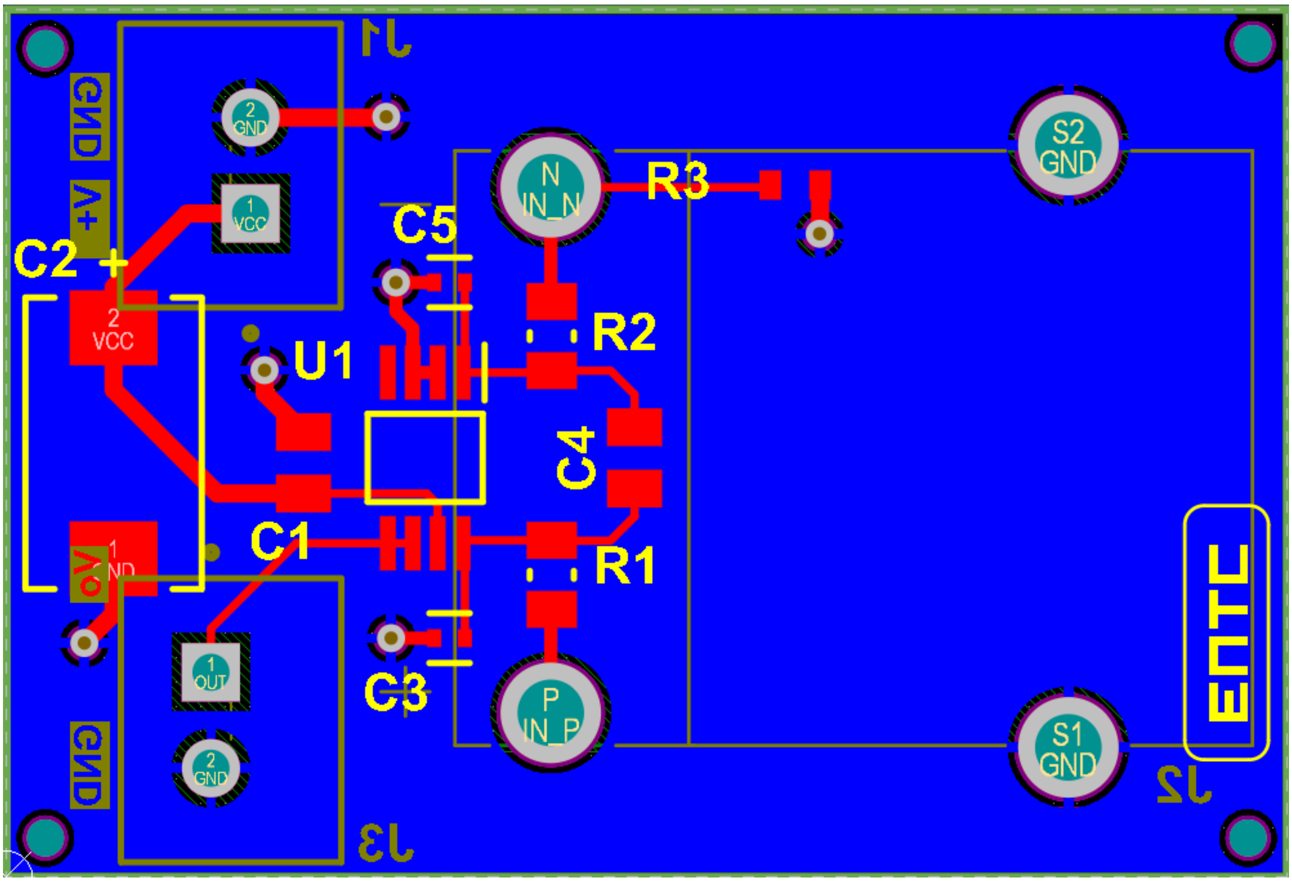


Figure 11: PCB Layout

All the connectors (J1,J2 and J3) are on the bottom side of the PCB and components are on the top side. To operate the cold junction compensation unit of AD8495, it is important to place the IC as close as possible to cold junction of the thermocouple. Decoupling capacitors are placed near to $+Vs$ pin of the IC. Also positive and negative input nets of the thermo-couple connector (J3) are routed using **Differential pair routing**.

### Design for manufacturing considerations

We imported the printed PCB's from china JLC PCB company. According to their capabilities of manufacturing process, we set the design rules and finally run the design rule check process in altium software to ensure the correctness.

| | JLC capability | In the design |
|---|---|---|
| **Minimum trace width** | 5mil | 10mil |
| **Minimum Via diameter** | 20mil | 20mil |
| **Minimum track spacing** | 5mil | 10mil |

Table 2: Design considerations

### Top Layer

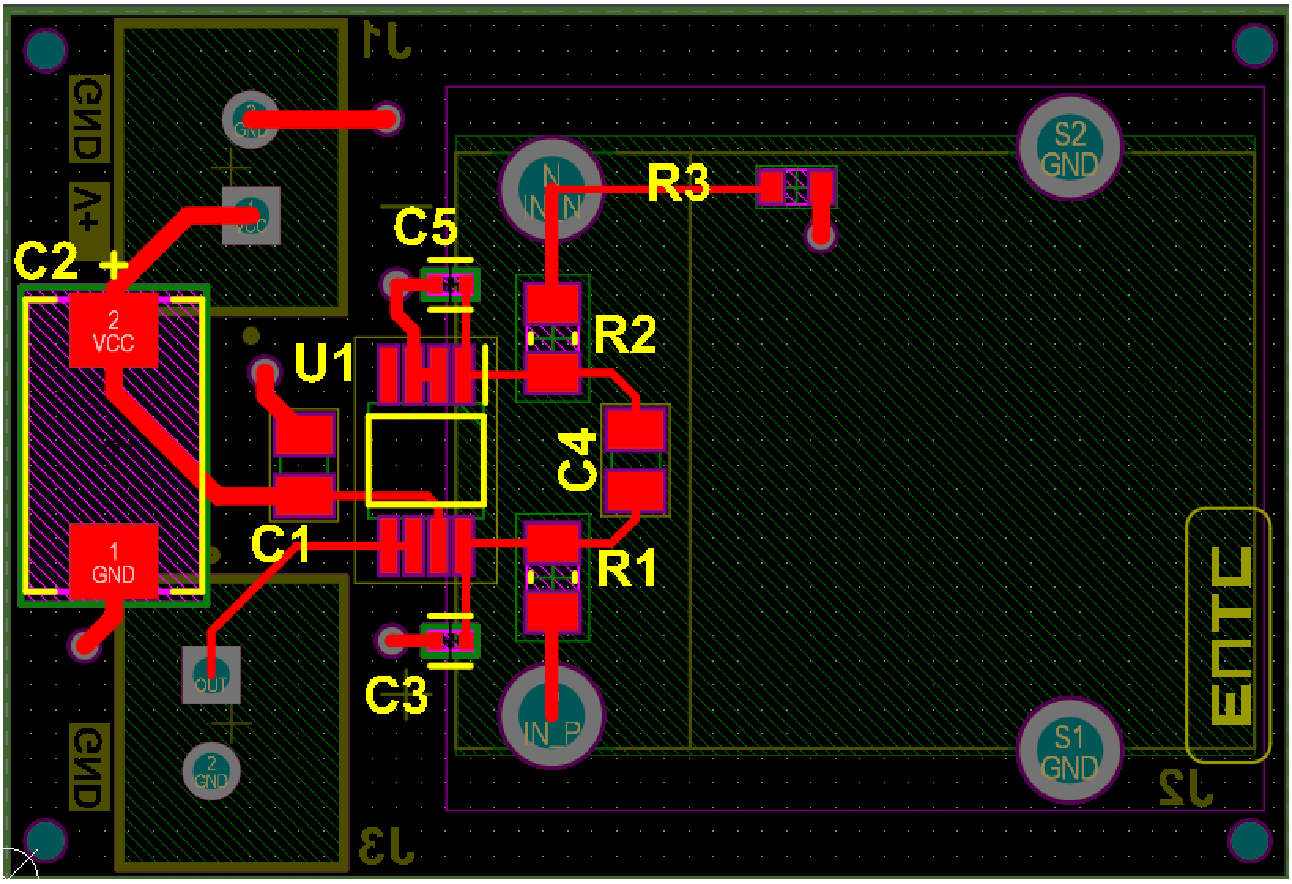


Figure 12: Top layer of the PCB

### Bottom Layer

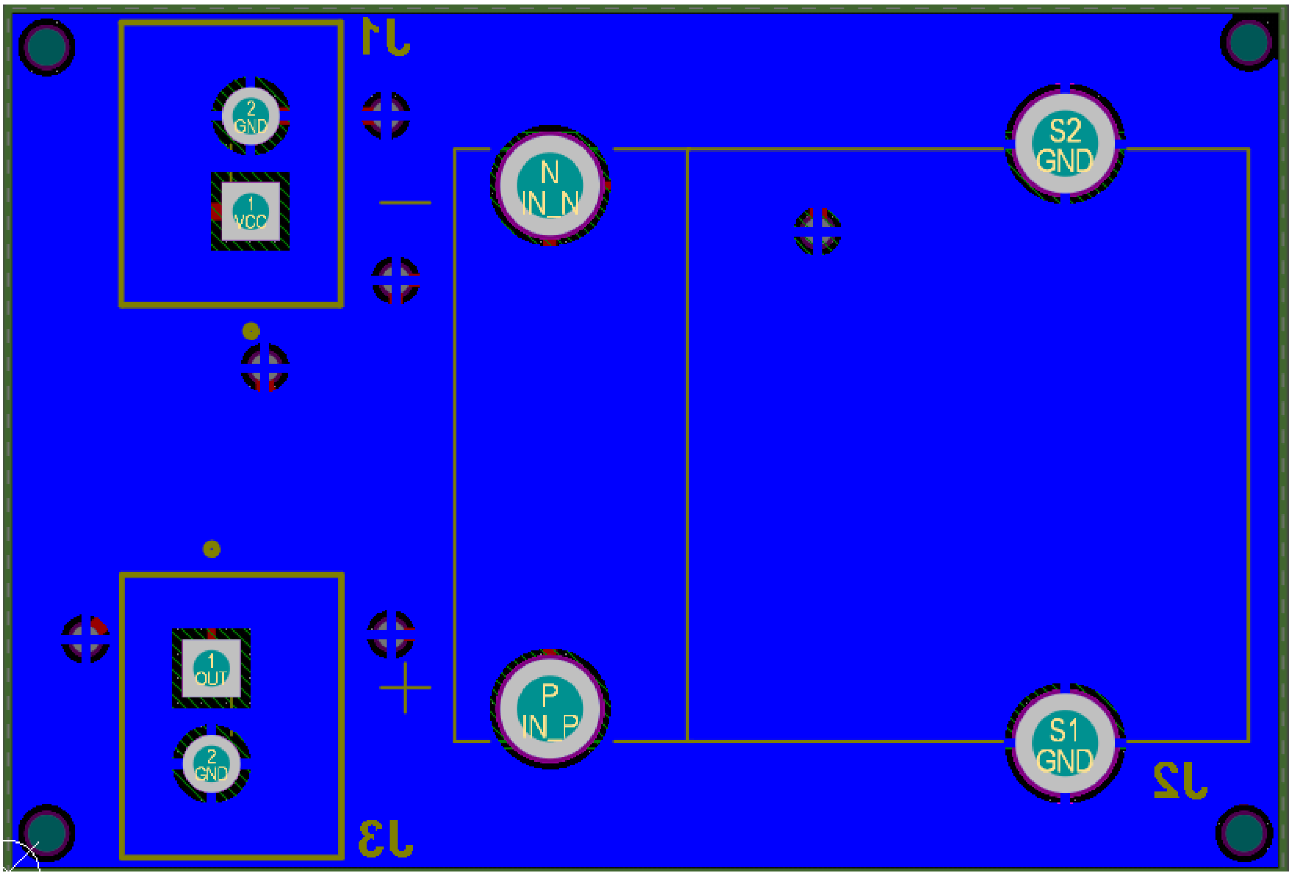


Figure 13: Bottom layer of the PCB

### 3D view

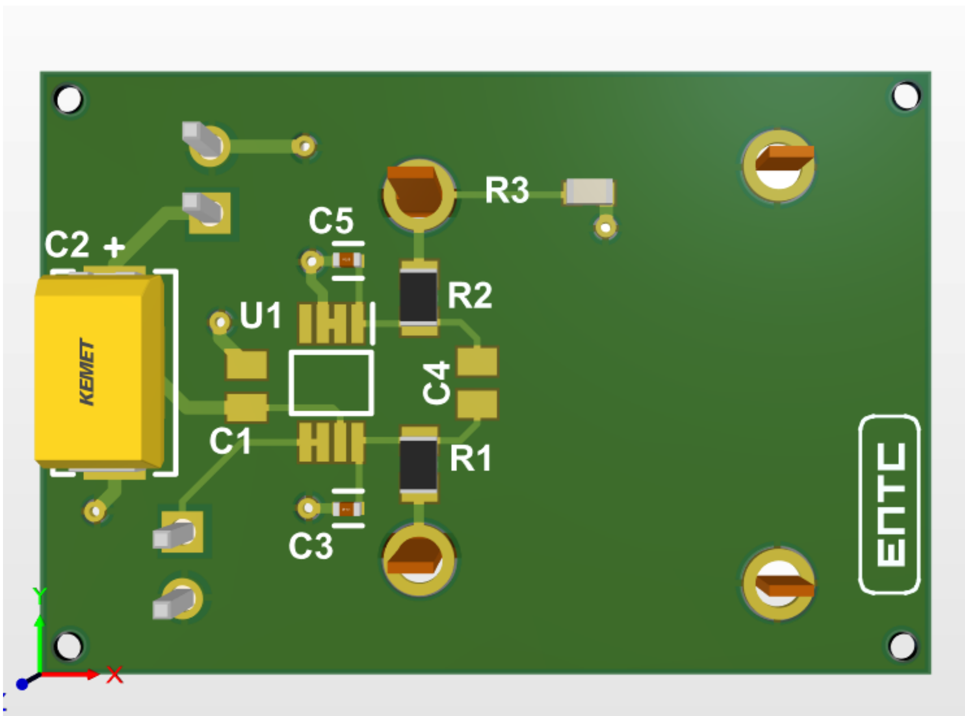


Figure 14: 3D view generated from Altium

## 0.5 *Bill of Materials*

| ***Comment*** | ***Designator*** | ***Footprint*** | ***Quantity*** |
|---|---|---|---|
| 10nF 25V | C1, C4 | CAPC2012X88N | 2 |
| 10uF 25V | C2 | FP-T491D-MFG | 1 |
| 100nF 16V | C3, C5 | FP-C1005-050-0_05-MFG | 2 |
| B2B-XH-A(LF)(SN) | J1, J3 | FP-B2B-XH-A_LF_SN-MFG | 2 |
| PCC-SMP-K-5 | J2 | OMEGA_PCC-SMP-K-5 | 1 |
| 10k 0.1W | R1, R2 | RESC2013X60X35NL10T20 | 2 |
| 1M | R3 | RESC1608X55X25LL10T15 | 1 |
| AD8495ARMZ | U1 | SOP65P490X110-8N | 1 |

Table 3: Bill of materials

We ordered these components from Mouser electronics.

# References


[1] Thermocouples: The Operating Principle Thermocouples Operating Principles. Available at: Here

[2] Precision thermocouple amplifiers with cold junction compensation data ... Available at: DATASHEET

[3] C table 9 type K thermocouple thermoelectric voltage as a ... - pyromation. Available at:Here


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