

LEVEL 4 ASSESSMENT SPECIFICATION

Student name:	Dafydd Adams	Student ID number:	
Programme:	HNC Instrumentation Engineering		
Module:	Instrumentation, Automation and Control		
Module code:	PCEE4011	Contribution to Overall Module Assessment (%):	50%
Lecturer:	Jason Pointer	Internal Verifier:	Nigel Richards
Assignment Title:	Temperature Measurement System and Signal Transmission	Word count (or equivalent):	2000
Submission deadline:	23/01/25	Return date of provisional marks & written feedback:	06/02/25
Submission method:	All written assessments, where practical and possible, must be submitted via Turnitin unless otherwise instructed by the Lecturer. (Please DO NOT put this assessment specification into Turnitin or it will match many similarities with other students' submissions.) Alternative submission method (if applicable): Late submission of the assessment will result in a late penalty mark: Work which is submitted up to 1 week late will be capped at 40% for the first attempt and will be awarded a mark of 0% for re-assessment. Late submission penalties may be lifted only if there is an approved extenuating circumstances claim. Work submitted more than 1 week late will be considered as a non-submission and will not be marked. The work may be considered as a submission for reassessment if offered by an Examining Board or if there is an approved extenuating circumstances claim.		
Academic honesty / referencing:	Academic honesty is required. In the main body of your submission you must give credit to authors on whose research and ideas your work is based. Append to your submission a reference list that indicates the books, articles, etc. that you have used, cited or quoted in order to complete this assessment.		

Module Learning Outcomes (from module syllabus)

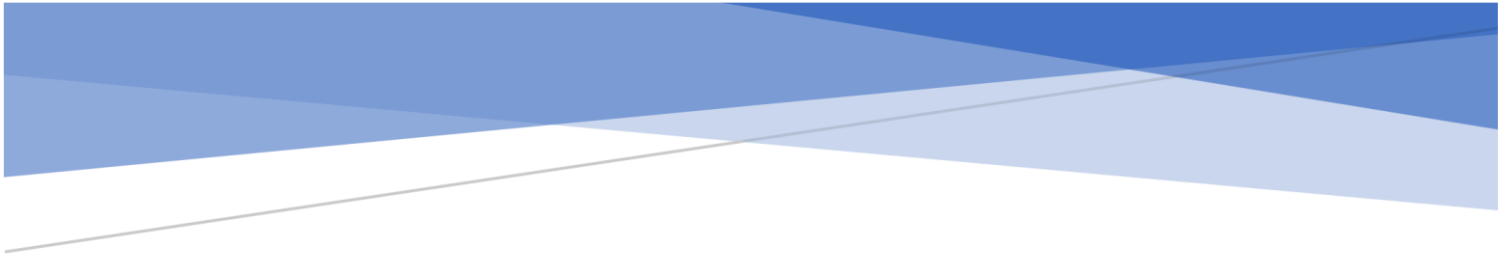
1. Explain the principles of operation for a range of industrial measuring systems and demonstrate an understanding of the requirement for interfacing sensors with conditioning, indication and analogue/digital signal transmission circuits.
2. Select an appropriate sensor for specific operation and demonstrate an understanding of their benefits and limitations with respect to measuring and control system applications.

STUDENT FEEDBACK FORM

This section details the *extent* to which the assessment criteria are demonstrated by you, which in turn determines your mark. The marks available for each category of skill are shown. Lecturers will use the space provided to comment on the achievement of the task(s), including those areas in which you have performed well and areas that would benefit from development/improvement.

Generic Assessment Criteria	Marks available	Marks awarded
1. Engagement with Literature Skills	15	9.9
Engagement with a wide range of literature, including sources retrieved independently. Generally sound referencing, with very few inaccuracies or inconsistencies.		
2. Knowledge and Understanding Skills	40	25.3
Task 1 - 58%. Task 2 - 62%. Task 3 - 65%. Task 4 - 68%. Competent knowledge of the underlying concepts and principles of measuring systems is accurate with a good understanding of the concepts of each task but in some places there needs to be more detail.		
3. Cognitive and Intellectual Skills	10	3.8
Largely superficial evaluation of the underlying concepts and principles for task 2 and 3.		
4. Practical Application Skills	25	19.63
Task 1 - 82%. Task 2 - 75%. An excellent application of practical work for tasks 2 and 3, very good use of the test equipment and Multisim to obtain the required test results.		
5. Transferable Skills for Life and Professional Practice	10	7
Work is coherent, very fluent and is presented professionally. Excellent layout making the assignment easy to read.		

Assessment Mark (Assessment marks are subject to ratification at the Exam Board. These comments and marks are to give feedback on module work and are for guidance only until they are confirmed.)	Late Submission Penalties (tick if appropriate)		66%
	Up to 1 week late (40% Max)		
	Over 1 week late (0%)		



TEMPERATURE MEASUREMENT SYSTEM AND SIGNAL TRANSMISSION

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Task 1 – Temperature Sensors Research

Platinum RTD

The platinum RTD is a type of temperature sensor called a Resistance Temperature Detector (RTD). The principle behind an RTD is the relationship between resistance and temperature with each material having a temperature coefficient of resistance. This coefficient refers to the change in resistance per degree (°C). The below equation can be used to calculate the temperature (Bird, 2003).

$$\text{Temperature, } \theta = \frac{R_{\theta} - R_0}{\alpha R_0}$$

R_{θ} = Resistance at Unknown Temperature

R_0 = Resistance at 0°C

α = Temperature Coefficient of Resistance

The Platinum RTD is very highly used within industry due to its linearity with the below figure demonstrating this.

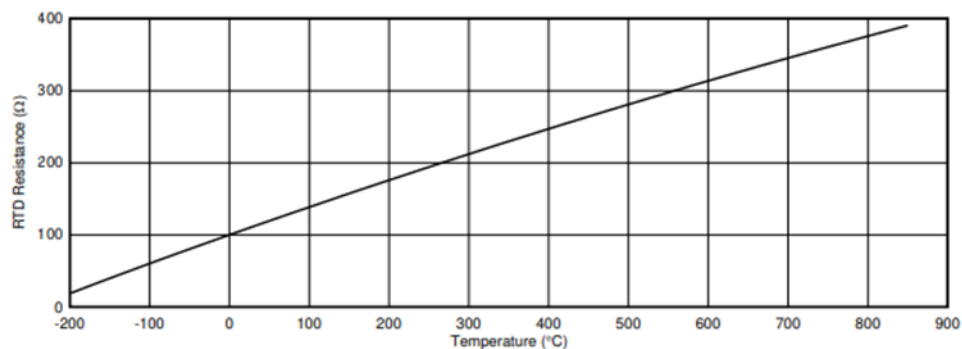


Figure 1 - Platinum RTD Resistance vs Temperature (Wu, 2018)

Another reason for its popularity is that it has a high melting point of 1786°C (Royal Society of Chemistry, 2025), can be calibrated to produce accurate readings to within a thousandth of a degree (Priest, 2004). Signal Conditioning is important with an RTD to negate the affect the wire resistance has on readings, to negate this a Wheatstone bridge (2 voltage dividers in parallel) and a 3-wire configuration is most used. The Wheatstone Bridge below allows the resistance of the RTD to be calculated using the below equation.

$$R_2 R_x = R_1 R_3$$

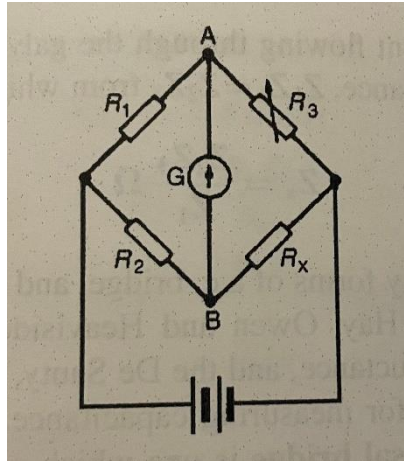


Figure 2 - Wheatstone Bridge Configuration (Bird, 2022)

In Figure 2 a Galvanometer is used to measure the current but a Voltmeter can also be used as an alternative. The main principle is that there will be 2 fixed resistors R_1 and R_2 a variable resistor R_3 and then R_x the RTD. When the bridge is balanced the above equation can be used to find the resistance of the RTD by changing the resistance of the variable resistor until there is no current detected.

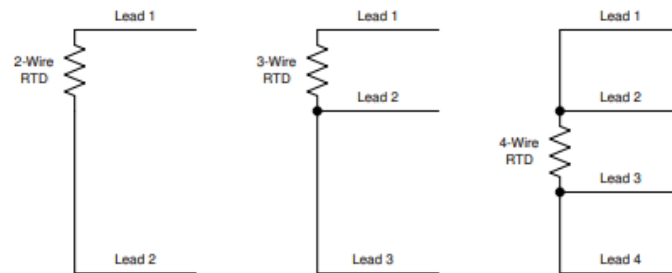


Figure 3 – 2 Wire, 3 Wire and 4 Wire RTD Configuration (Wu, 2018)

When long leads are used to connect the RTD the wire resistance can affect the accuracy of the readings and to negate this a 3 and 4 wire configuration is used. The 3 wire is the most common and it uses a 3rd wire to 'compensate for the impact of lead resistance' (Gill, 2024). A 4 wire is most accurate but also most expensive and it 'completely eliminates the impact of lead wire resistance' (Gill, 2024). *would like to see information about the construction and tech spec.*

A few drawbacks of the RTD are the cost can be high when compared to to other forms of temperature detection such as a Thermocouple or Thermistor. They also have 'a higher thermal mass which causes them to respond more slowly to changes in temperature than thermocouples.' (Probes Unlimited, 2025) The operating range of an RTD is between -200°C and 850°C. The RTD is also a very sensitive probe and 'excessive vibration or mechanical shock can cause the RTD wiring to break or loosen over time, resulting in intermittent connections or open circuits.' (Peak Sensors, 2025). Physical damage to the probe can also cause failure or inaccurate readings.

NTC Thermistor

A thermistor is a semi-conductive material which can be used to measure temperature by measuring the resistance like an RTD. 'The thermistor is basically a two-terminal solid state thermally sensitive transducer constructed using sensitive semiconductor-based metal oxides with metallised or sintered connecting leads formed into a ceramic disc or bead.' (Electronics Tutorials, 2025). The NTC

(Negative Temperature Coefficient) thermistor however has a 'sharp decrease in resistance as temperature increases' (TDK Corporation, 2022). The decrease in resistance with temperature is also non-linear, the nature of an NTC also means that an NTC thermistor is mostly used between -55°C to 200°C as this is 'where they give their most precise reading' (EE Power, 2025). As seen from the Figure above the semiconductor's resistance drops dramatically with temperature. ✓

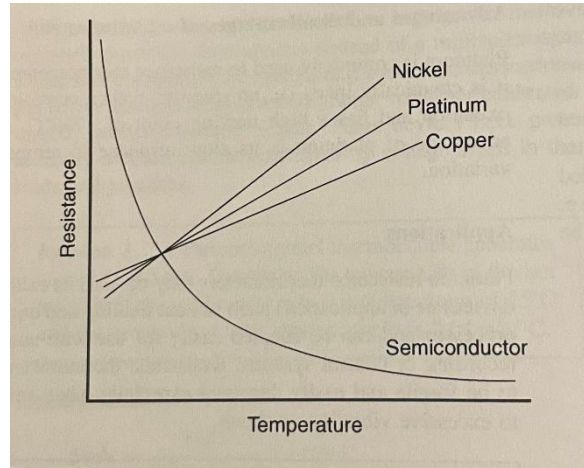


Figure 4 - Temperature vs Resistance Graph (Bird, 2003)

The curve of the semi-conductor is also an exponential curve which is characterised by B, the material constant. This value can be calculated using the below equation or used to calculate a temperature at a certain point.

Thermistor Equation

$$B_{(T_1/T_2)} = \frac{T_2 \times T_1}{T_2 - T_1} \times \ln\left(\frac{R_1}{R_2}\right) \quad \checkmark$$

Where:

T_1 is the first temperature point in Kelvin

T_2 is the second temperature point in Kelvin

R_1 is the thermistors resistance at temperature T_1 in Ohms

R_2 is the thermistors resistance at temperature T_2 in Ohms

Figure 5- Thermistor Equation (Electronics Tutorials, 2025)

A Wheatstone bridge can be used to measure the resistance of the thermistor and then calculate the temperature like the RTD seen in Figure 2. An ammeter can also be used in series with the thermistor to calculate the temperature. Positives of a Thermistor is the quick response time to changes in temperature making them a good choice for where this is important, they are also inexpensive making them a cheap alternative to RTDs. They are most used at lower temperatures where they have higher resistance and also the linearity of temperature vs resistance is better allowing more accurate readings. A downside to these temperature detectors is that they are only linear for a small temperature window when compared to an RTD. They are also susceptible to a self-heating effect which is when the Thermistor is heated by the current flowing through, the amount of heating depends on the current. This can lead to inaccurate temperature readings ✓

Task 2 – Testing The Sensors

The PT100 and the Thermistor discussed above were compared against an integrated circuit (IC) temperature over a 10-minute period with heat increasing. The temperature readings were taken at an interval of 1s and the results collated into a graph for both sensors.

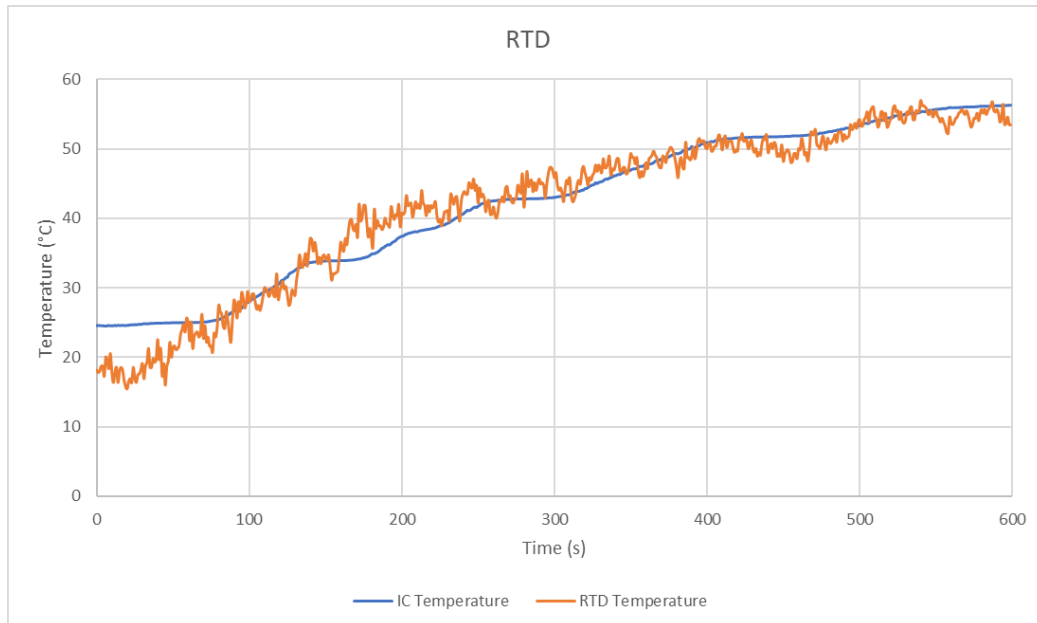


Figure 6 - Comparison of IC and PT100

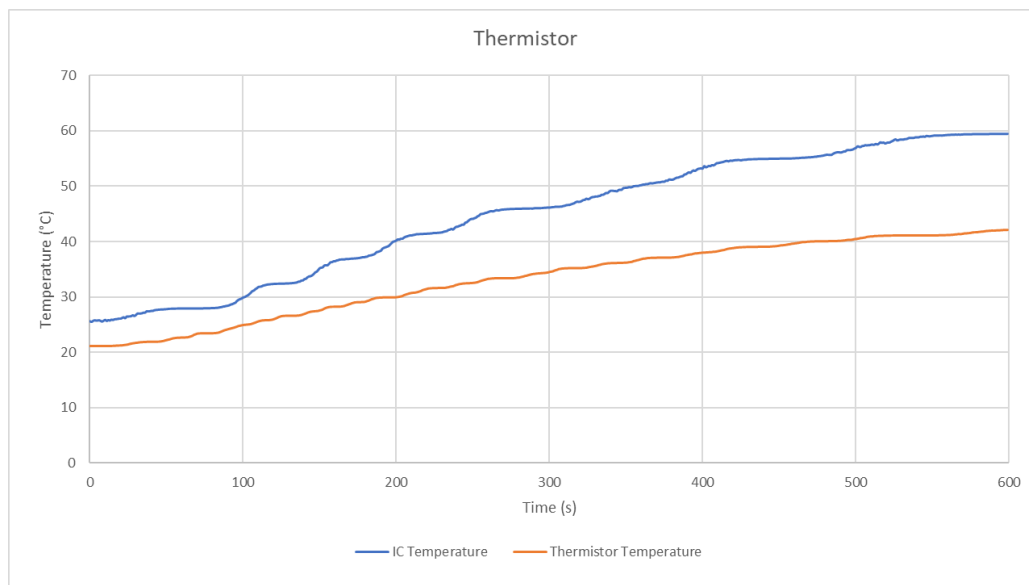


Figure 7 - Comparison of IC and Thermistor

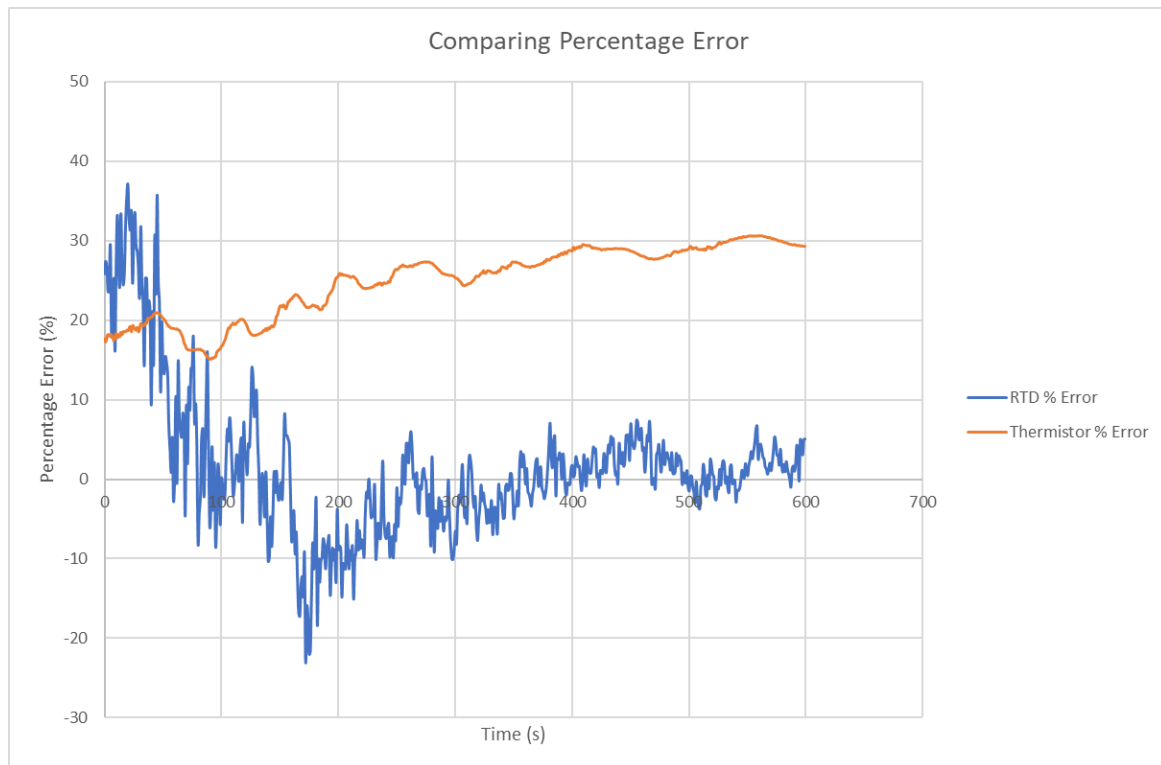


Figure 8 - Comparison of Percentage Error between PT100 and Thermistor

The percentage error was also calculated for both the PT100 and the Thermistor which can be seen in Figure 8.

From the data presented above the RTD is seen to be slightly inaccurate at the start of the test measuring below the IC value but as the temperature increased it began to follow a similar curve to that of the IC with improved accuracy. The readings itself fluctuate a lot due to the sensitivity of the RTD and the sampling time being 1s. If a smoother temperature curve where response time isn't of importance is required increasing the sampling frequency from 1s to 10s would smoothen the curve. ✓

The Thermistor is inaccurate when compared to the IC as it is reading a lower temperature than the IC across the whole range of temperatures. This inaccuracy could be resolved using an offset if found that the temperature was a constant value below the IC temperature. However, in this case the inaccuracy increases as the temperature increases and is therefore not an option. The sensitivity of the Thermistor is also less than that of the RTD as can be seen by the smoothness of the curve. ✓

When comparing both and looking at the percentage error compared to IC excluding the first part of the experiment the RTD's percentage error fluctuates from around -8% to +8% with the fluctuation due to the sensitivity of the instrument. The Thermistor however has a roughly 19% error to begin and this then increased to approximately 30% by the end of the 10-minute period which is a significant percentage error. Therefore, when choosing a sensor from the two options above the RTD is the preferred option as although it fluctuates a lot due to sensitivity overall the performance is much greater than that of the Thermistor producing much more accurate results when compared to the IC. ✓

Task 3 – Temperature Circuit Design

Task 3 – Temperature Circuit Design

The company requires you to select the more suitable of the 2 sensors that have been tested. You are to design a measuring circuit that will convert the resistance of the sensor to a comparative voltage value. The measuring instrument should have the following input and output ranges:

- Input range: 0 to 100°C
- Output range: 0 to 10 volts

Design and build a signal processing circuit containing a Wheatstone bridge and instrumentation amplifier that will meet the system specification. The circuit will be prototype using MultiSim and you are required to evaluate its overall performance.

Figure 9 - Assignment Brief Task 3

Following on from Task 2 where the RTD was selected as the most appropriate sensor a measuring circuit was designed which converts the resistance into a corresponding Voltage which can then be used to transfer the signal. As explained above in Task 1 a Wheatstone Bridge will be used to measure the resistance of the RTD with a Voltmeter used instead of the Galvanometer in Figure 2 and then an operational amplifier will then amplify the signal ready to be transmitted. 'An operational amplifier is an integrated circuit that can amplify weak electric signals.' (ABLIC, 2025). In this case it will allow the voltage measured within the Wheatstone Bridge to be amplified to a value readable by a microcontroller or programmable logic controller.

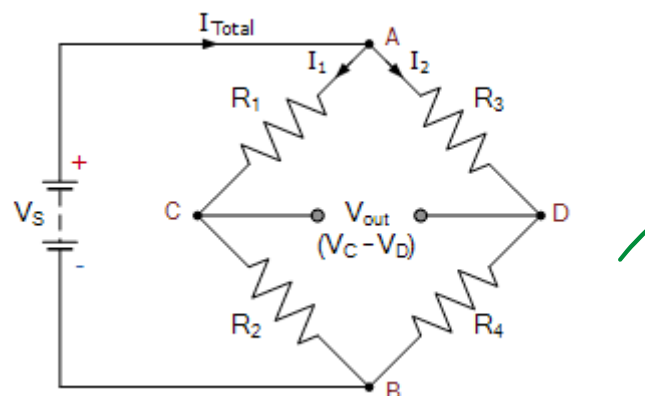


Figure 10 - Wheatstone Bridge (Electronics Tutorial, 2025)

To calculate the V_{out} the below equation is used.

$$V_{Out} = V_S \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right)$$

In the circuit designed for this task both R_1 and R_3 are resistors of 270Ω, R_2 is 100Ω and R_4 is the PT100 RTD. R_2 is 100Ω so as when the temperature is 0°C the Bridge will be balanced and the V_{out} will be 0 V. Below is a table of temperature, the resistance of the PT100 probe, V_{out} of the Wheatstone Bridge and the Voltage Output of the operational amplifier.

The resistance at each temperature was calculated using the below equation.

$$R_{\theta} = R_0(1 + \alpha_0\theta)$$

where R_0 = resistance at 0°C

R_{θ} = resistance at temperature $\theta^{\circ}\text{C}$

α_0 = temperature coefficient of resistance at 0°C .

Figure 11 - Resistance and Temperature Coefficient Equation (Bird, 2022)

why not type this yourself?

By knowing that a PT100 has a resistance of $100\ \Omega$ at 0°C and that platinum has a temperature coefficient of $0.00385\ \Omega / ^{\circ}\text{C}$ as per the DIN 43760 standard (Omega, 2025). The resistance at each temperature can be calculated using the above equation an example for 30°C is shown below.

$$R_{\theta} = 100 (1 + 0.00385 \times 30)$$

$$R_{\theta} = 111.55$$

This was done for all temperatures from $0 - 100^{\circ}\text{C}$ at a 10°C interval and can be seen in the above figure. The voltage output was calculated using the previous equation and the results seen in the below table.

For the output of the operational amplifier the below calculations were performed. Firstly, the voltage gain (A_V) was calculated using the below equation and the highest values for V_{out} and V_{in} were used which in this case is $10\ \text{V}$ and $0.688\ \text{V}$ respectively.

$$A_V = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{10}{0.688} = 14.53$$

To calculate the resistor needed for the Operational Amplifier the below equation was used, the gain resistor (R_{Gain}) in this operational amplifier is $2.2\ \text{k}\Omega$.

$$R = \frac{R_{\text{Gain}} (A_V - 1)}{2} = \frac{2200 (14.53 - 1)}{2} = 14883\ \Omega$$

The closest resistor to this calculated value is rate $15\ \text{k}\Omega$ and therefore a $15\ \text{k}\Omega$ was used for the operational amplifier. Finally, to calculate the voltage produced by the Operational Amplifier the below equation was used.

$$\text{Operational Amplifier Output (V)} = \frac{V_{\text{out of Wheatstone Bridge (mV)}} \times \left(1 + 2 \left(\frac{R}{R_{\text{Gain}}}\right)\right)}{1000}$$

For 30°C the below output is calculated for the operational amplifier.

$$\text{Operational Amplifier Output (V)} = 220.898 \times \left(1 + 2 \left(\frac{15000}{2200}\right)\right) = 3.23\ \text{V}$$

The results can be seen below.

Temperature (°C)	PT 100 (Ω)	Wheatstone Bridge V out (mV)	Amplifier Output Voltage
0	100.00	0.000	0.00
10	103.85	75.149	1.10
20	107.70	148.767	2.18
30	111.55	220.898	3.23
40	115.40	291.589	4.27
50	119.25	360.881	5.28
60	123.10	428.816	6.28
70	126.95	495.433	7.25
80	130.80	560.770	8.21
90	134.65	624.864	9.15
100	138.50	687.750	10.07

Figure 12 - Data for the Operational Amplifier (Theoretical)

The operational amplifier was then built on Multisim and the values for the PT100 probe varied to provide the outputs at each temperature. The below examples show 10 °C, 40 °C and 90°C.

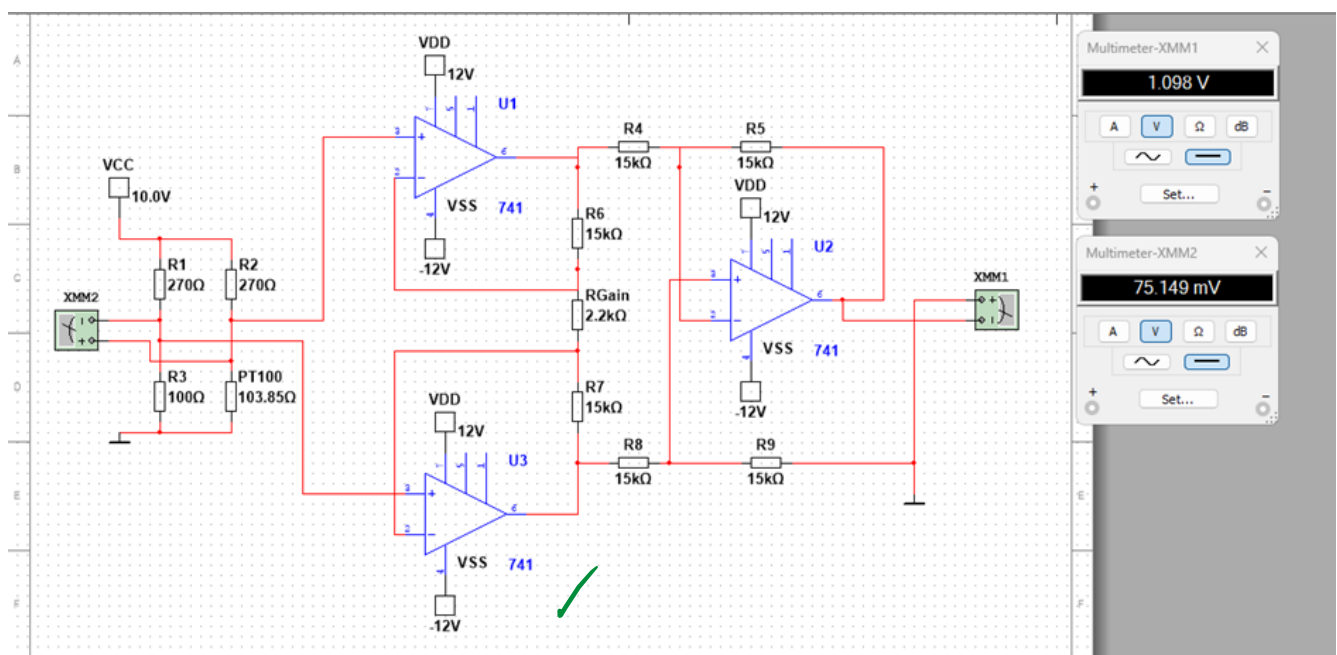
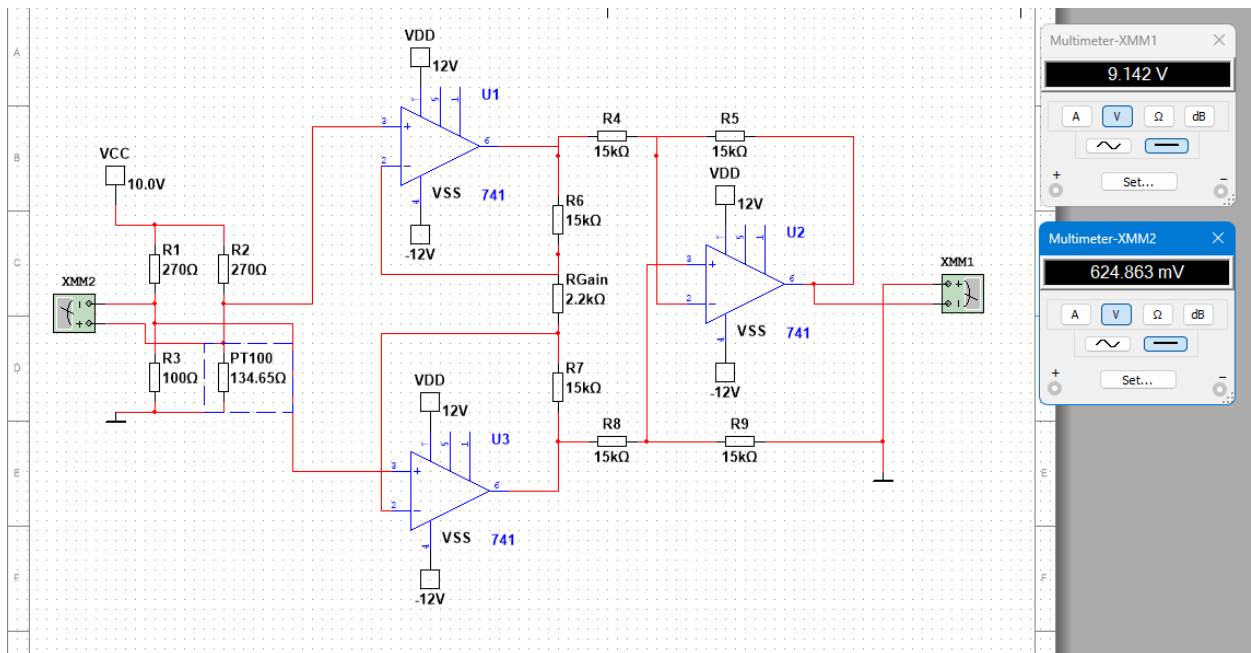
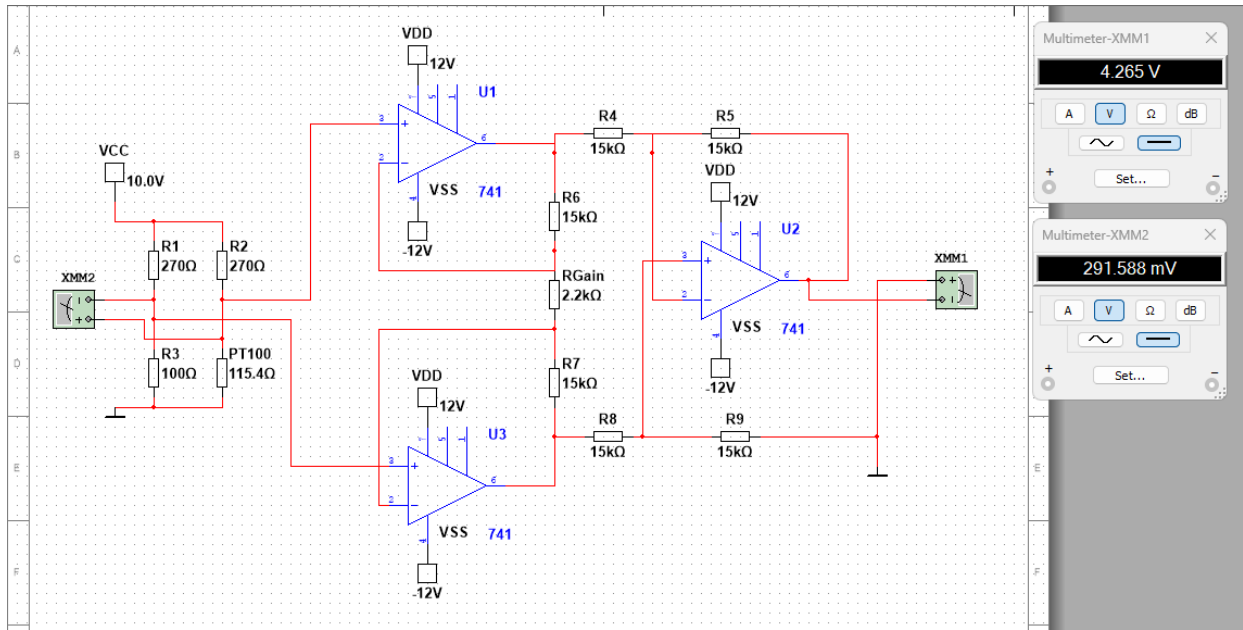


Figure 13 - Operational Amplifier with PT100 set at 10 °C



The Wheatstone Bridge outputs, and the operational amplifier outputs are shown in the table below.

Temperature (°C)	PT 100 (Ω)	Wheatstone Bridge V out (mV)	Amplifier Output Voltage (V)
0	100.00	0.000	0.00
10	103.85	75.149	1.10
20	107.70	148.766	2.18
30	111.55	220.898	3.23
40	115.40	291.588	4.27
50	119.25	360.880	5.28
60	123.10	428.815	6.27
70	126.95	495.432	7.25
80	130.80	560.769	8.20
90	134.65	624.863	9.14
100	138.50	687.749	10.06

Figure 16 - Data for the Operational Amplifier (Simulated)

As you can see when comparing both the simulated data and the theoretical data for the operational amplifier there are some discrepancies albeit small ones with the largest difference in output being 0.01 V. The differences between the theoretical and simulated values can be as 'characteristics may drift with age and temperature' (All About Circuits, 2025). Another reason for the difference is the potential for input offset which equates to not correctly zeroing an analogue meter. The resistance of the wires could also play a role in altering the output of the Wheatstone bridge with any small difference in the output of the Wheatstone Bridge magnified by the operational amplifier. Depending on the tolerance of the resistors used within the circuit this could also introduce error to the simulated results as they could have an error of $\pm 5\%$.

You have made statement that donot relate to the simulation work i.e. zeroing an analogue meter?

Task 4 – Signal Transmission

Fieldbus Foundation

'Fieldbus is a bidirectional communication protocol that provides real-time, closed-loop control between intelligent field instruments and host systems.' (FieldComm, 2025). This system is completely digital, and communication can occur not only between the device and the PLC but between each device if they are compatible with Fieldbus.

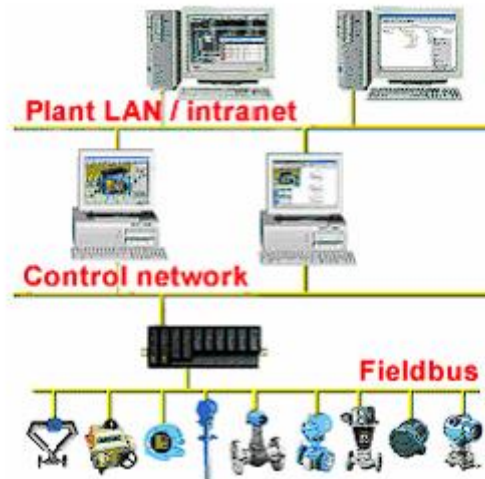


Figure 17 - FOUNDATION Fieldbus diagram (Emerson, 2002)

There are 2 different types of Fieldbuses, H1 and HSE. H1 operates at a speed of 31.25 Kbit/sec and can be transmitted over a standard twisted pair wire. This is used to communicate between the field devices and is the most used. HSE (High-Speed Ethernet) operates at a much faster speed of 100 Mbit / sec and is generally used to connect field devices to the PLC or Control network and uses standard Ethernet cables. Advantages of using Fieldbus as a communication protocol including considerably less wiring allowing money to be saved. A company in Alaska found that a reduction of 98% in wiring was achieved using Fieldbus, time taken to install each transmitter was roughly 20 minutes compared to 2 hours using non Fieldbus technology (Instrumentation Tools, 2025). More data can also be transmitted when compared to analog systems.

The downside of having all devices connected on a loop using a 'T' connection is if one device were to short-circuit or encounter problems the whole system could potentially be disrupted or taken offline. To solve this issue the junction boxes designed for Fieldbus can be used as an alternative. Troubleshooting also required specialized tools. This can add to the cost of using Fieldbus Foundation.

Hart Protocol

'HART is a bi-directional communication protocol that provides data access between intelligent field instruments and host systems' (FieldComm, 2025). Hart stands for Highway Addressable Remote Transducer and is used in many factories. It uses a 4-20 mA loop and is a hybrid of digital and analog using the 4-20 mA to communicate a single variable whilst also sending digital information on a superimposed digital system.

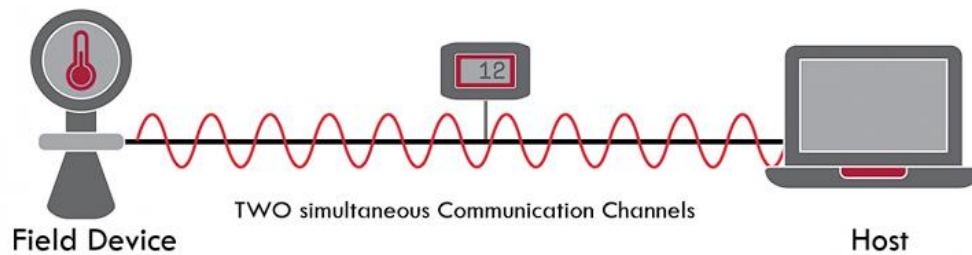


Figure 18 - Hart Communication (FieldComm, 2025)

This figure shows the two signals transferred simultaneously. The main signal is the analog one which carries the primary variable for example temperature or pressure which is converted at the host from a current into the correct variable. An example could be 6 mA converted at the host to 34°C. The other signal transmitted is a digital one 'carried by a low-level modulation superimposed on the standard 4-to-20 mA current loop.' (Emerson, 2002). This signal does not affect the analog signal which is removed by standard filtering techniques. ✓

Due to the HART protocol allowing a signal to be imposed over the analog current signal the existing wiring within a factory could be re-purposed and used for HART. This would save a lot of money on re-wiring as it would not be required. The only requirement would be to ensure the device is compatible with the HART protocol. The system works with a request-response system with the PLC or microcontroller initiating a request of information from the instrument such as temperature. ✓

The above Figure shows the several types of Hart commands ranging from the universal ones down to the ones only used by the manufacturer. A downside to HART communications is the speed which compared to modern standards is slow at 1200 bits per second and it can only accommodate up to 16 devices on a loop. The HART protocol is a Master Slave protocol like Profibus and uses the same system as explained in Figure 20. ✓

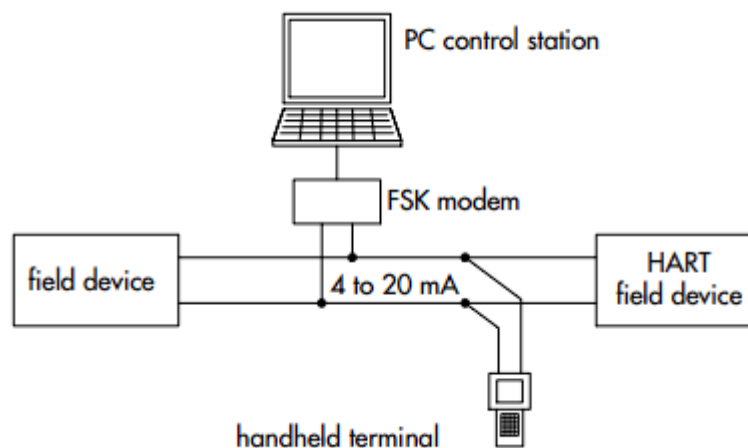


Figure 19 – Connection of HART devices (SAMSON, 2025)

As seen above a handheld terminal can be used to access the data being transmitted by acting as a master whilst connected. This is commonly used for calibration and diagnostics of the various connected devices.

Profibus

As a communications protocol Profibus (Process Field Bus) was developed as an upgrade to HART discussed previously and was created in 1989 but was upgraded in 1993. Profibus communication uses a physical layer of RS-485 wiring. Using a master - slave protocol with the PLC being the master and all field devices slaves the master then requests data such as pressure from the slave when required and the slave then sends the requested data back to the master. This usually occurs with one slave at a time meaning 'that a master sends a message and the slave gives a response. After receiving the response, the master directs itself to the next slave.' (PROCENETEC, 2025). This data can be exchanged regularly (cyclically) or when requested (acyclically). The below diagram shows a PROFIBUS setup with 2 masters that can both request information by sending tokens to each other granting access to request from any slave.

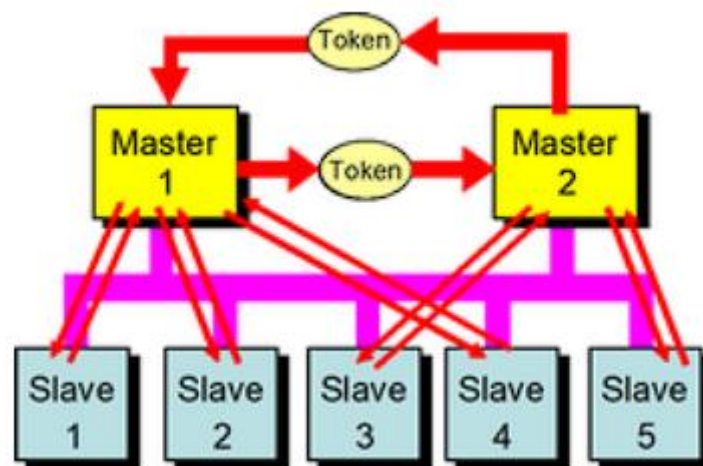


Figure 20 - PROFIBUS Diagram (Worth, 2023)

There are two types of PROFIBUS available PA (Process Automation), DP (Decentralized peripherals) and FMS (Fieldbus Message Specification). FMS was an earlier variant used to communicate between devices however this is less used compared to the other two. PA is an intrinsically safe and is used in environments such as oil refinery where explosion protection is essential. DP is described above and involves the master - slave interactions and can typically have up to 32 devices connected to the system. PROFIBUS DP can operate at speeds of between 9.6 kbit/s and 12 Mbit/s depending on factors such as the configuration of the system whereas PA operates at a fixed speed of 31.25 kbit/s the same as Fieldbus Foundation and uses 'two-wire technology based on the (international standard (IEC) 1158-2.' (El - Pro - Cus, 2025). Some positives of PROFIBUS are they are generally low cost and the ability to be intrinsically safe is very important for some industries. However it may not be able to meet the speed demands of some applications and the length of cable depends on the speed required with faster speeds limiting the length of cable, 12 Mbit/s limited to 100m of cable. This is a limitation when compared to other communication systems such as PROFINET which has a much higher bandwidth and can transfer large amounts of data it has limitations.

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