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Order of Linearities of temperature Sensors: A Comparative Study

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***Abstract*— Temperature sensors play a vital role in thermometry industry. A comparative analysis of order of linearities of different temperature sensors is presented. Order of linearity plays a vital role in senor measurement as with this an unified or universal linearizer can be modeled to ease out the problems of handling different types of sensors with different responses. This analysis will be beneficial for all the designers to choose sensors for better linearizer design.**

Keywords*— Sensors, Transducers, linearization, Analog Sensors, Digital Sensors, Sensor Linearization. Neural Network, Universal Linearizer.

I. Introduction (*Heading 1*)

Most of the sensors provide nonlinear characteristics in real life. Nonlinear signals must be linearized to get rid of the design complexity of the system. Different types of sensor linearization techniques available in the market. Each one of them deals with one single type of sensor and tries to linearize its output. Instead of specific technique if measurement is taken to find symmetry between a nonlinear sensors with a known device, which is already present in the linear domain then the linearization process becomes much easier. Characteristic of most sensors is nonlinear in nature [2, 3], obtaining data from a nonlinear sensor by using a normal digital device has always been a design challenge [4]. Analog sensors have always been better in getting the response from the measuring entity [5]. Digital Sensors always provide better linearity but lacks continuity of data when processing. It is undoubtedly clear that for a better sensor, Analog models are the best [6]. Unfortunately each one shows their own version of non-linearity with their characteristics. As a result a major task becomes is to convert that non linearity into linearity. Each one of the sensor characteristics must be linearized to get an Ultimate Universal linearizer which can linearize any nonlinear response from any of the sensor available Analog linearization techniques are in general the simpler ones and can have a low cost in terms of silicon area and power consumption. Their main drawbacks are sensitivity to environmental conditions (mainly temperature), lack of flexibility when a different kind of sensor is employed, and that accuracy is high typically only in a small input range [7]. Hence, they are usually the preferred choice in lowcost, low performance applications where the linearized output is required in analog form.

Thermocouple Nonlinearity: The table in Figure.1 shows the difference between output characteristics of thermocouple type temperature sensors. [1]

The chart in Figure 2 shows the difference in output response of different types of Thermocouples [8]. As the chart shows starting from 0^0 C to 100^0 C, the non-linearity ratio is less in comparison to the higher temperature. To use different types of Thermocouple in a single system it's essential that every sensors output must be linearized to a single linear curve.

The chart in Figure 3 shows the usage details and specifications of different types of Thermocouples. As the chart shows [2,3] Type K, N, R, S, B are much more expandable in temperature range in comparison with the Type E, J, T. [9] Whereas for continuous use Type R and S [10] shows the best results, however non linearity portion is also very high for the upper temperature range.

Comparative Analysis between different Sensors Linearities: The table in Figure 4 shows the difference of specifications between all the different types of temperature sensors [11]. Specification wise Thermocouples are mostly used for long expansions of temperatures. Compared to the thermocouple RTD [12], Thermistor [13] or Semiconductor Diodes [14] proved response for a small range of Temperatures. Whereas linearity wise Semiconductor IC based sensors provide best linear result in comparison with the RTD or Thermistors.

At a glance Thermistor provides least amount of linearity in comparison with the other types of Sensors. The following graph shows the advantages and disadvantages along with a graphical representation of nonlinearity between all the four type of sensors in Figure.5 and Figure.6 [13, 14, 15]

The main goal of our work is to design a Universal system comprising of both analog and digital system. [2, 3] The system will be able to use a number of analog and digital sensors, get nonlinear data from them, and convert each nonlinear data into its linear form. The system will bring each converted data less than one specific measurement system so that complexity becomes less. Users need not to choose separate system to convert linearized data for different sensors, but the universal linearizer will automatically convert nonlinear values to linear value for a specific number of sensors. In the proposed system a number of sensors can be connected as input device but the processed output will be linear and mapped into a specific set of values predefined by the system itself.

Sensor Linearizer for Basic temperature is already present for implementation [16]. However as different linearizer provides different nonlinear outputs it's almost impossible for a single circuit to linearize multiple types of sensors. The basic Linearization flow process is described in Figure 7.

Implementing Universal Linearizer: The alternate way through which we can create an universal linearizer is emulating the behavior of different sensors to a particular senor. The block diagram below shows the basic concept of the project through which we can create an universal Linearizer. For the project as base model we create a basic Neural Network Model for Thermocouple linearization as shown in Figure 8.

TOLERANCE OF THERMOCOUPLES

ANSI/ASTM	°C			°F		
	Temperature Range	Standard	Special	Temperature Range	Standard	Special
T	-200° to -67°	± 1.5% T	± 0.8% T*	-328° to -88°	± 1.5% (T − 32)	± 0.8% (T − 32)*
	-67° to -62°	± 1°	± 0.8% T*	-88° to -80°	± 1.8°	± 0.8% (T − 32)*
	-62° to 125°	± 1°	± 0.5°	-80° to 257°	± 1.8°	± 0.9° *
	125° to 133°	± 1°	± 0.4% T	257° to 272°	± 1.8°	± 0.4% (T − 32)
	133° to 370°	± 0.75% T	± 0.4% T	272° to 700°	± 0.75% (T − 32)	± 0.4% (T − 32)
J	0° to 275°	± 2.2°	± 1.1°	32° to 527°	± 3.96°	± 1.98°
	275° to 293°	± 2.2°	± 0.4% T	527° to 560°	± 3.96°	± 0.4% (T − 32)
	293° to 760°	± 0.75% T	± 0.4% T	560° to 1400°	± 0.75% (T − 32)	± 0.4% (T − 32)
E	-200° to -170°	± 1% T	± 1°*	-328° to -274°	± 1% (T − 32)	± 1.8°*
	-170° to 250°	± 1.7°	± 1°*	-274° to 482°	± 3.06°	± 1.8°*
	250° to 340°	± 1.7°	± 0.4% T	482° to 644°	± 3.06°	± 0.4% (T − 32)
	340° to 870°	± 0.5% T	± 0.4% T	644° to 1600°	± 0.5% (T − 32)	± 0.4% (T − 32)
K	-200° to -110°	± 2% T	—	-328° to -166°	± 2% (T − 32)	—
	-100° to 0°	± 2.2°	—	-166° to 32°	± 3.96°	—
	0° to 275°	± 2.2°	± 1.1°	32° to 527°	± 3.96°	± 1.98°
	275° to 293°	± 2.2°	± 0.4% T	527° to 560°	± 3.96°	± 0.4% (T − 32)
	293° to 1260°	± 0.75% T	± 0.4% T	560° to 2300°	± 0.75% (T − 32)	± 0.4% (T − 32)
N	0° to 275°	± 2.2°	± 1.1°	32° to 527°	± 3.96°	± 1.98°
	275° to 293°	± 2.2°	± 0.4% T	527° to 560°	± 3.96°	± 0.4% (T − 32)
	293° to 1250°	± 0.75% T	± 0.4% T	560° to 2300°	± 0.75% (T − 32)	± 0.4% (T − 32)
R or S	0° to 1260°	± 1.5°	± 0.6°	32° to 1112°	± 2.7°	± 1.08°
	1260° to 1480°	± 0.25% T	± 0.1% T	1112° to 2700°	± 0.25% (T − 32)	± 0.1% (T − 32)
B	870° to 1700°	± 0.5% T	± 0.25%	1600° to 3100°	± 0.5% (T − 32)	± 0.25% (T − 32)
C**	0° to 426°	± 4.4°	—	32° to 800°	± 8°	—
	426° to 2315°	± 1% T	—	800° to 4200°	± 1% (T − 32)	—

Figure 1 Thermocouple non-Linearity comparison

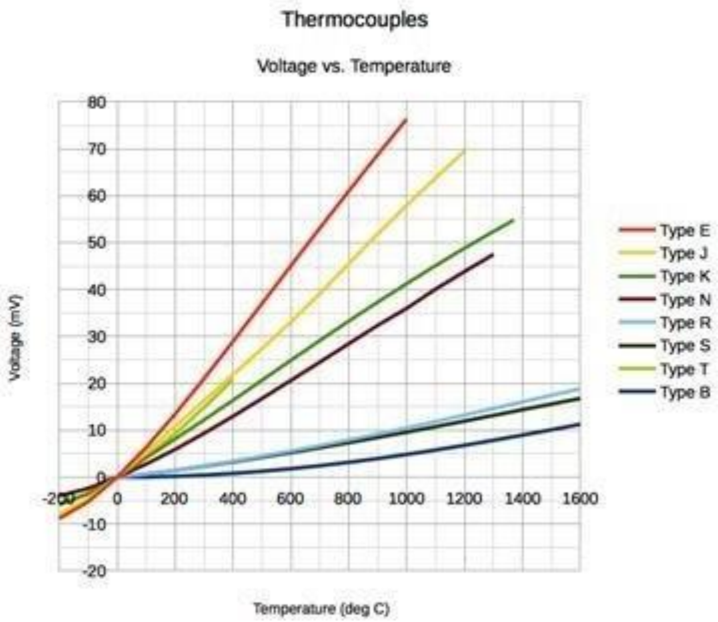

Figure 2 Thermocouple: Temperature vs. Output for each and every type

Thermocouple Type	Temperature Range (°C)				
	Short Term Use	Continuous Use	Class 1 Tolerance	Class 2 Tolerance	Class 3 Tolerance
Type E	- 40 to +900	0 to +800	-40 to +800	-40 to +900	-200 to +40
Type J	- 180 to +800	0 to +750	-40 to +750	-40 to +750	N/A
Type K	- 180 to +1300	0 to +1100	-40 to +1000	-40 to +1200	-200 to +40
Type N	- 270 to +1300	0 to +1100	-40 to +1000	-40 to +1200	-200 to +40
Type R	-50 to +1700	0 to +1600	0 to +1600	0 to +1600	N/A
Type S	-50 to +1750	0 to +1600	0 to +1600	0 to +1600	N/A
Type T	- 250 to +400	- 185 to +300	-40 to +350	-40 to +350	-200 to +40
Type B	0 to +1820	+200 to +1700	N/A	+600 to +1700	+600 to +1700

Figure 3 Comparative Analysis between different types of Thermocouples

Typical Temperature Sensor Characteristics				
Typical Characteristics	Thermistor General Purpose	Resistance Temperature Devices (RTDs)	Thermocouples (TCs)	Semiconductor Temperature Sensors
Temperature Range	- 55 C to + 125 C	- 200 C to + 850 C	- 600 C to + 2000 C	- 50 C to + 150 C
Linearity	Exponential	Fairly Linear	Fairly Linear	Best
Sensitivity	High	Low	Medium	Highest
Response Time	Fast	Slow	Fast to Slow	Slow
Excitation or Power	Needed	Needed	Not Needed	Not Needed
Long-Term Stability	Low	High	High	Medium
Self-Heating	Yes	Yes	No	Yes
Cost	Low	Low (film) High (wire wound)	Moderate to High	Low to Moderate

Figure 4 Comparative Analysis between different types of Temperature Sensors

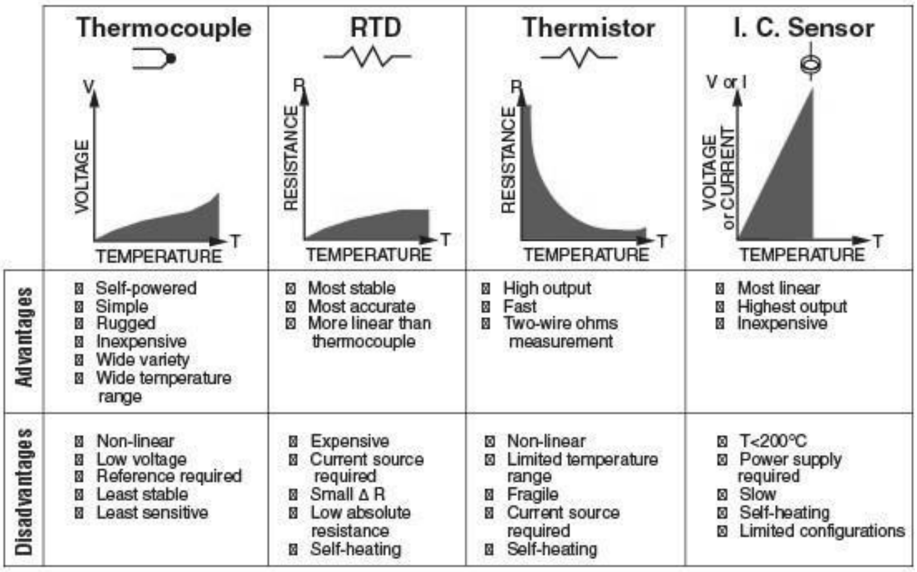

Figure 5 Comparative Analysis Between output response of Different Sensors

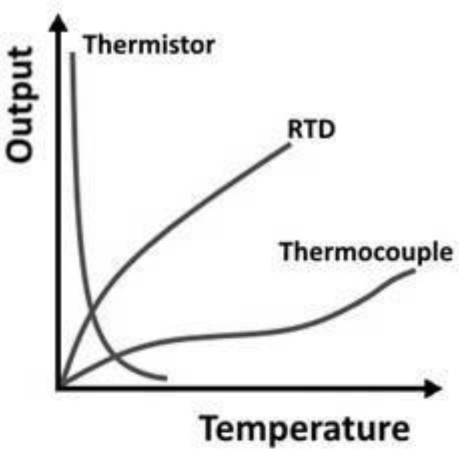

Figure 6 General Comparison between non linearity of Different temperature Sensors (Not in Scale)

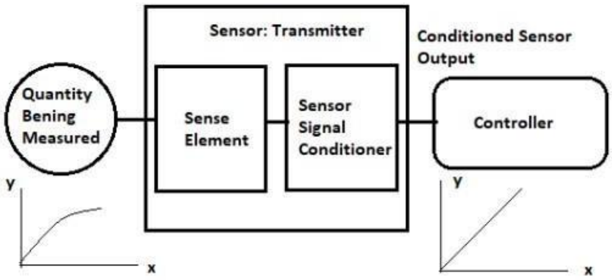

Figure 7 Basic Sensor Linearization workflow

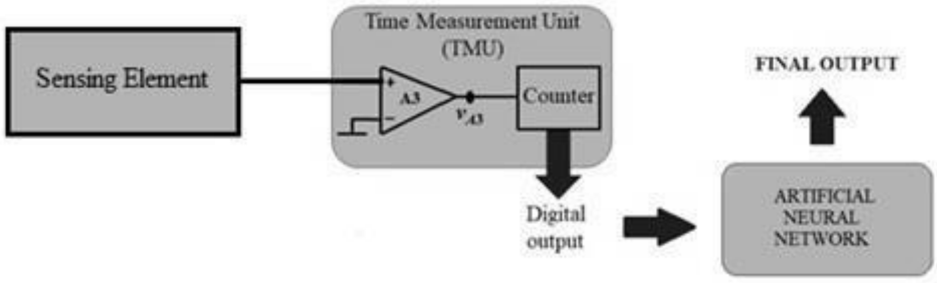

Figure 8 Basic Neural Network based Thermocouple Linerizer

The idea is to create a linearizer converter circuit (Figure 9) at the initial stage of the circuit. This circuit will emulate the output of any nonlinear linearizer to the output of a nonlinear thermocouple. As the thermocouple linearizer is already present then it will become easy for the existing circuit to linearize that output to a standard value.

Comparison Results: As the above Picture Shows the Proposed work. As the non-Linearity between different Sensors are very much different. The project work becomes very Complex and Mathematically Challenging. However a Universal Lineariser can be used as a great device in Thermometry for easy measurement of temperature in socio economic scenario where choice of sensor is a luxury. The thermocouple voltage, VTC, is a function of the thermocouple type, the measurement junction temperature (TMJ), and the reference junction temperature (TRJ).

$$V_{TC} \propto T_{MJ} - T_{RJ} = (T_{MJ} - 0) - (T_{RJ} - 0) \quad \text{… (i)}$$

Thermistor is characterized by The Steinhart-Hart equation. This is a model that was developed at a time when computers were not ubiquitous and most mathematical calculations were done using slide rules and other mathematical aids, such as transcendental function tables. The equation was developed as a simple method for modelling thermistor temperatures easily and more precisely. The Steinhart-Hart equation is:

1/T = A + B(lnR) + C(lnR)2 + D(lnR)3 + E(lnR)4 … (ii)

Where: T is temperature, in Kelvins (K, Kelvin = Celsius + 273.15) , R is resistance at T, in Ohms (Ω), A, B, C, D, and E are the Steinhart-Hart coefficients that vary depending on the type of thermistor used and the range of temperature being detected. ln is Natural Log, or Log to the Napierian base 2.71828

For RTD, The relationship between the RTD’s resistance and temperature is described by the Callendar-Van Dusen equation,

RRTD = R0[1 + AT + BT2 + C(T – 100)T3] … (iii)

Whose values are defined as follows: R0 is a 100-W resistance at 0°C (Pt100) A = 3.9083 × 10–3 B = –5.775 × 10–7 C = 0 for T > 0°C, or C = –4.23225 × 10–12 for T < 0°C

As the comparisons in shown in Figure 10 show that Thermistor provides an exponential decay in non-linearity with respect to increase in temperature.

Thermocouple is much more linear device when it comes as the temperature equation and we can see for a range temperature selected. Figure 10 shows the full scale for a Thermocouple when put under a range of Temperatures. Please refer to Figure 11.

For RTD the resistance (voltage) vs. temperature curve shows fairly linear characteristics in comparison with the Thermistor and Thermocouple and can be used without much complexity for a wide range of temperatures. If course reading is to be taken analog RTD provides far better option as shown in Figure 12

IC sensors provide far more superior linearity in comparison with the rest of the three as depicted above and has highest order of linearity compared to all. However in many cases IC sensors will work on for limited no. of temperature changes so with that even with its linearity order, it can’t be used in all the areas where high temperature is to be monitored.

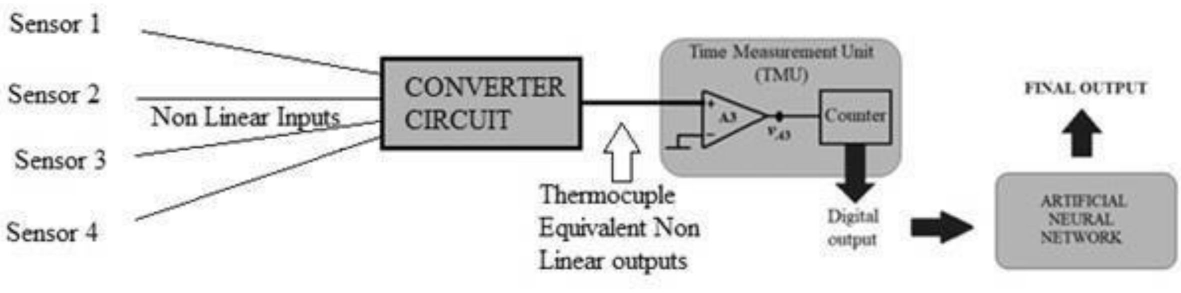

Figure 9 Proposed Universal Linerizer

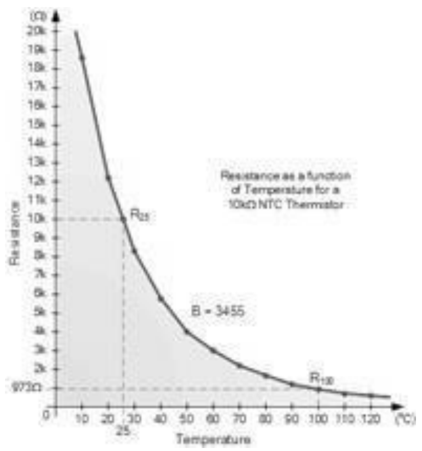

Figure 10 Thermistor non Linearity with respect to temperature

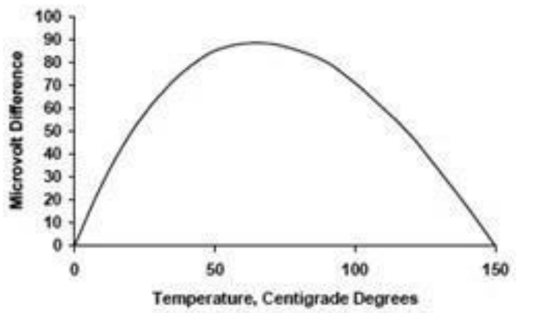

Figure 11 Thermocouple linearity range for a range of temperatures.

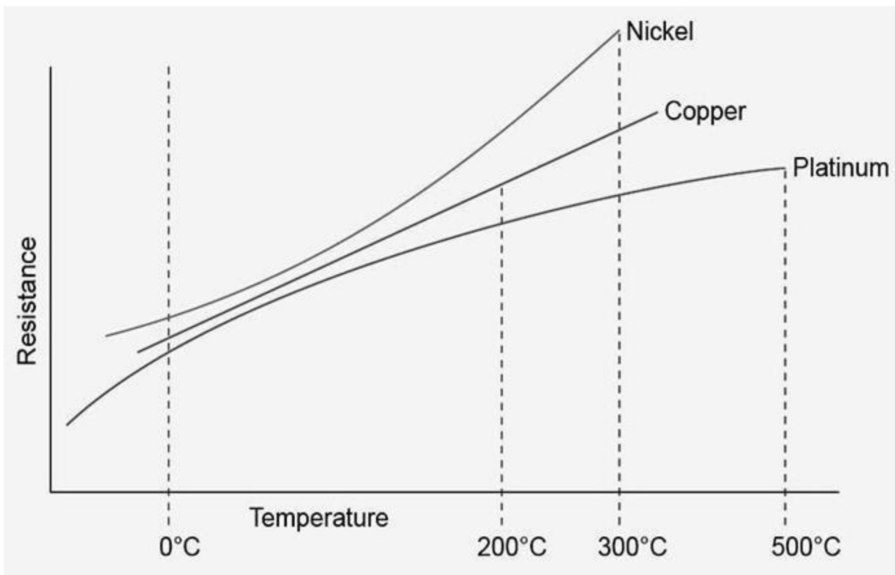

Figure 12 RTD Temperature vs. Resistance linearity

Conclusion: Scarcity of Universal Linearizer has made the industry rely on specific sensor and specific system design. This in turn has increased the cost of manufacturing and use of costly systems. As each sensor shows separate type of non-linearity it is evident that this situation will prevail until something is done specifically. The goal of this research proposal has been to focus on scientific and economic conditions to ease the difficulty faced by the industry. The invention of Universal Linearizer will create both scientific breakthrough as well as will make the choice of specific sensor for measuring thermometric activities optional.

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