

IMPLEMENTATION OF COLD JUNCTION COMPENSATION IN A THERMOCOUPLE USING A TEMPERATURE SENSING CAPACITOR

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Abstract

Thermocouples are widely used for temperature measurement, however they, need linearization and cold-junction compensation. This paper proposes an embedded system for a K-type thermocouple with cold junction compensation using a temperature sensing capacitor. Even though capacitive sensors are widely used for measuring various parameters, using them for measuring temperature is a recent research area. The proposed system has a minimal signal conditioning circuit for linearization and cold-junction compensation. Linearization was achieved using the NIST standard polynomial and cold-junction compensation was accomplished using a Class 1 U2J/N750 ceramic capacitor. The capacitance of this ceramic capacitor varies linearly as a function of temperature. Maximum error for the temperature sensing capacitive sensor was 0.25°C. A K-type thermocouple without any signal conditioning circuit possesses 2.03% nonlinearity over the range –100°C to 1372°C. Maximum error after linearization and cold junction compensation was found to be 0.52°C. The proposed embedded system is simple and cost effective.

Keywords: temperature sensing capacitor, cold junction compensation, linearization, thermocouple.

1. Introduction

Thermocouples are sturdy, cost-effective, have a long operational life and have a wide operating range. They are used in industries like power unit production, nuclear sector, pharmaceuticals, *etc.* However, they are nonlinear and produce output depending on its cold junction. The need to compensate for ambient temperature at the cold junction leads to various compensating methods as seen in literature. In the study reported in [1], cold junction was maintained at ice point, but maintaining it at this level was very difficult and not practical. Linearization of a thermocouple was achieved using *Artificial Neural Networks* (ANN). In the work [2], the cold junction temperature was measured using a thermistor for compensation. The strong nonlinearity of thermistor required

linearization, which was addressed using a *Deep Recurrent Neural Network* (DRNN). The thermocouple was also linearized using a *Deep Feedforward Neural Network* (DFNN). This method required a sophisticated processor for training and deployment. Paper [3] shows signal conditioning circuits to interface the thermocouple along with *Cold Junction Compensation* (CJC) using a thermistor. The high nonlinearity of thermistor requires linearization and the associated circuit is analogue and complex in nature. The output of the thermocouple with CJC is a frequency proportional to the temperature. The authors in [4], devised a smart temperature measurement system using a thermocouple along with CJC. Signal conditioning was achieved using an *Analog to Digital Converter* (ADC), instrumentation amplifier and microcontroller. The CJC was obtained inputting a pre-calibrated temperature signal to the digital converter. The circuit performed well, but again the complexity involved was high. Another research work on temperature measurement using a thermocouple was reported in [5]. The CJC was implemented using a *Look Up Table* (LUT) for the thermistor. The drawback of the solution was that the LUT tables required large memory while intermediate values needed interpolation. The thermocouple was linearized using multi linear models. In [6], an analogue signal conditioning circuit for K-type thermocouple was used with CJC using a semiconductor diode.

Most of the available literature presents how resistive sensors and semiconductor temperature sensors are used for cold junction compensation. Although connecting a thermocouple is simple as it generates a voltage output, the interfacing circuit becomes complex due to cold junction compensation. Linearization of a thermistor requires either a dedicated linearization circuit or artificial intelligence to linearize the thermistor. A suitable linear sensor is required as a replacement for the thermistor. The complexity associated with the CJC methods shown in [2, 3, 5, 6] can be significantly reduced when a linear sensor is used for cold junction temperature measurement. A lot of advancement is taking place in this field and still there is a scope for improvement with new sensors or new technologies.

Today's demand is to mitigate signal conditioning circuits and interface sensors with a minimal signal conditioning circuit to an embedded system. Thermocouples generate output voltage so that it can be interfaced with a microcontroller through an ADC without any other signal conditioning circuit. But the signal conditioning needed for cold junction compensation makes the circuit complex and hence a simple circuit is of key importance. Capacitive sensors are used widely to sense various physical parameters such as humidity, flow, level, moisture, and pressure [7]. The use of capacitive sensors for temperature measurement has not been largely explored and constitutes an emerging research area. Use of capacitive sensor for cold junction compensation of thermocouple is not reported. The interface of capacitive sensors with microcontrollers is an interesting topic. Several techniques are available for interfacing a capacitive sensor, some of them are listed as follows. The book cited in [8] explains in detail the advanced techniques of interfacing both perfect and lossy capacitive sensors in Chapter 2. An analogue circuit for water level measurement using capacitance to frequency conversion technique was reported in [9]. The circuit uses an operational amplifier, a flip-flop, and switches for conversion from capacitance to frequency. In [10], a closed-loop-switched capacitor to convert capacitance to frequency for single and differential capacitive sensors was presented. A relaxation oscillator-based capacitance to frequency conversion was reported in [11] where a transformer ratio arm bridge circuit was used as the signal conditioning circuit. The output frequency was linear with respect to change in capacitance. Multiple approaches to interface capacitive sensors are reviewed in [12]. It discusses in detail the capacitance-to-frequency conversion method along with other techniques.

An additional method to interface capacitive sensors using capacitive bridge circuits is reported in [13]. The capacitive sensor is interfaced using a relaxation oscillator-based circuit. Output is obtained in the form of a frequency signal. It has an analogue signal conditioning bridge circuit with

microcontroller compatibility. A low-cost low value capacitive sensor interface circuit using the resistor-capacitor (RC) method was reported in [14]. The change in capacitance was there converted to a change in the time period. The measurement was obtained using reference capacitance. [15] shows the interface of a capacitive sensor with a microcontroller to measure humidity. The research reported in [16] also reveals the direct interface technique of both resistive and capacitive sensors with a microcontroller using the RC method to time-conversion technique. This paper also gives details on interfacing single, differential and lossy capacitors. All these methods reported in [14–16] use three measurement cycles. A relative humidity capacitive sensor is directly interfaced using an RC circuit in [17] where analogue comparators, analogue-to-digital converter, potential divider, trigger and timer were used to measure the capacitance value. The article [18] shows the interface of a capacitive sensor with a microcontroller revealing the advantages of cost and space reduction. In [18], capacitance is measured using two measurement cycles. In [19], using liquid-level sensors of low-cost together with a microcontroller is reported. The RC interfacing technique along with an analogue comparator was used to determine capacitance change. The papers [20, 21] show the interface of differential and lossy capacitive sensors using an RC circuit along with a microcontroller. The effect of parasitic capacitance on the RC interface using microcontrollers for differential sensors is dealt with in [20]. RC interface techniques are very popular, accurate, simple and cost-effective methods, while microcontroller-based systems are beneficial as they result in smart, lucid, compact, cheap and less power consuming electronic interfaces.

This paper presents how a Class 1 *Multilayer Ceramic Capacitor* (MLCC) can be used as a temperature sensor for cold junction compensation. Class 1 ceramic capacitors are known for their stability and low loss. They possess a different temperature coefficient based on the type of material used. For instance, C0G/NP0 is a Class 1 MLCC which is unaffected by temperature. There are also other Class 1 MLCCs such as N33, N150, N470, N750, *etc.*, which exhibit a linear capacitance change with respect to temperature. In this article, it is proposed to use the U2J/N750 Class 1 MLCC whose capacitance change with respect to temperature is -750 ± 120 ppm/°C in the operating range -55°C to 125°C . This linear change with respect to ambient temperature can be utilized for cold junction compensation of a thermocouple. There are different methods to interface a capacitive sensor to a microcontroller, namely an AC bridge, relaxation oscillator, capacitance to frequency/time, charge-transfer method *etc.*, Capacitance-to-time conversion using the RC interface is a simple, low power and low-cost technique. A simple RC circuit is used here to interface the capacitive sensor with a microcontroller for temperature measurement.

2. Description of the proposed measurement system

The proposed embedded system of the thermocouple along with cold junction compensation is shown in Fig. 1. The thermocouple is connected to ports P1 and P2 of a Raspberry Pi microcontroller [22] through a 24-bit ADC ADS1256 [23]. The voltage ΔV generated by the K-type thermocouple is passed through an inverse model based on NIST polynomials [24] to obtain a linearized temperature output, it needs to be compensated as the ambient temperature is not fixed at 0°C . A temperature compensating capacitor C_T made of Class 1 Surface Mount Multilayer Ceramic Capacitor U2J/N750 is used to measure ambient temperature. The capacitor C1206C104F5JACTU [25] has a nominal value of 100 nF at 25°C and capacitance variation of -750 ± 120 ppm/°C in the operating range -55°C to 125°C . The capacitance sensor is connected to a 555 timer in astable mode.

Capacitance C_T changes according to ambient temperature variation while the astable multi-vibrator generates a corresponding pulsed output waveform. The temperature sensing capacitor charges up to upper threshold voltage V_{TH} equal to $2/3$ rd of V_{CC} through the fixed resistors R_1

and R_2 and discharges till lower threshold voltage V_{TL} is equal to 1/3rd of V_{CC} through the fixed resistor R_2 as shown in Fig. 2a. The output of the astable multivibrator is HIGH during charging and LOW during the discharging of the capacitor as depicted in Fig. 2b.

The time taken by the astable multivibrator to discharge from upper threshold to lower threshold voltage is as follows:

$$T_x = R_2 C_T \ln \left(\frac{V_{TH}}{V_{TL}} \right). \quad (1)$$

Here, the upper threshold voltage $V_{TH} \left(\frac{2}{3} V_{CC} \right)$ and the lower threshold voltage $V_{TL} \left(\frac{1}{3} V_{CC} \right)$ are constant and R_2 is a constant resistance in series with the temperature sensing capacitor C_T . So, from (1), a change in discharge time is directly proportional to a change in capacitance as ambient temperature varies. The discharge time period is measured by connecting the output of the astable multivibrator to the *General-Purpose Input Output* (GPIO) pin P3 of Raspberry Pi. This time-period is calibrated in terms of temperature and is used to compensate the cold junction of the thermocouple connected to the microcontroller.

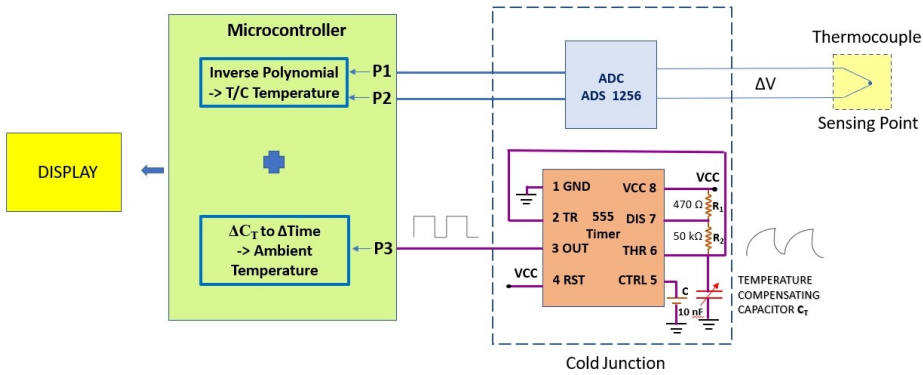


Fig. 1. Direct interface of the thermocouple along with cold junction compensation.

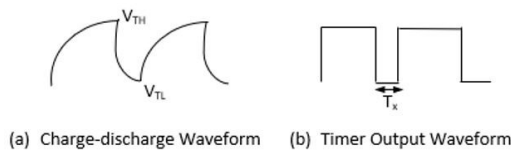


Fig. 2. Model graph.

3. Experimental evaluation of the proposed circuit

3.1. Characterization of the capacitor as a temperature sensor

The temperature sensing capacitor is kept in a temperature regulated environment and its capacitance is observed using a Hioki LCR meter [26] as illustrated in Fig. 3. The characteristic of the capacitive sensor is studied for the range 0°C to 100°C. The lower temperature range 0°C to 50°C is varied in a temperature-controlled chamber [27] and the higher range of 50°C to 100°C varied in a Venticell oven [28]. The capacitance decreases from 101.9 nF to 94.4 nF as temperature increases from 0°C to 100°C.

The resultant characteristic of the capacitive sensor as temperature varies is shown in Fig. 4a and it can be observed that Class 1 MLCC U2J/N750 has a linear characteristic. The time taken to discharge the voltage across capacitance decreases as ambient temperature increases as shown in Fig 4b. The time taken by the capacitor to discharge was observed for each ambient temperature in steps of 5°C from 0°C to 100°C. Ambient temperature reading is calculated by the time taken to discharge the capacitor using the astable circuit through a digital storage oscilloscope, as discussed earlier. Maximum error observed while using the capacitive sensor for temperature measurement was 0.25°C.

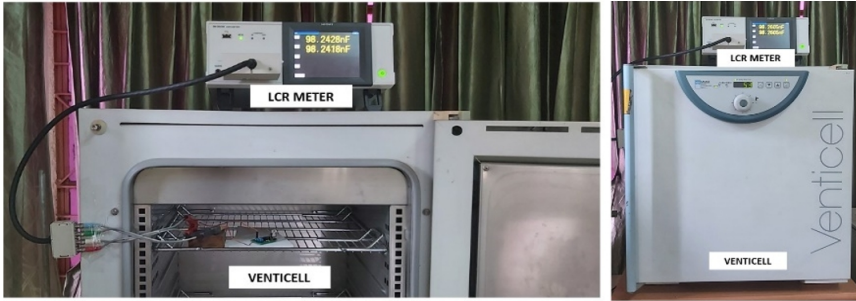


Fig. 3. Experimental setup designed to show the characteristics of the capacitor as a temperature sensor.

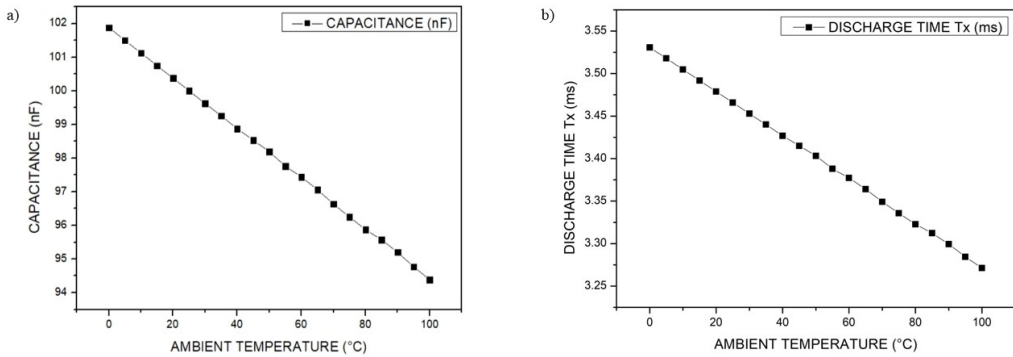


Fig. 4. a) Ambient temperature vs capacitive sensor output and b) ambient temperature vs discharge time.

4. Experimental evaluation using the Yokogawa calibrator

The working of the proposed circuit shown in Fig. 1 for cold junction compensation was verified using the embedded system setup as shown in the Fig. 5. A Yokogawa calibrator [29] was used to simulate K-type thermocouple output in the required millivolt range. The calibrator output was varied from -3.554 mV to 54.886 mV corresponding to the temperature range -100 to 1372°C. This was fed to a 24-bit ADS1256 ADC in differential mode. The measured thermocouple voltage was filtered using a Finite Impulse Response filter of window size 20 and passed through an inverse model polynomial in the Raspberry Pi embedded system. The inverse polynomials were as per NIST standards [24] as shown in Table 1. In (2), (3) and (4), x is the uncompensated thermocouple voltage, which needs to be linearized. Based on the ADC data, one of the three polynomials was chosen by the embedded system for linearization and the nonlinearity was reduced from 2.03% to 0.02%.

Table 1. Inverse polynomial for linearization of the thermocouple.

Inverse Polynomial	Operating Range
$25.17x - 1.17x^2 - 1.08x^3 - 8.98 \cdot 10^{-1}x^4 - 3.73 \cdot 10^{-1}x^5$ $-8.66 \cdot 10^{-1}x^6 - 1.05 \cdot 10^{-2}x^7 - 5.19 \cdot 10^{-4}x^8$ (2)	-100°C to 0°C
$25.08x + 7.86 \cdot 10^{-2}x^2 - 2.5 \cdot 10^{-1}x^3 + 8.32 \cdot 10^{-2}x^4 - 1.23 \cdot 10^{-2}x^5$ $+9.8 \cdot 10^{-4}x^6 - 4.41 \cdot 10^{-5}x^7 + 1.06 \cdot 10^{-6}x^8 - 1.05 \cdot 10^{-8}x^9$ (3)	0°C to 500°C
$-1.32 \cdot 10^2 + 4.83 \cdot 10^1x - 1.65 \cdot 10^0x^2 + 5.47 \cdot 10^{-2}x^3$ $-9.65 \cdot 10^{-4}x^4 - 8.8 \cdot 10^{-6}x^5 - 3.11 \cdot 10^{-8}x^6$ (4)	500°C to 1372°C

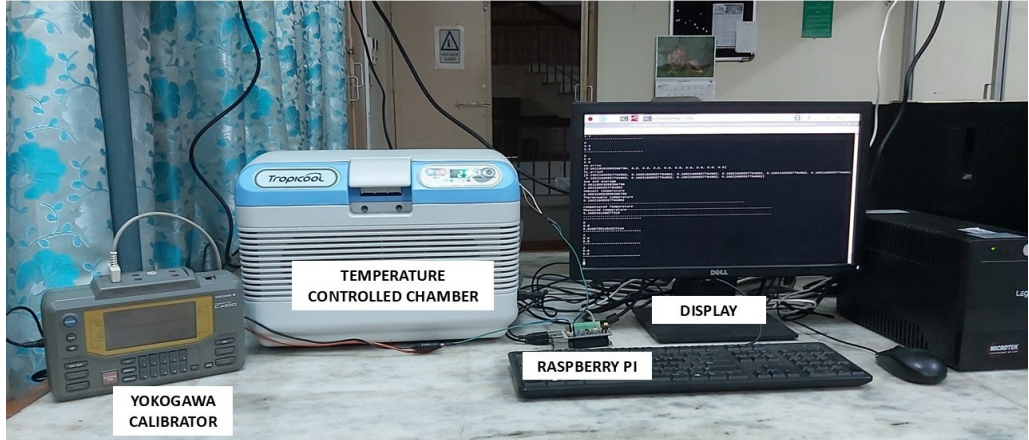


Fig. 5. Experimental set up (using the Yokogawa calibrator).

The output obtained after passing through the inverse polynomial needs to be cold junction compensated if ambient temperature is not maintained at 0°C . A temperature compensating capacitor was used to sense ambient temperature which was varied from 0°C to 40°C in steps of 10°C as the measured temperature was simulated from -100°C to 1372°C . The linearized thermocouple output and temperature sensing capacitor output calibrated in temperature scale were added together to get the cold junction compensated thermocouple output. Fig. 6(a) shows the measured output temperature at various cold-junction (ambient) temperatures. Figure 6(b) shows the corresponding error. Figure 6(a) indicates that the variation of ambient temperature does not affect the measured temperature. Note that for the same variation in the measured input temperature, only the ambient temperature is varied from 0°C to 40°C in steps of 10°C . But the compensated measured output remains unchanged. In other words, the variations in ambient temperature does not affect the measured output.

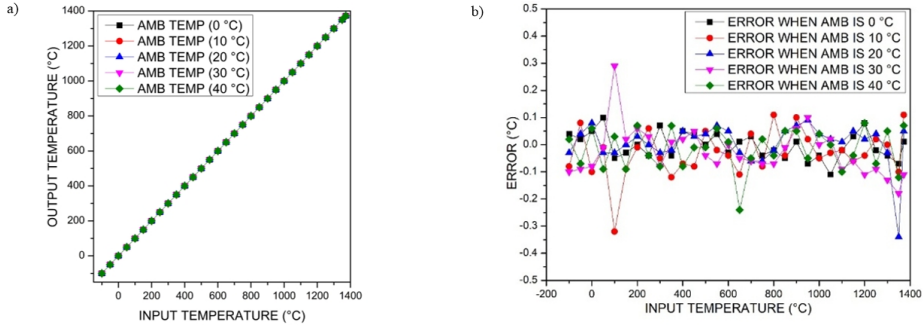


Fig. 6. a) Input temperature vs output temperature with CJC (using the Yokogawa calibrator) and b) error observed at different ambient temperatures.

A counter is used inside Raspberry Pi to count the time taken to discharge the capacitor of the astable multivibrator at a given temperature. These counter values are calibrated to temperature as shown in the Table 2.

Table 2. Conversion of counter values to temperature.

Ambient Temperature °C	Counter Value corresponding to Discharge Time	Measured Ambient Temperature °C
0	3482272	0
10	3456636	10
20	3431004	19.99844
25	3418184	24.99922
30	3405364	30
40	3379728	40

The procedure for calibration of counter values for 25 °C is as follows:

$$T_{25} = \frac{\text{Counter value corresponds to } 25^{\circ}\text{C} - \text{counter value corresponds to } 0^{\circ}\text{C}}{\text{Counter value corresponds to } 40^{\circ}\text{C} - \text{counter value corresponds to } 0^{\circ}\text{C}} \cdot 40, \quad (5)$$

$$T_{25} = \frac{3418184 - 3482272}{3379728 - 3482272} \cdot 40, \quad (6)$$

$$T_{25} = 24.99922^{\circ}\text{C}. \quad (7)$$

Suppose the measured thermocouple voltage is 10.971 mV. It is passed through the NIST polynomial and converted as 270 °C as the measured uncompensated temperature. This temperature is measured with respect to ambient temperature 25 °C. Therefore, the actual measured temperature with respect to 0 °C is sum of ambient temperature and thermocouple measured temperature. Hence, the measured temperature with respect to 0 °C is 270 °C + 24.99922 °C = 294.99922 °C as shown in Table 3.

Maximum error found during this measurement process was 0.34 °C. Parasitic capacitance/stray capacitance would affect measurement in capacitive sensors. The capacitive sensor was not remotely located and hence stray capacitance due to connecting wires was eliminated. However, the parasitic capacitance due to port pins in the astable multivibrator needs to be considered. Proteus software was used to test the effect of parasitic capacitance. In due course, a parasitic capacitance of 8–10 pF was added in parallel to the capacitive sensor [20]. It turned out that the discharge time was not affected by parasitic capacitance. As parasitic capacitance was in pF and sensor in nF there was no appreciable error in the circuit.

Table 3. Comparison of uncompensated and compensated temperature.

Measured Hot-Junction Temperature	270°C
Actual Hot-Junction Temperature	295°C
Measured Ambient Temperature	24.99922°C
Compensated Measured Temperature	294.99922°C
Uncompensated Measured Temperature	270°C
Error due to un-compensation in Temperature	25°C

4.1. Experimental Validation

The working of the proposed circuit was validated using a K-type thermocouple [30] with the set up as shown in the Fig. 7. A Venticell oven was used to vary the input temperature of the thermocouple chamber from 50°C to 300°C and the ambient temperature varied from 0°C to 40°C in steps of 10°C using a temperature-controlled chamber. Raspberry Pi reads the thermocouple generated voltage using ADC followed by the discharge time period using GPIO pins and executes linearization of thermocouple output and cold junction compensation by adding the ambient temperature obtained using the capacitive sensor. The cold junction compensated output is sent to the monitor. Fig. 8 shows the input vs output temperature and maximum error observed in thermocouple output temperature along with cold junction compensation was 0.52°C.



Fig. 7. Experimental setup.

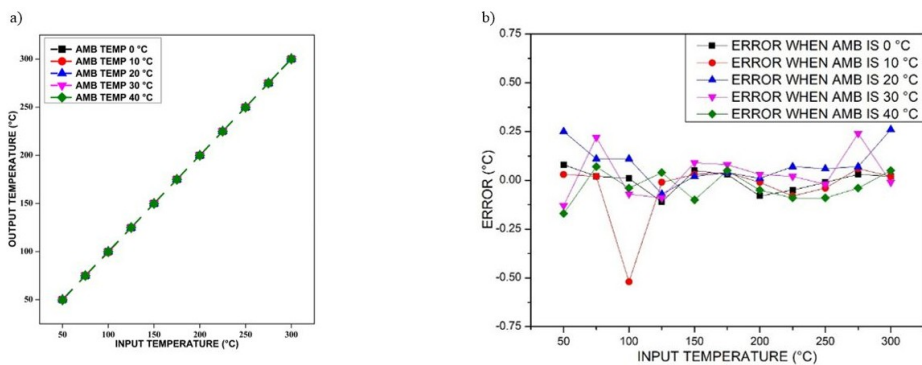


Fig. 8. a) Input temperature vs output temperature with CJC using a K-type thermocouple (50 to 300°C) and b) error observed for different ambient temperatures.

5. Results and discussion

The embedded system was tested for the entire range (-100°C to 1372°C) of the thermocouple using the Yokogawa temperature calibrator with CJC and maximum error was found to be 0.34°C . Finally, the embedded system was validated with a K-type thermocouple for the range of 50 – 300°C . Maximum error was found to be 0.52°C . The results are compared with reported work as shown in Table 4. The use of linear capacitive sensor resulted in a simpler interface circuit. The drawback of the capacitive sensor is that it cannot be used in high humidity conditions (above 70% relative humidity).

Table 4. Comparison of results for inverse polynomial for linearization of the thermocouple with the reported work.

No.	Method	Sensors used	Range [$^{\circ}\text{C}$]	Error	Comments
1	Design of a high precision temperature measurement system based on ANN [1]	K-type thermocouple CJ: Ice point (0°C)	-200 to 1000	MSE: $7.7 \cdot 10^{-4}$	There is no cold junction compensation.
2	Deep Learning based Linearization [2]	K-type thermocouple CJC: $1\text{ k}\Omega$ NTC thermistor	0 to 300	0.34°C	Requires sophisticated processor for training and deployment. Linearization of thermistor is required.
3	A synergy of voltage-to-frequency converter and continued-fraction algorithm [3]	S-type thermocouple CJC: $50\text{ k}\Omega$ NTC thermistor	45 to 100	max error: $\pm 1.4^{\circ}\text{C}$	The system is complex. Requires dual power supply with the operating range being short. Analog circuit.
4	Thermocouple based smart industrial thermometer [4]	K-type thermocouple CJC: digital sensor	0 to 200	0.6°C	Not tested for a wide operating range. Complex signal conditioning circuit was used. NIST polynomial was used for linearization.
5	Multilinear Model Technique for Thermocouple Linearization [5]	J-type thermocouple K-type thermocouple CJC: $5\text{ k}\Omega$ thermistor (30°C)	0 to 7600 0 to 320	Simulation: 0.12% NL Experiment: 0.41% NL	Piecewise linearization and CJC was based on LUT, and thus required large memory and interpolation.
6	Proposed method	K-type thermocouple CJC: capacitive sensor	-100 to 1372 (Yokogawa temperature calibrator 50 to 300)	0.34°C 0.52°C	Designed for a wide range of thermocouple operation from -100 to 1372°C . It worked well for ambient temperature varied from 0 to 40°C . Simple and compact circuit.

6. Conclusions

A cold junction compensation using temperature measurement using capacitive sensor for a thermocouple was proposed. Interface of a capacitive sensor using the RC method with an embedded system was executed. The characteristics of the ceramic capacitive sensor used for temperature measurement was linear in the range from -55°C to 125°C . The hot junction of thermocouple was simulated using a Yokogawa calibrator, working in a wide range and maximum error was found to be 0.34°C . The proposed system was also tested using a K-type thermocouple for a temperature range 50°C to 300°C as ambient temperature varied from 0°C to 40°C . Maximum error along with CJC using capacitive sensor was found to be 0.52°C . The results validated the efficiency of the proposed method. This Class 1 Ceramic Capacitor can also be used as temperature sensors for other applications.

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