Optimized Thermocouple Temperature Sensor using 555 Timer and ANN Based Linearization

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***Abstract*—The presented work reports a low-cost, two-stage linearization scheme for thermocouple based temperature sensing. The first stage involves IC555 based astable multivibrator. An NTC thermistor is employed as a discharging resistor of multivibrator to facilitate reference junction compensation as well as the measurement of ambient temperature. The second stage of linearization employs ANN based fitting between the output of IC555 and true temperature. The linearization scheme uses a trade-off between the fast response of IC555 based arrangement and exorbitant accuracy of ANN-based arrangement, to optimize the performance of the sensor. The PSpice based simulation study is carried out with a T-type thermocouple for temperature range of 80°C to 125°C while the ambient temperature varies from 25°C up to 40°C. It offers absolute maximum full-scale error of 0.13%, as little as in the best existing literature, with a reduced computational burden upon the processing unit.**

***Keywords*—IC555, ANN, Temperature sensor, Linearization, Astable Multivibrator.**

I. Introduction

As the temperature transducers commonly used in practice (eg.: thermocouple, thermistors, and the rest), have non-linear transfer characteristics [1], the linearizing arrangement is almost an inextricable part of a temperature sensing element. To start with, analog passive components based linearizing circuits [1] and opamp based logarithmic amplifiers [2] [3] emerged. They produced a fast response. Much later, with the advent and subsequent use of digital signal processing systems, software based linearization schemes were introduced and gained popularity [4]. Most widely used linearization techniques employ look-up tables (LUT) or a combination of LUT with appropriate interpolation algorithm. Subsequently, some FPGA based systems performed decent linearization [5]. In addition, the linearizing arrangements, based on modulation of the pulse train, obtained from IC555 timer, had gained popularity as stated in [6] and [7]. Very soon, advanced processor-based linearizers, like the ANN-based linearizer [8] [9] [10], rose to prominence, surpassing the opamp based linearizers as the latter were prone to aging and drift. Due to the rapid development of 'Very Large Scale Integration' (VLSI) technology, these microcontroller and microprocessor-based systems have come up with excellent solutions in terms of superlative accuracy as compared to the previous. Nevertheless, some of these software-based solutions cannot be implemented in the feedback path of a control system as they impose a huge computational burden and therefore a time-delay, and furthermore, they may require plug-in-modules

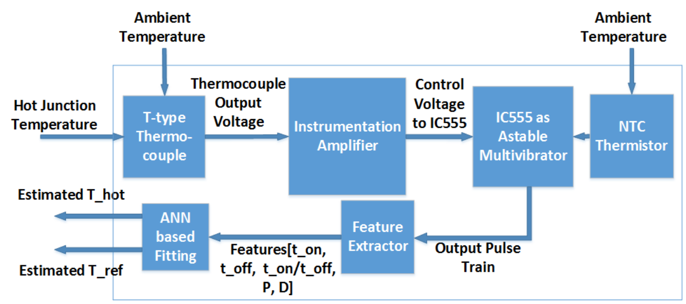


Fig. 1: Block Diagram of Proposed Temperature Sensor

(PIM) with a microcontroller, that further increases the cost of implementation as described in [11]. Therefore, a trade-off between speed of response and accuracy of the sensor is required. In this work, such a scheme has been proposed for a thermocouple transducer. In the work presented in this paper, T-type thermocouple has been used as a temperature transducer, followed by linearizing arrangement. It is worth noting that for a thermocouple temperature sensor, the linearizer is required to perform the task of linearizing the output versus measurand (temperature) characteristic, together with the task of reference junction compensation [12]–[15] Thus, in essence, the duty of the linearizer is to perform 2D signal processing, where the information related to the temperature under measurement and reference junction temperature of the thermocouple, are the two inputs. In this work, the linearization scheme is split into two stages. In the first stage, 555 timer operating in astable multivibrator mode serves as linearizer. In the second stage, an Artificial Neural Network (ANN) based fitting between input and output is done to further improve the linear characteristics. The overall system, therefore, utilizes the high accuracy of the processor-based system. Moreover, due to the preceding linearization stage, the computational burden of the processor is significantly reduced. The concept of such two-stage linearization has been previously reported in [10]–[12]. In this context, the analog linearizing circuits are still relevant as first stage linearizers

[16]. But, the approach presented here has performed better in terms of higher accuracy as revealed by PSpice simulation studies and has the potential for faster response.

II. System Architecture

The proposed sensing arrangement is shown in figure 1.

A. The thermocouple

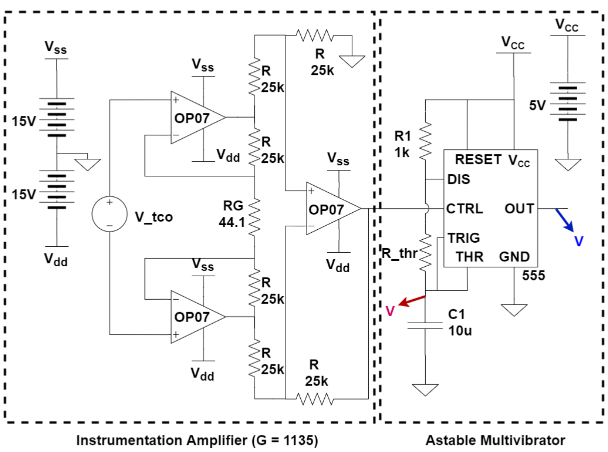
Let, E(T) be the thermal emf generated by the thermocouple when the hot junction and reference junction are maintained at T°C and 0°C junction respectively. Then, the thermal emf, when hot-junction and reference junction temperatures are T_{hot} and T_{ref} respectively, is:

$$E(T_{hot}, T_{ref}) = E(T_{hot}) - E(T_{ref}) \tag{1}$$

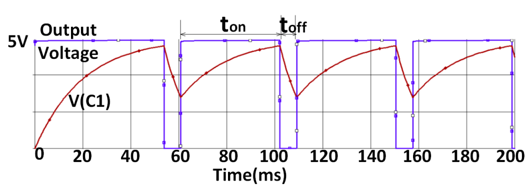
T_{ref} indicates the ambient temperature to which the reference junction is exposed.

B. Instrumentation Amplifier (IA)

A three-opamp based IA has been used. The OP07 ICs, an opamp, additional circuitry consisting of 25kΩ standard precision resistors and a 100Ω pot as gain resistor served the purpose as in figure 2(a). It is seen from PSpice simulation that, if the control voltage of the 555 timers is either greater than 4.6V or less than 1.5V, then t_{on} and t_{off} deviate from equation 6 considerably. The output voltage of IA is also the control voltage of IC555 as can be seen from figure 2(a). So,



(a) Circuit diagram for first Stage linearization. V_{tco}(=E(T_{hot},T_{ref})) denotes thermocouple voltage under hot and reference junction temperatures T_{hot}°C and T_{ref}°C respectively. R_{thr} denotes thermistor resistance at T_{ref}°C



(b) Pulse train from pin3 of IC555

Fig. 2: Astable Multivibrator based First Stage Linearization Using IC555

$$1.5V \leq G \cdot E(T_{hot}, T_{ref}) \leq 4.6V \tag{2}$$

From equations 1 and 2, it can be inferred that,

$$G \cdot E(T^m_{hot}, T^M_{ref}) = 1.5V \tag{3}$$

$$G \cdot E(T^M_{hot}, T^m_{ref}) = 4.5V \tag{4}$$

where $T^m_{hot} \leq T_{hot} \leq T^M_{hot}$, $T^m_{ref} \leq T_{ref} \leq T^M_{ref}$ and G is gain of instrumentation amplifier. Now, with the help of T-type thermocouple reference table, T^M_{hot}, T^m_{hot}, T^M_{ref}, T^m_{ref} are considered to be 125°C, 80°C, 40°C and 25°C respectively to accommodate mentioned ambient temperature variation, whilst satisfying constraints 3 and 4 as well. Also, G is found to be 1135. So,

$$1 + \frac{2R}{R_G} = 1135 \tag{5}$$

where R=25kΩ and R_G is gain resistor in figure 2(a). So, R_G is obtained as 44.1 Ω from equation 5 and is adjusted to this value by varying the 100Ω pot.

C. 555 timer based astable multivibrator

The 555 timer in astable multivibrator mode, in figure 2(a), generates output pulse train, as shown in figure 2(b). R_1 and R_2, the timing resistors and the timing capacitor C_1 determine t_{on}, the ON time, and t_{off}, the OFF time, of the output pulse train, as shown in figure 2(b).

$$\{t_{on}, t_{off}\} = \left\{(R_1 + R_2)C_1 \ln \frac{1 - (\frac{V_c}{V_{cc}})}{1 - 0.5(\frac{V_c}{V_{cc}})}, R_2 C_1 \ln 2\right\} \tag{6}$$

Here, V_c is control voltage at pin 5 and V_{cc} = 5V. As seen from equation 6, the pulse width modulation (PWM) of the output pulse train can be performed by varying V_c, R_1 and R_2. $G \cdot E\{T_{hot}, T_{ref}\}$, the output of IA is V_c, the control voltage of IC555. An NTC thermisor of nominal value 5kΩ at 25°C is used as R_2. It is exposed to ambient temperature, T_{ref}. Therefore, from equation 6,

$$\{t_{on}, t_{off}\} = \{f(T_{hot}, T_{ref}), f(T_{ref})\} \tag{7}$$

Conclusively, information about t_{on} and t_{off} are sufficient to get values of T_{hot} and T_{ref}. This conclusion is utilized later to form feature vector F.

D. Feature Extractor

A MATLAB based feature extraction of the pulse train yields the feature vector,

$$F = [t_{on}, t_{off}, \frac{t_{on}}{t_{off}}, P(= t_{on} + t_{off}), D(= t_{on}/P)] \tag{8}$$

P and D are the time period and the duty cycle of the pulse train in figure 2(b) respectively. The pulse train from IC555 is sampled with sampling interval, τ = 10μs, to get the sequence, $S_{pulse}(n\tau)$, n = 0,1,2 etc. Then it is processed to extract F vector.

E. Artificial Neural Network (ANN)

An ANN model, a feed-forward neural network, is used to map F to T_{hot} and T_{ref}. F constitutes the input layer and the output layer comprises of T_{hot} and T_{ref}. In this study,

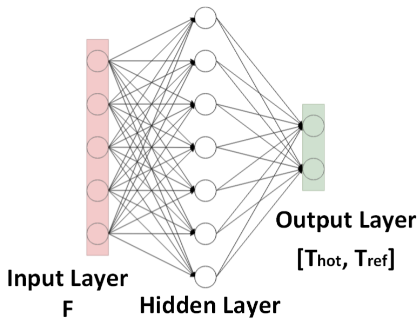


Fig. 3: Architecture of the ANN

one hidden layer has been used, comprising of 7 neurons, as shown in figure 3. In our analysis, $80°C \leq T_{hot} \leq 125°C$ and $25°C \leq T_{ref} \leq 40°C$, and both are varied at intervals of 1°C. As T_{ref} is varied for constant T_{hot}, the measurement of T_{hot} is cold-junction compensated. For simulation studies, T-type thermocouple data available from standard tables and the resistance-temperature data from the manufacturer for a commercially available 5kΩ thermistor, have been utilized.

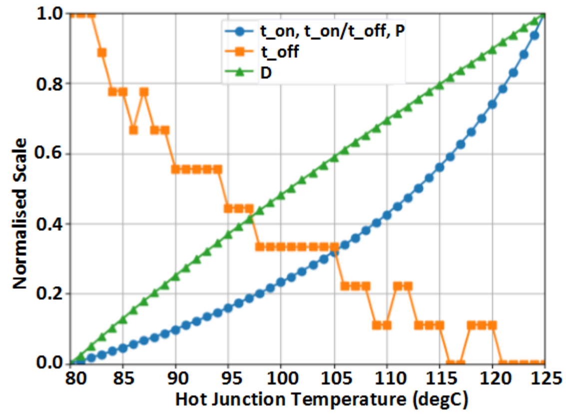
III. Simulation Studies

A. First Stage Linearization

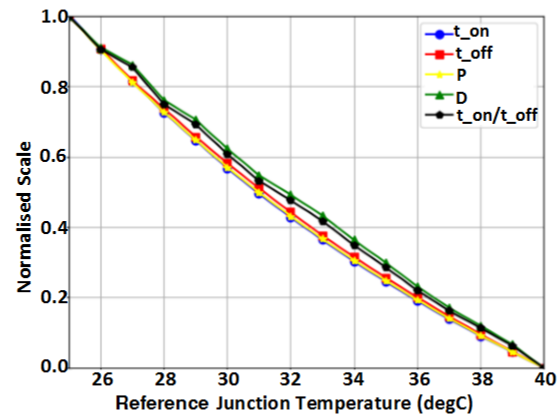
PSpice simulations have been carried out by replacing V11, in figure 2(a), by $E(T_{hot}, T_{ref})$ for every possible combination of $\{T_{hot}, T_{ref}\}$, for first stage linearization. Values of $E(T_{hot}, T_{ref})$ from T type thermocouple reference table, have been used. The thermistor resistance R_2 is also replaced by corresponding resistance for temperature T_{ref} as it is exposed to the ambient condition like reference junction of thermocouple. We used Omega 44007 thermistor datasheet, having nominal resistance R_{25}=5000Ω at 25°C. After first stage of linearization, the characteristics between elements of F and each of $\{T_{hot}$,$T_{ref}\}$, keeping T_{ref}/T_{hot} constant, are shown in figures 4(a) and 4(b) respectively. As we see, for F vs T_{hot} characteristics, D vs T_{hot} has become much linear compared to others. For F vs T_{ref} characteristics, almost all elements have shown good linearity with T_{ref}. The first stage linearization has created 736 samples of input vector, F and output vector, [T_{hot},T_{ref}].

B. Second Stage Linearization

In second stage linearization, out of 736 samples of input and output vector, half samples are used to train the ANN and the remaining half are used to test the performance, using Neural Network Toolbox in MATLAB. After this final stage of linearization, the input and output vector exhibits excellent linear fitting with coefficient of determination, $R^2 \approx 100\%$.



(a) Elements of F vector vs T_{hot} for T_{ref}=30°C

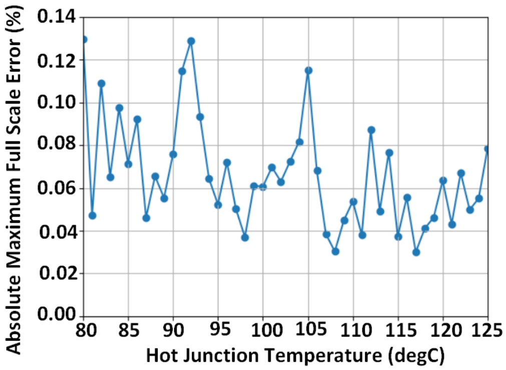


(b) Elements of F vector vs T_{ref} for T_{hot}=100°C

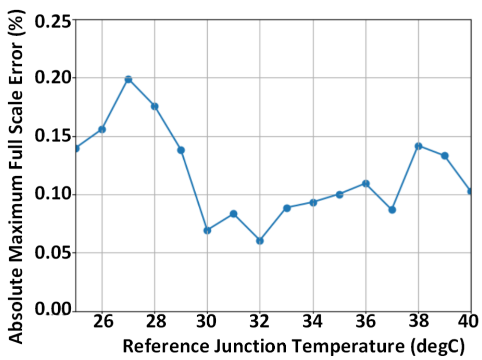
Fig. 4: Characteristics of elements of F vector for varying T_{hot} and T_{ref}

C. Performance Analysis

After two stage linearization, the maximum absolute error in hot and reference temperature estimation, as percentage of full scale value, are represented in figures 5(a) and 5(b). The maximum error of T_{hot} is 0.13% at 92°C. The maximum error of T_{ref} is 0.2% at 27°C. The proposed scheme is compared with those reported in existing literature [10]–[13] as shown in Table I, where studies were carried out using thermocouple based sensors. The papers, taken for comparison, had reported the maximum absolute error in unit of degree celsius. Therefore, for comparison, absolute value in degree celsius is taken for our work as well, instead of percentage absolute full scale error. As evident from Table I, the proposed scheme exhibited least error among recently reported schemes. The presented scheme resulted maximum absolute error of 0.16°C whereas Ximin et al. [14], Mukherjee et al. [16] and Murmu et. al. [15] reported it as 0.8°C, 0.76°C and 1.4°C. The maximum absolute error for Xiimin et al. [14] is taken for -100°C-



(a) Error plotted against T_{hot} ($25°C \leq T_{ref} \leq 40°C$)



(b) Error plotted against T_{ref} ($80°C \leq T_{hot} \leq 125°C$)

Fig. 5: Maximum absolute full-scale error in estimated and actual temperatures

1300°C range. Therefore, far better accuracy, exhibited by the proposed scheme, manifested supremacy of the reported linearization scheme.

IV. Conclusion

In our two-stage linearization scheme for the temperature sensor, a 555 timer based astable multivibrator reduces the computational burden on processor-based second stage linearizer. ANN based second stage linearization inordinately improves the accuracy of the system. So, the system makes optimal use of advantages of both the timer-based linearizer and ANN-based linearizer. Therefore, the proposed sensor can make a firm footing in the embedded systems applications.

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TABLE I: Comparative study of our work with existing literature

Method Proposed By	Maximum Absolute Error (°C)
Danisman et al [10]	0.5%
Ximin [14]	1.0%
Mukherjee et al [16]	0.8%
Murmu et al [15]	1.4%
Authors of this paper	**0.13%**

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