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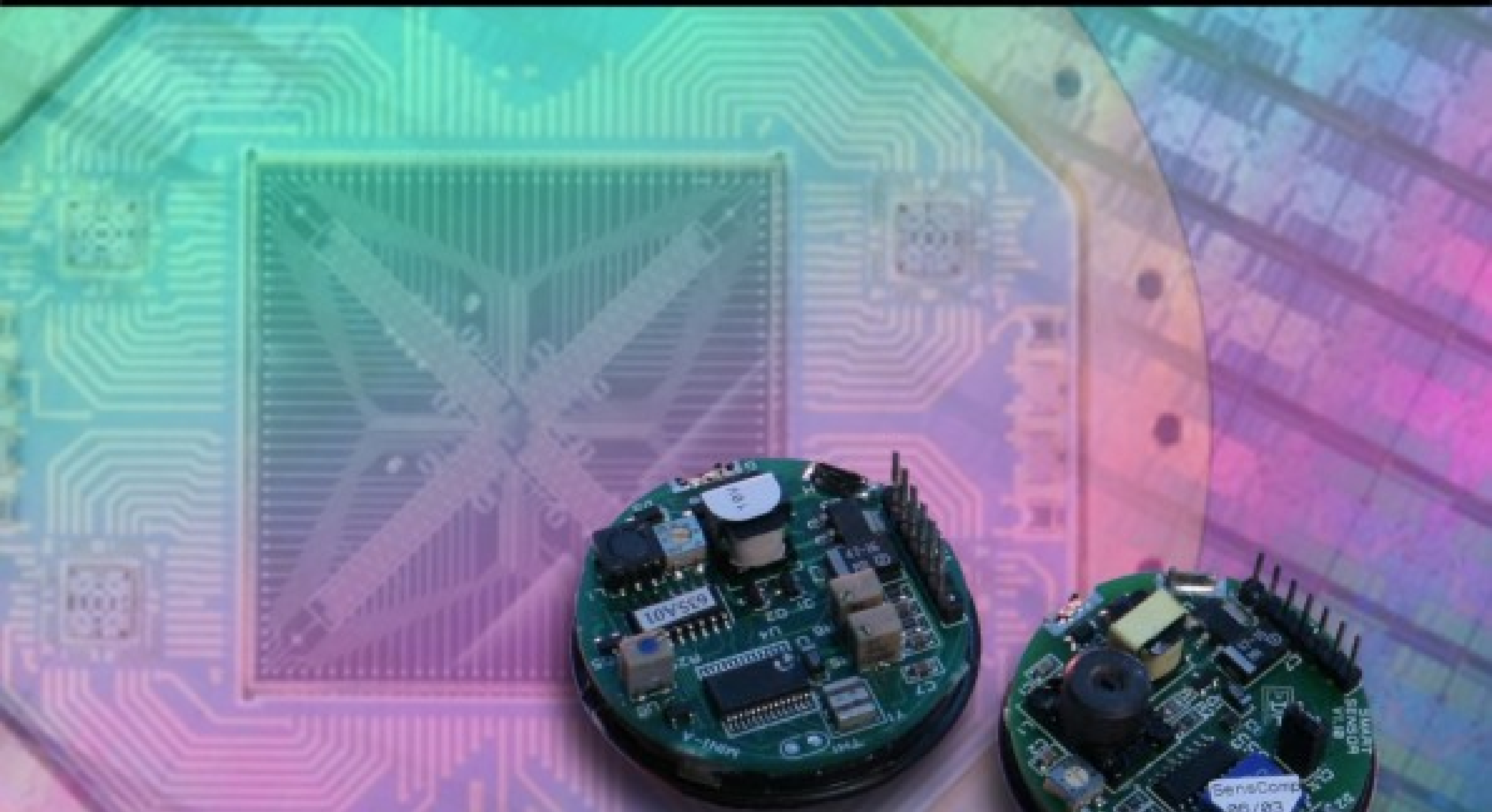

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Design of a Smart and High Precision Industrial Temperature Measurement and Monitoring System Using K-type Thermocouple and SPI-compatible Temperature Sensor

Utpal Sarma, Digbijoy Chakraborty, P. K. Boruah
Department of Instrumentation and USIC, Gauhati University, Guwahati-781014, India
E-mail: utpalsarma@gauhati.ac.in

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Abstract: This paper describes the design of a smart and high accuracy industrial temperature measurement and monitoring system using K-type thermocouple (TC). Normally errors are introduced due to non linear response of the thermocouple. We have linearised the amplified thermoemf using least square polynomial fitting algorithm. The reference junction temperature compensation is done by temperature to digital converter TMP121. Four temperature ranges are selected such that it can be implemented to a 12-bit ADC which operates from a 5 Volt DC source. The description of the system and accuracy obtained in four different temperature ranges is discussed. *Copyright © 2009 IFSA.*

Keywords: Sensor linearisation, Smart sensor, Data acquisition circuits

1. Introduction

Temperature is one of the most important variables in industrial process monitoring and control. Based on the demand of accuracy, resolution, environment suitability, range of operation different sensors is used for temperature measurement. Thermocouples are one of the most popular and reliable sensors, which have a very wide range of operation and can be applied to many different industrial environments. The first intricacy with TC for high accuracy measurement is that there is no fixed relationship for temperature and emf produced. So look-up table [4, 7] is one of the options. Look-up tables require many calibration points, whose number can be reduced by interpolating between them. Calculating the inverse of the function (polynomial fit) that relates the input and the output requires us first to determine that function; which needs many reference inputs again. Storage need is smaller than that for the look-up table method [3]. In smart sensor application, this polynomial [9] fit can be done within STIM (Smart Transducer Interface module) [5, 8] or by the host PC.

The second problem is that it needs automatic room temperature compensation. Here, we employ a temperature to digital converter, TMP121 which has SPI-interface.

1.1. Smart Sensors

STIM (Smart Transducer Interface module) is one of the components of smart sensor [5, 8]. When TC is taken as dumb sensor, signal conditioner in STIM amplifies the thermo emf linearly. The analog signal is then converted to digital form. A processor processes this digital data. The digital data is also linearly varying with temperature. But TC output is quite non-linear [6]. So the temperature corresponding to this analog as well as digital signal will have large errors, which affects the accuracy. The required relation between this conditioned emf and temperature is derived applying the polynomial-fitting algorithm to the amplified thermoemf. The increase in accuracy thus obtained is observed. The polynomial for temperature are calculated for four different ranges viz 0-200 ^{o}C, 0-490 ^{o}C, 0-990 ^{o}C and 0-1200 ^{o}C (i.e. for full range) such that it is compatible with 12-bit resolution ADC (ADS1286, Texas Instruments) that runs with 5 V dc source. We have used NIST-90 data for K-type thermocouple.

1.2. Reference Junction Compensation

For TCs reference junction temperature compensation is done by different methods, viz, using diode sensor [11], PT-100 [12] etc. In all these cases signal conditioning is necessary. In the present case for cold junction temperature compensation we have used a pre-calibrated temperature to digital converter which eliminates the necessity of taking into account the response of other detectors. The pre-calibrated temperature to digital converter removes this problem.

2. System Description

The basic block diagram of the system is shown in Fig. 1.

2.1. Analog Part

The bath temperature is read by a K-type TC. Thermoemf is filtered with a low pass (10 Hz) filter. This signal is amplified with required gain with a variable gain instrumentation amplifier (INA110 from Texas Instruments) with high CMRR (106 dB). The gain of the instrumentation amplifier available is 10, 100, 200, and 500. The polynomial is fitted for these gains at four temperature ranges.

2.2. Digital Part

The amplified thermoemf is digitized by a serial interfaced 12-bit ADC (ADS1286). This is interfaced with an 8051 core microcontroller (AT89c2051) with SSI interface. This serial ADC operates with no missing code, low power consumption (typically 250 μA) and occupies less board space (8 pin PDIP). Reading of data and its processing is controlled by a firmware developed for this purpose. The firmware also sends the data serially to PC via RS232. MAX 232 is used for TTL to RS232 logic level translator.

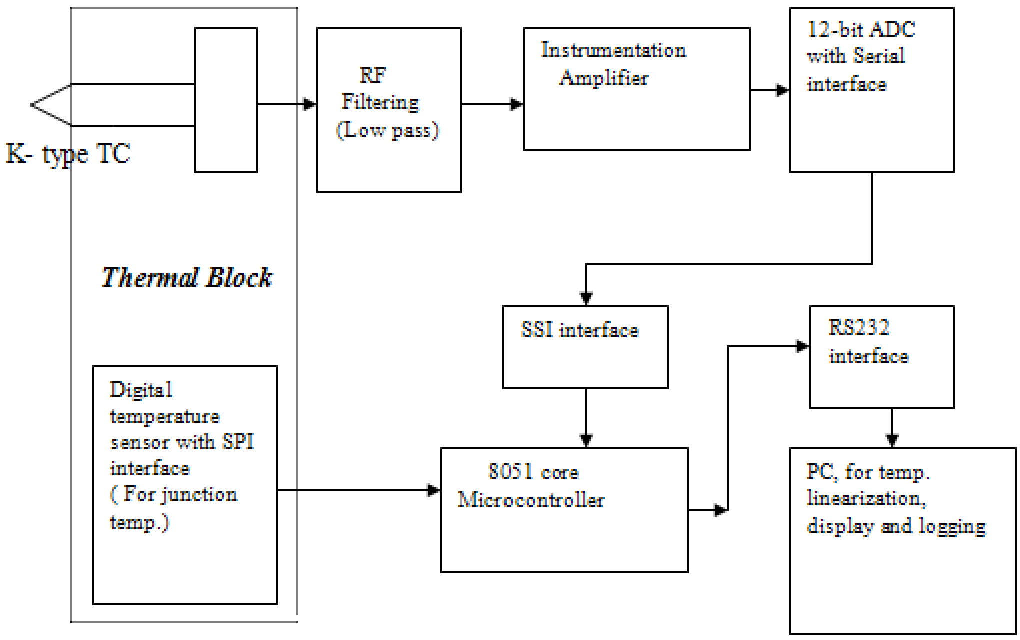

Fig. 1. Block Diagram of the System.

The junction temperature is read from SPI interfaced temperature to digital temperature sensor. This reduces errors arising from trimming potentiometers, different response of TC and reference junction temperature sensor (like diode, RTD etc.) as it is pre calibrated. The temperature is given by T= (Temp. calculated from polynomial i.e. linearised temp.)+(Temp. of reference junction read from TMP121). Both parts are independently processed so this difference in temperature dependence will not cause any error.

Using the in built UART of the microcontroller the digital data is transmitted to the host PC via RS232.

2.3. Program for the Host PC

The program in the host PC written in Visual Basic performs the following tasks

i. Receive 4 bytes of digital data through COM port
ii. Separates 2 bytes for junction temperature and 2 bytes for reference junction.
iii. The first two byte is converted to temperature with the help of the co-efficient of the required polynomial
iv. Corrected temperature is calculated, displayed and stored onto the HDD.

3. Method of Analysis

For the K-type TC (wire type) the highest temperature extends up to 1372^{o}C.The maximum input for a common ADC with 12-bit resolution is 4095 mV. Calculations are made for four different full scale temperature ranges. For each range of temperature the amplifier gain is set as required.

The least square polynomial fitting algorithm is used to find the co-relation of temperature and amplified thermoemf.

For different ranges the value of the coefficients of the polynomial are shown in the Table 1.

Table 1. Coefficients of the polynomial.

Range→	0-1200^0 C	0-990^0 C	0-490^0 C	0-100^0 C
Gain of the amplifier→	500	200	100	10
B0→	-0.06004	1.21526	1.31842	1.09043
B1→	0.05113	0.11706	0.23218	2.34351
B2→	-2.26645×10^{-6}	5.83249×10^{-6}	3.0638×10^{-5}	0.00259
B3→	6.91094×10^{-10}	-1.96266×10^{-9}	-2.57368×10^{-8}	-2.15713×10^{-5}
B4→	-6.20159×10^{-14}	1.86137×10^{-13}	8.81474×10^{-12}	7.12748×10^{-8}
B5→	**NA**	**NA**	-1.36369×10^{-15}	-1.0448×10^{-10}
B6→	**NA**	**NA**	8.15768×10^{-20}	5.8838×10^{-14}

- B0---B6 are coefficients
- NA→ Not applied

Table 2. Value of the coefficients for linear fit.

Range	0-1200^0 C	0-990^0 C	0-490^0 C	0-100^0 C
Gain of the amplifier	500	200	100	10
B0	0.27183	1.42097	3.79725	-5.56053
B1	0.04887	0.12153	0.23996	2.45668

Table 3. Value of the errors.

Temperature Range	**Maximum error in polynomial (in ^{0}C)**			**Maximum error in linear regression (in ^{0}C)**		
	Reference Fig.	Positive	Negative	Reference Fig.	Positive	Negative
0^{0}C-200^{0}C	Fig. 2	0.04	-0.04	Fig. 3	0.83	-0.5
0^{0}C-490^{0}C	Fig. 4	0.62	-1.2	Fig. 5	1.9	-3.2
0^{0}C-990^{0}C	Fig. 6	0.68	-1.3	Fig. 7	5.1	-3.97
0^{0}C-1200^{0}C	Fig. 8	0.59	0.4	Fig. 9	1.3	-18.0

3.1. Range 0^{0}C -200^{0}C

For 0 ^{0}C -200 ^{0}C the gain of the amplifier is found to be 500 for getting full scale at 200 ^{0}C. The polynomial regression is done for temperature with the amplified thermo emf i.e. 500 times the TC output a fourth order polynomial is fitted for those data points. The temperature is recalculated from the polynomial and the variation of error with actual temperature is observed (Fig. 2). It is found that maximum error in fourth order polynomial regression is +/- 0.04 ^{0}C, but in linear regression it is found to be +0.83 ^{0}C to -0.5 ^{0}C (Fig. 3).

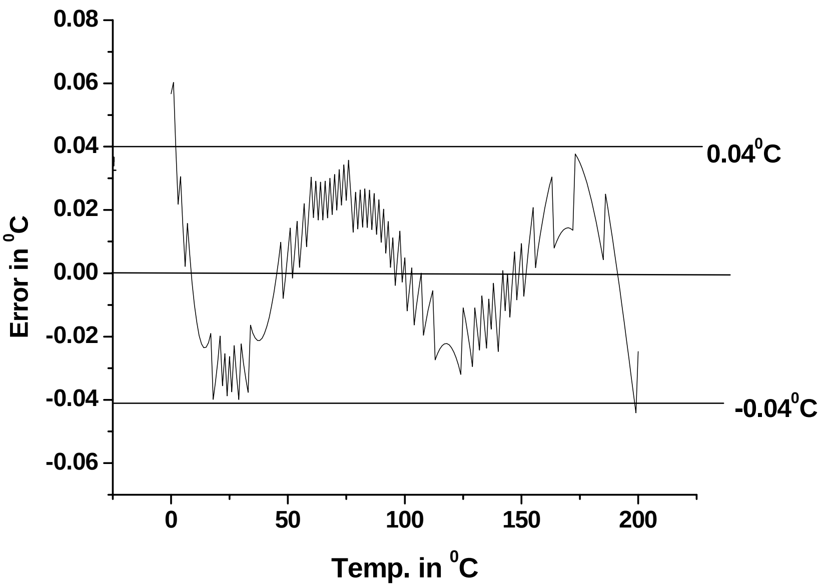

Fig. 2. Error curve for the range 0 ^{0}C -200 ^{0}C with polynomial fitting.

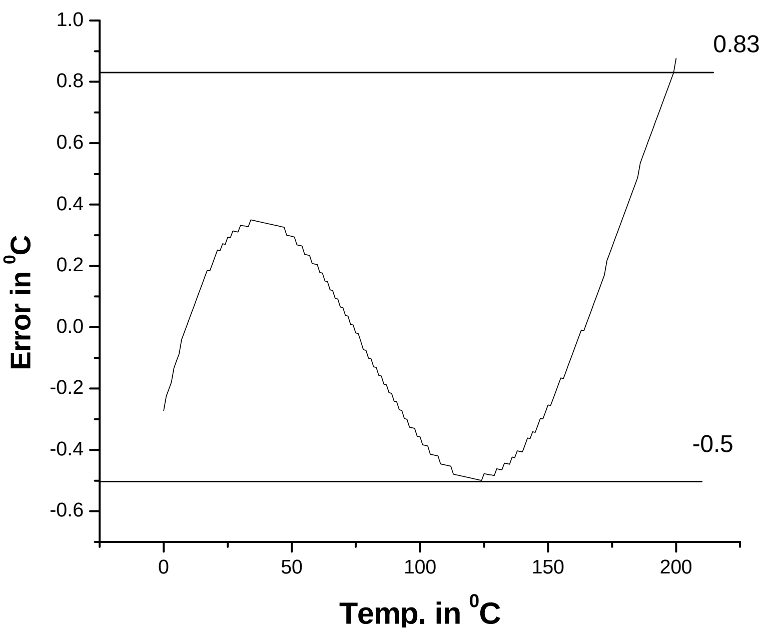

Fig. 3. Error curve for the range 0^{0}C -200^{0}C with linear fitting.

3.2. Range 0^{0}C -490^{0}C

For 0^{0}C -490^{0}C the required gain of the amplifier is found to be 200 for getting full scale at 400^{0}C. The polynomial regression is calculated in the same way, only the thermo emf is multiplied by 200. A fourth order polynomial is fitted for those data points. The temperature is recalculated from the polynomial and the variation of error with temperature is observed (Fig. 4). It is found that maximum error in fourth order polynomial regression is 0.62 ^{0}C to -1.2^{0}C, but above 10.6 ^{0}C the error reduces to +0.62 ^{0}C to -0.5 ^{0}C and above 200 ^{0}C it becomes +0.3 to -0.16 ^{0}C. In linear regression it is found to be +1.9 ^{0}C to -3.2 ^{0}C (Fig. 5).

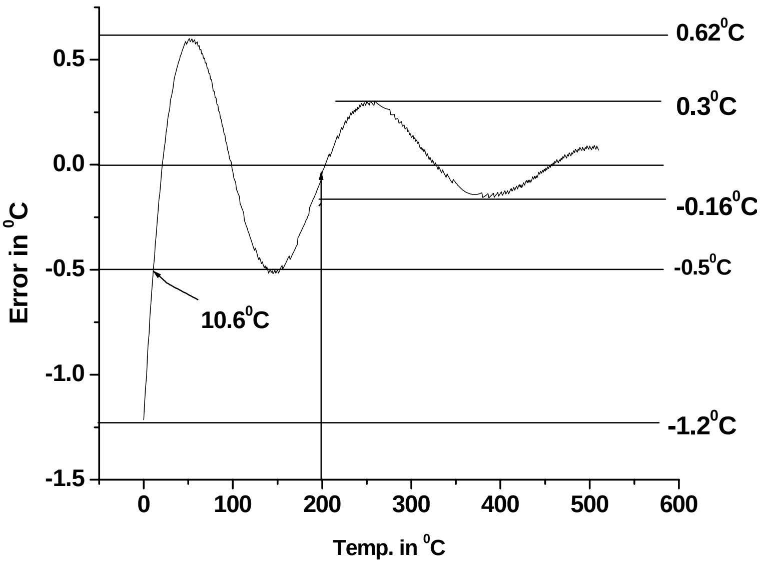

Fig. 4. Error curve for the range 0 ^{0}C -490 ^{0}C with polynomial fitting**.**

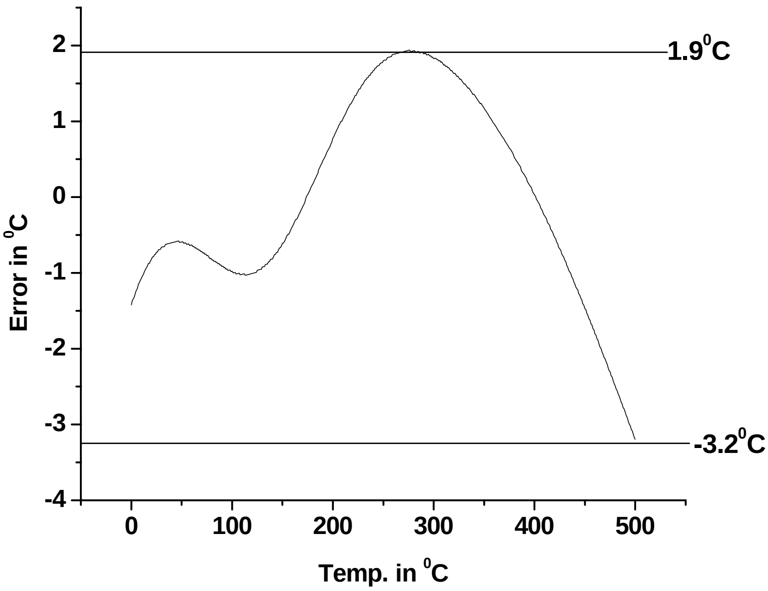

Fig. 5. Error curve for the range 0 ^{0}C -490 ^{0}C with linear fitting**.**

3.3. Range 0^{0}C -990^{0}C

For 0 ^{0}C -990 ^{0}C the required gain of the amplifier is found be 100 for getting full scale at 990 ^{0}C. The polynomial regression is calculated in the same way only the thermo emf is multiplied by 100. A sixth order polynomial is fitted for those data points .Sixth order is chosen for minimizing the error at higher temperatures. The temperature is recalculated from the polynomial and the variation of error with temperature is observed (Fig. 6). It is found that maximum error in sixth order polynomial regression is 0.68 ^{0}C to -1.3 ^{0}C, but in linear regression it is found to be +5.11 ^{0}C to -3.8 ^{0}C (Fig. 7). Here it is found that the maximum error is -1.3 ^{0}C at around 0 ^{0}C and decreases for higher temperatures. At temperature above 200 ^{0}C it shows a limiting error of 0.35 ^{0}C to -0.206 ^{0}C.

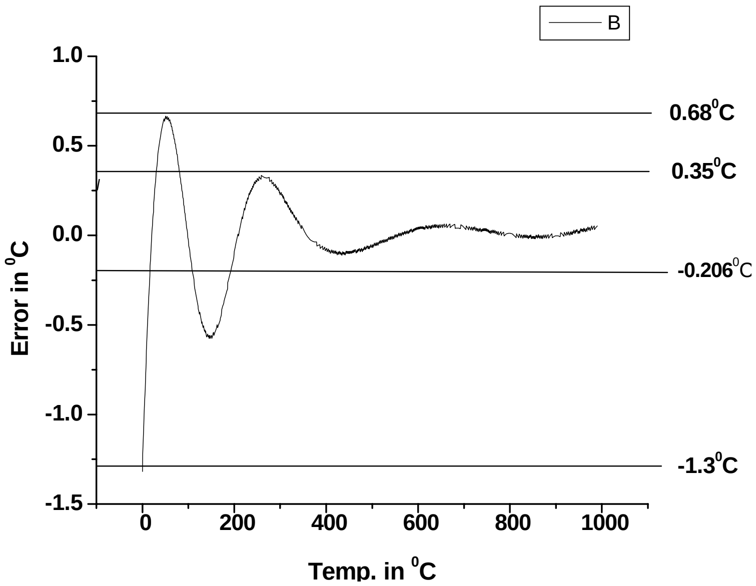

Fig. 6. Error curve for the range 0^0C -990^0C with polynomial fitting.

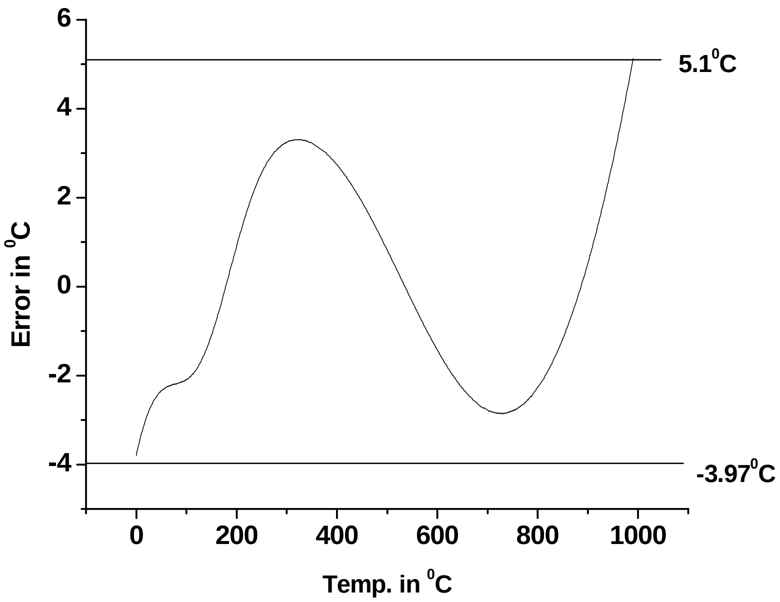

Fig. 7. Error curve for the range 0^0C -990^0C with linear fitting**.**

3.4. Range 0^0C -1200^0C

For 0 ^{0}C -1200 ^{0}C the required gain of the amplifier will be 10 for getting full scale at 1200 ^{0}C. The polynomial regression is calculated in the same way, only the thermo emf is multiplied by 10. A sixth order polynomial is fitted for those data points (Fig. 1). Sixth order is chosen for minimizing the error at higher temperatures. The temperature is recalculated from the polynomial and the variation of error with temperature is observed (Fig. 8). It is found that maximum error in sixth order polynomial regression is +0.59 ^{0}C to -0.67 ^{0}C, but in linear regression it is found to be 1.3 ^{0}C to -18.0 ^{0}C. Here it is found that the maximum error is 0.59 ^{0}C at around 0 ^{0}C and decreases for higher temperatures. At temperature above 200 ^{0}C it shows a maximum error of 0.08 ^{0}C to -0.4 ^{0}C (Fig. 9).

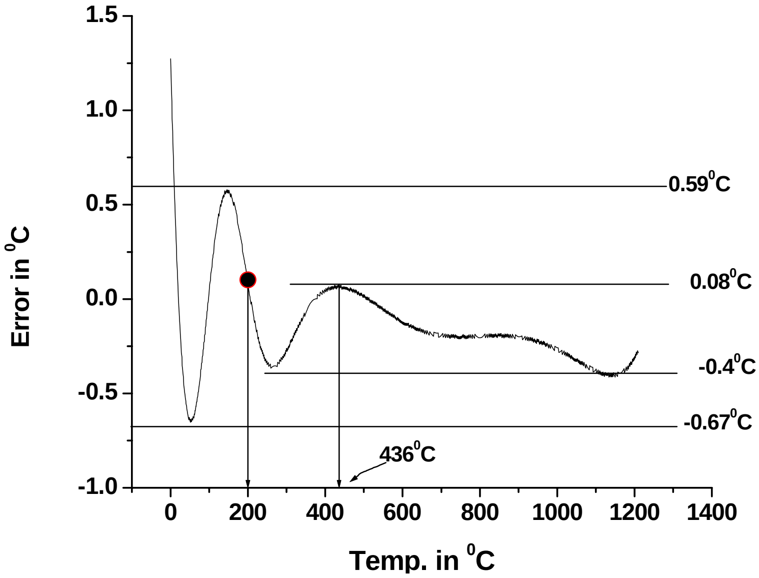

Fig. 8. Error curve for the range 0 ^{0}C -1200 ^{0}C with polynomial fitting.

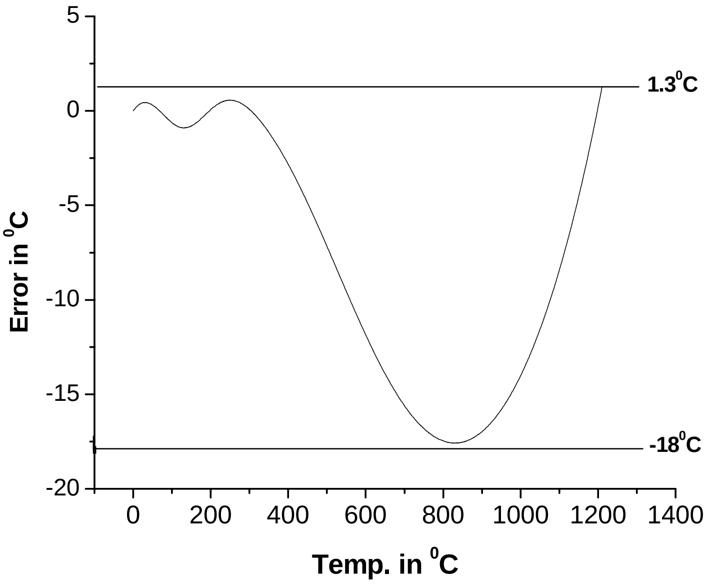

Fig. 9. Error curve for the range 0 ^{0}C -1200 ^{0}C with linear fitting**.**

2. 4. Conclusion

The well known method of polynomial fitting is used for thermocouple based temperature measurement system. The accuracy obtained improves by a factor of 17 at 200 ^{0}C range, 11 from 200 ^{0}C to 400 ^{0}C in 400 ^{0}C range, 16 from 400 ^{0}C to 990 ^{0}C in 990 ^{0}C range and 40 from 436 ^{0}C to 1200 ^{0}C in 1200 ^{0}C range. The observed accuracy is dependant on temperature range. Such a system has been successfully implemented in smart transducer interface module. This method can also be applied for other sensors with nonlinear characteristics.

Use of temperature to digital converter reduces errors arising out of difference of response between TC and reference junction compensation sensor. This also reduces the parts count like ADC, amplifier for reference junction compensation sensor and therefore reduces the cost.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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