AN EMBEDDED SYSTEM FOR COMPARATIVE PERFORMANCE ANALYSIS OF MONOLITHIC TEMPERATURE SENSORS

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ABSTRACT

Indeed, for many industrial applications precise and reliable monitoring of the temperature is significantly important. To ensure this various temperature sensors such as Thermocouples, Thermistors, RTDs, Pyrometers and semiconductor sensors, etc., are readily available. These sensors depict their own salient features. For accurate and reliable temperature monitoring, the monolithic temperature sensor are always recommended. Moreover, it is found that, monolithic temperature sensors demonstrate diversity in sensing mechanism, which results into diversity in the values of the temperature to be monitored. This may results into degradation in reliability of the temperature monitoring system. To explore the details, an embedded system is designed for comparative performance analysis of monolithic temperature sensors and results of investigation are presented in this paper.

The multichannel an embedded system is developed by deploying the 89S52 microcontroller wherein data acquisition and computing is carried out precisely. The two monolithic temperature sensors; temperature dependent voltage sensors, (LM35: $\alpha = 1$ mV/^{0}C) and temperature dependent current sensor (AD590 : $\alpha = 1$ µA/K), have been interfaced. Digital readout unit is developed about smart 16X2 LCD module. The Integrated Development Environment (IDE), Keil uVision4, is utilized for the firmware development in C environment. Present monitoring system is scientifically calibrated to the temperature in degree Celsius. Temperature values shown by both temperature sensor are simultaneously recorded and results are interpreted in this paper.

Keywords: Embedded System, Microcontroller, LM35, AD590, ADC0808, Temperature.

INTRODUCTION

The precise and accurate measurement of temperature is vital across a broad domain of applications such as physical and chemical laboratories, health care, industry, meteorology, etc. Temperature is the critical and widely measured physical parameter for wide variety of needs and applications [Rongxia, (2009); Raji, (2016); Singh, (2015)]. To cater these needs variety of temperature sensors, of different sensing mechanism are available. These temperature sensing devices are broadly classified according to the fabrication processes, materials used, characteristics, working principles, output and application areas etc. Generally, the temperature monitoring devices are of two types such as direct type (Thermometers, Temperature probes, etc.) and indirect type (Transducers). The transducers are mostly utilized for many applications and broadly categorized as resistance elements, thermopiles and semiconductor devices and monolithic devices. In fact, sensors are featured with the characteristics such as, sensitivity, range of implementation, accuracy, response times, repeatability, hysteresis, stability etc. and play crucial role in designing the temperature measuring instrumentation [Rajita, (2016)].

Present Embedded System Under the Investigation (ESUI) is designed, wherein the comparative study of two monolithic semiconductor temperature sensors of different working principles is emphasized. Most recommended monolithic temperature sensors LM 35 and AD590 are employed for present ESUI design and comparative performance analysis. The sensor LM35 operates with the principle of change in voltage in proportion with change in temperature and exhibit temperature coefficient as $\alpha = 1$ mV/^{0}C [Arunaganesan, (2013)]. Moreover, another temperature sensor, AD590, is the realization of integrated circuit. It demonstrate proportional variation current with temperature in Kelvin and gives temperature coefficient as $\alpha = 1$ μA/K [Pease, (2007)].These two temperature sensors are considered for present ESUI as these temperature sensors are recommended by many investigators to employ for temperature measurement instrumentation [Chatterji, (2013); Mane Deshmukh, (2016); Luo, (2007); Tilekar, (2008)].

Indeed, the microcontroller based embedded system design is highly suitable technology for the development of instrumentation for precise and reliable measurement of physical quantity such as humidity, pressure, temperature, etc. (Kumaravel, (2010); Saleha Begum, (2013); Tamayo, (2010)]. In early days, the electronic system designers rely on discrete circuit components and such electronic system well known as System on Board (SoB). Now days a microcontroller based embedded technology is flourishing well and realizing the themes of System on Chip (SoC). Therefore, it is proposed to avail most pervasive technology, embedded technology for present investigation. An embedded system is developed to explore behaviour of these two monolithic temperature sensors and results of comparative performance analysis are interpreted in this paper.

1. Architecture of the Embedded System

The present ESUI emphasizes the design and development of microcontroller AT89S52 based an embedded system for simultaneous performance analysis of monolithic temperature sensors. The hardware and software co-development is mandatory any embedded system. Both hardware and firmware is developed and details are presented.

The architecture of the system is depicted in the block diagram, Figure 1. It consists of monolithic temperature sensors, LM35 and AD590, signal conditioning unit, a microcontroller AT89S52, smart LCD display, power supply unit, etc. Ensuring the importance of the virtual instrumentation, the hardware of the system is designed and simulated in the Proteus7, an Integrated Development Environment (IDE). While playing with the Proteus, it is found that the circuit designing is one of the interesting works in the electronic industry [Khan, (2014)]. The schematic of the circuit designed in Proteus tool is shown in the figure 2. The required embedded firmware is developed in KeilμVision4 in embedded C environment and programmed into target memory of the device with virtual programmer. Both hardware and software are optimized for proper synchronization. After programming the device, it is simulated.

The precision monolithic temperature sensor LM35, three terminal, is popular in various industrial applications due to wide sensing range (-55 ^{0}C to +150 ^{0}C) with 0.5^{0}C accuracy, excellent characteristics, inexpensive and wide operating voltage range (4 V to 30 V). This precision temperature sensor has linear output voltage with the temperature coefficient of 10 mV/^{0}C. The LM35 is suitable for remote applications due to its low output impedance, 0.1 Ω for 1 mA load. Furthermore, it has less than 60 μA current drain and low self-heating, 0.08^{0}C in still air. For the present ESUI, TO-92 plastic package LM35 is powered with 5 V at pin 1 and temperature dependent output at pin 2 is extracted in mV, which has adequate signal strength and applied to the channel-0 of the ADC0808 for further processing. In the present investigation the output of LM35 is not extracted across load resistor, but it is extracted directly, shown in Figure 2.

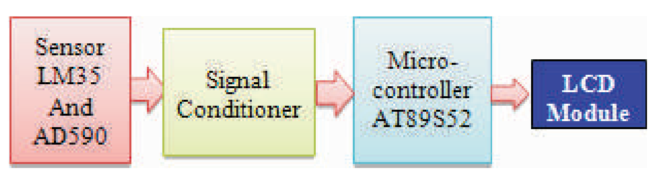

Figure 1. The block diagram the ESUI

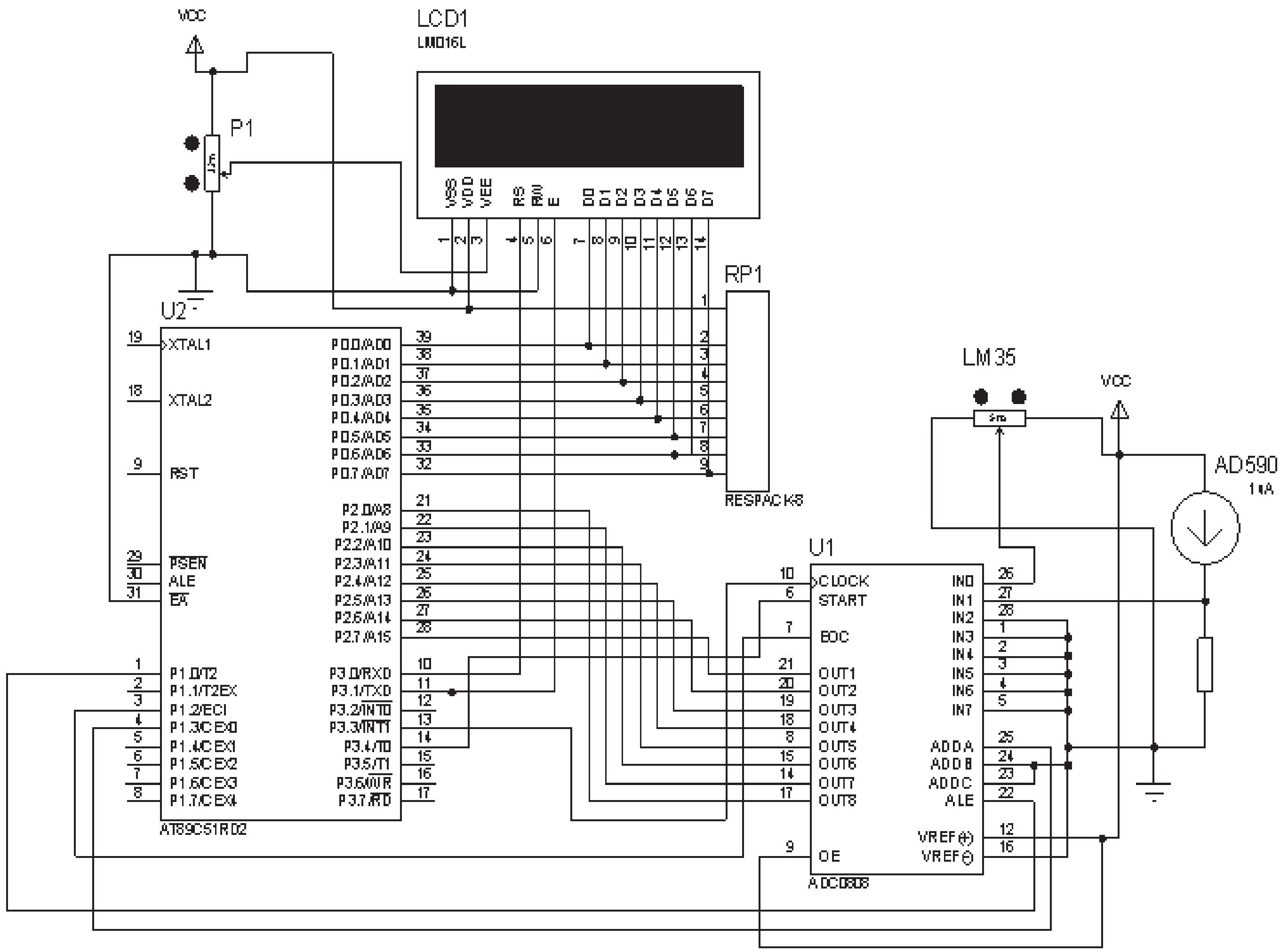

Figure 2. The Complete Schematic Diagram of the ESUI

Another precision monolithic temperature sensor AD590, two or three terminal, is having wide temperature range (-55°C to +150°C) with ±0.5°C accuracy, expensive, excellent linearity and good stability. This sensor depicts high impedance and has inherent monolithic integrated circuit combined with the elimination of support circuitry, which makes the AD590 an attractive alternative for many temperature measurement situations. Moreover, linearization circuitry, precision voltage amplifiers, resistance measuring circuitry and cold junction compensation are not needed while deploying AD590. As this device provides high impedance current output it is insensitive to voltage drop over long transmission line. In present ESUI, TO-52 three-terminal metal package AD590 is powered with 5V, at pin1, and the temperature dependent output current (IT) is extracted from pin 2. This analog current IT is extracted in voltage, in mV, across the 1 KΩ load. And it has adequate signal strength and applied to the Channel-1 of the ADC0808 for further processing [Pease, (2007)].

The CMOS ADC0808 device is utilized for present ESUI to digitize the sensors signal. It is utilized to minimize the complexity of the design and to avoid unnecessary utilization large number of I/O ports of the microcontroller [Tilekar, (2013)]. The ADC has 8-bit resolution, 8-channel multiplexer, 15 mW low power consumption and 100 µs conversion time. As depicted above LM35 and AD590 are interfaced to Channel-0 and Channel-1 of ADC respectively. The digitized 8-bit output of ADC is interfaced to the port P2 of the microcontroller. The remaining channels from Channel-2 to Channel-7 are grounded as they are not needed. The Channel Selection (CS) input ADD A is controlled through the software, so, it is interfaced to microcontroller port P1.3. Other two CS inputs ADDB and ADD Care grounded as they are not needed. The Output Enable (OE) terminal is connected to the 5 V, VCC. The START, EOC and ALE terminals are software controlled, so, they are interfaced to the microcontroller ports P3.4, P1.2 and P1.0, respectively. The necessary 500 KHz clock signal for ADC is generated through software and extracted from the microcontroller port P3.3, which is applied to the Clock input pin of ADC.

The multiplexed temperature dependent unprocessed digital data of these two temperature sensors is processed by the microcontroller AT89S52. The unprocessed digital data of the AD590 is in mV/K form and the LM35 is in mV/^{0}C form. Both these unprocessed data of sensors is processed in real temperature form in ^{0}C unit. The necessary clock and reset circuits are designed around the microcontroller. The processed real temperature data of the two sensors is displayed on the smart 16X2 LCD module which is interfaced to the microcontroller port P0. The control lines RS, RW and E necessary for LCD module are software controlled, so, they are derived from port P3.0 and P3.1, respectively, and control line RW is directly grounded to avoid unnecessary utilization of I/O ports of the microcontroller.

The firmware development is equally important in case of embedded system, as hardware and firmware are the two side of the coin. The software, mentioned earlier, is developed in 'C' using Keil µVision4, an IDE, wherein various 'users defined function' are called in the main programme wherever necessary. Prior to the main programme listing AT89S52 header file, reg51.h, is included to initialize the entire architecture of the microcontroller and then required variables, ports and subroutines are declared globally. The main programme reflects the use of the super-loop and it is prime important characteristic of the embedded software, which is incorporated in the main programme of ESUI. The various subroutines such as Clock Generation Routine, ADC Channel Selection Routine, Calibration Routine, Character Display Routine, BCD Conversion Routine, LCD Initialization, Control and Data Command Routine and Delay Routine etc. are utilized for data processing and displaying the respective sensor's real temperature data in 0C unit. In between, super-loop executes continuously, which detects the real temperature dependent data continuously and process and display it continuously. Typically, temperature calibration module developed for present ESUI is presented in Figure 3.

2. Architecture of the Embedded System

The ESUI extract the temperature dependant analog data from the both the monolithic sensors under the investigation and it is proportional to the body temperature of the sensors. Both the sensors are well standardized by manufacturer to optimise the sensitivity over the mentioned temperature range. Moreover, present ESUI, because of dedicated design of analog and digital part of the hardware, should be essentially calibrated to the scientific units [Pertijs, (2010)]. Therefore, the ESUI is subjected to process of calibration. An experimental arrangement is shown in Figure 4. As shown in Figure 4, for calibration and standardization, the standard digital thermometer meter Scientech make model DM97 is deployed.

2.1 The ESUI Calibration Process

The ESUI's two temperature sensors, AD590 and LM35, and digital thermometer are exposed to the same

```
{
//For AD590 sensor
AD590 = adc_data(1);
AD =(AD590*(5000/255));
AD_Cal =(0.0861*AD)-263.7;
cmd(0xc8);
convertanddispaly(AD_Cal);
delay(1);

//For LM35 sensor
LM35 = adc_data(0);
LM =(LM35*(5000/255));
LM_Cal =(LM*0.1022)-4.3858);
cmd(0xc0);
convertanddispaly(LM_Cal);
delay(1);
}
```

Figure 3. Firmware Module for Calibration of the ESUI for Temperature in Degree Centigrade

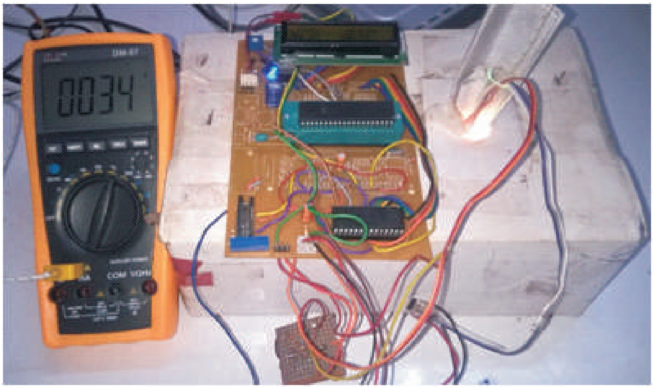

Figure 4. The Experimental Setup of the ESUI for Calibration

temperature by using temperature bath having temperature ranging from 35°C to 80°C. The emfs, obtained from respective channels, V_{AD590} and V_{LM35}, in mV shown by the system under investigation are recorded against the temperature values shown by standard thermometer. For more accuracy and reliability of the ESUI the three iterations are recorded for each sensor for same environmental conditions and then it is averaged and plotted. The graphs of observed emf, V_{AD590} and V_{LM35}, against applied temperature are shown in Figure 5 and 6 respectively for AD590 and LM35. From these calibration graphs, it can be said that, the relation of observed emf, V_{AD590} and V_{LM35}, with applied temperature is quite linear through the entire range of investigation. So, to find the respective empirical relations, the curve is subjected to the statistical process of regression [Pertijs, (2010); Frischer, (2014)]. The linear empirical expressions obtained are as

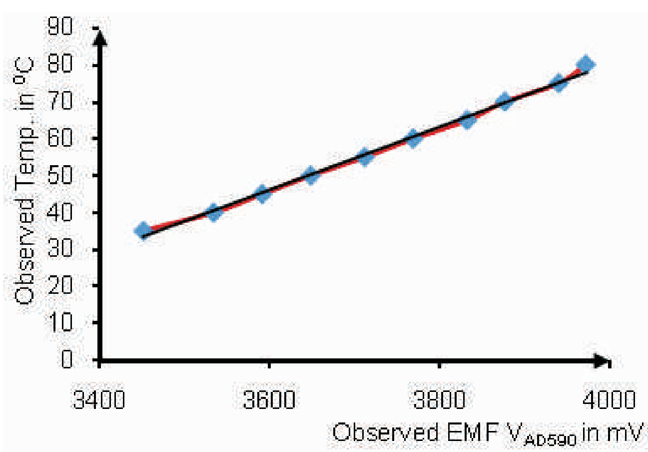

Figure 5. The Plot of emf Observed in mV on ESUI against Temperature in °C on Standard Meter for Sensor Ad590

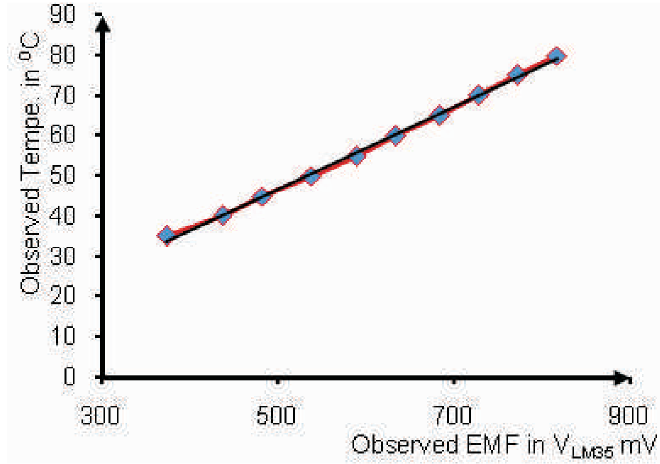

Figure 6. The plot of emf Observed in mV on ESUI against Temperature in °C on Standard Meter for Sensor Lm35

follows.

For monolithic temperature sensor AD590 is

$$\text{Temp. in } ^{0}\text{C} = 0.0861\ V_{AD590} - 263.7 \quad (1)$$

And for monolithic temperature sensor LM35 is

$$\text{Temp. in } ^{0}\text{C} = 0.1022\ V_{LM35} - 4.3858 \quad (2)$$

Both expressions, 1 and 2, are employed in the firmware [Figure 3], to standardize the ESUI in °C unit. Thus, this ESUI is calibrated and standardized to temperature scale in scientific unit degree centigrade (°C).

2.2 The ESUI Calibration Process

To validate the ESUI design and to ensure investigation of temperature measurement, the ESUI is subjected to measure the varying temperature, 35°C to 80°C, in temperature bath, wherein both temperature sensors and same digital thermometer are again housed in same temperature bath. The observations on ESUI for AD590 and LM35 against digital thermometer are recorded for number of iterations the same temperature data is recorded at every time. The graph of observed temperatures in °C on ESUI by both the sensors against applied temperature on digital thermometer is plotted and shown in Figure 7. On inspection of the Figure 7, it is found that, the temperature values of both the monolithic temperature sensors observed on ESUI are precise and shows a good agreement in most of all the cases to each other and also shows a good agreement with the standard digital thermometer. This validates the

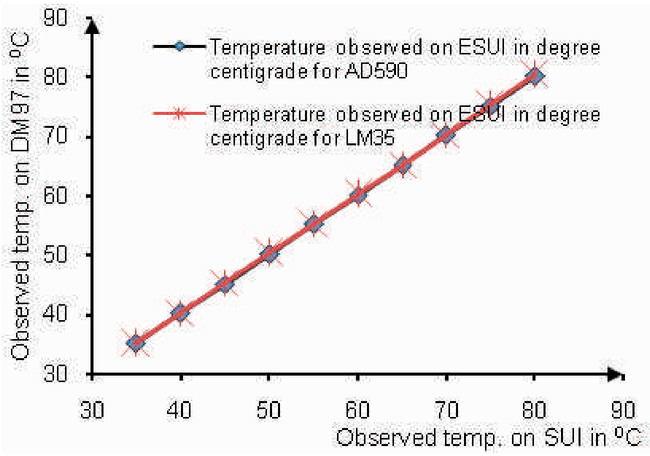

Figure 7. The plot of Temperature Observed in 0C on ESUI against Temperature in °C on DM97 Meter for Sensor AD590 and Lm35

developed ESUI for precise temperature measurements [Che, (2017)].

2.3 Comparative Analysis of Observed Data on ESUI

After successfully standardization, performance of two sensors is investigated. The temperature values shown by both sensors are recorded for various applied temperature. It is found that, there is significant deviation from expected results. Deviation in the temperature values shown by the two sensors and actual temperature are estimated. This estimation of the deviation is carried out for number of iterations. Resulting deviations are plotted against the temperature shown by standard digital thermometer and presented in Figure 8. The average temperature deviation between the digital thermometer and monolithic sensor is 0.172 °C for AD590 and 0.341 °C for LM35, respectively. On statistical analysis it is found that the standard deviation for AD590 and LM35 is 0.0133 % and 0.0885 %, respectively. This clears that the standard deviation for temperature sensor AD590 is minimum than that of temperature sensor LM35. The deviation in the temperature values obtained from two sensors are also plotted [Figure 8]. On inspection figure 8, it can be said that, the two sensors are not showing same temperatures. A significant deviation is recorded. The average temperature difference of 0.169 °C is observed between the temperature sensors on ESUI. Figure 8 also shows non linearity in the deviations. This may be due to design tolerances ±0.8 % and ±0.35% in the monolithic temperature sensors AD590 and LM35 mentioned by the manufacturer, respectively [Rajita, (2016)-Arunaganesan, (2013)]. From results of investigation, it can be concluded that AD590 is most suitable sensor for development of temperature monitoring system.

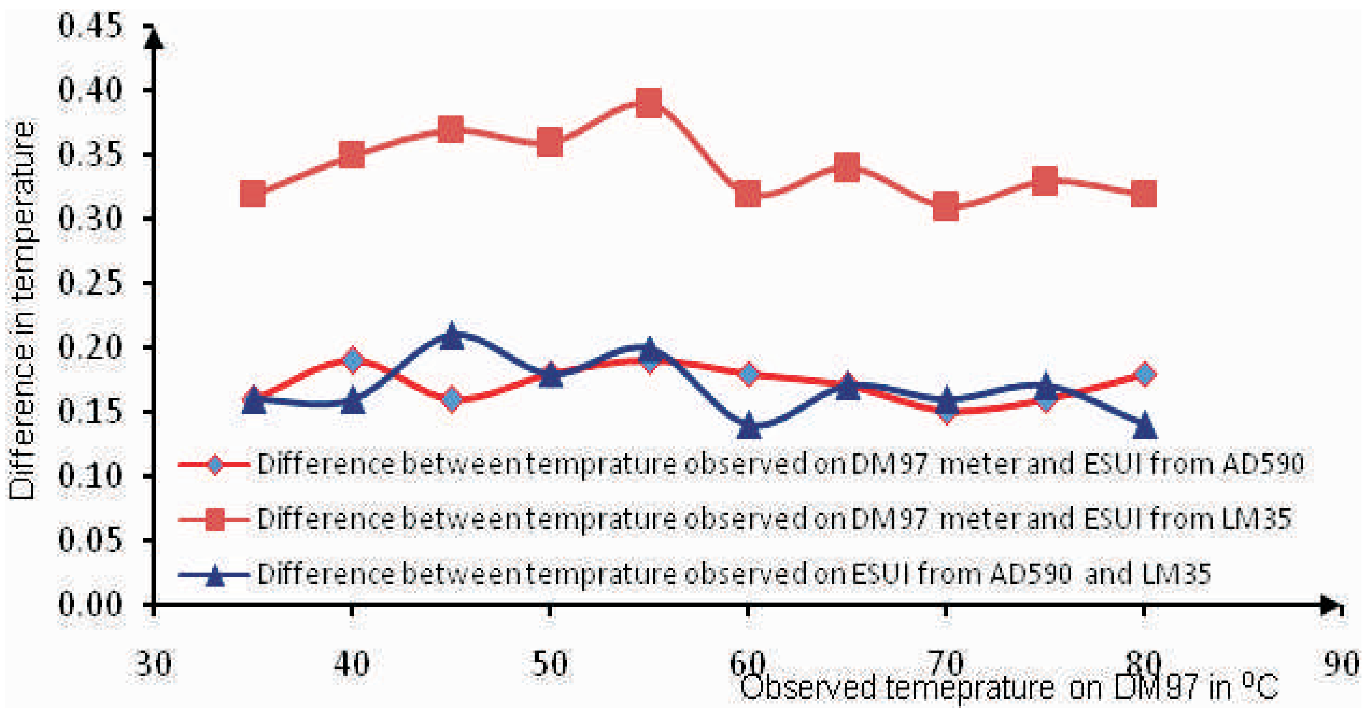

Figure 8. The Plot of Difference in Temperature Observed in between DM97 Thermometer and Monolithic Temperature Sensors on ESUI in °C

Conclusion

The microcontroller AT89S52 based embedded system is designed and developed for comparative performance analysis of two monolithic temperature sensors, LM35 and AD590, successfully. Upon performance analysis, it can be concluded that the temperature sensor AD590 is more precise and having minimum standard deviation over the range of investigation than that of temperature sensor Lm35.

References

[1]. Rongxia, S., Yi, T., & Yibing, D. (2009, November). Design and implementation of industrial multi-parameter data acquisition system based on AT89S52. In *Intelligent Information Technology Application Workshops, 2009. IITAW'09. Third International Symposium on* (pp. 169-172). IEEE.

[2]. Raji, A., Devi, P. K., Jeyaseeli, P. G., & Balaganesh, N. (2016, November). Respiratory monitoring system for asthma patients based on IoT. In *Green Engineering and Technologies (IC-GET), 2016 Online International Conference on* (pp. 1-6). IEEE.

[3]. Singh, A. K., Chatterji, S., Shimi, S. L., & Gaur, A. (2015). Remote Lab in Instrumentation and Control Engineering Using LabVIEW. *International Journal of Electronics and Electrical Engineering*, 3(4).

[4]. Rajita, G., Mondal, B., Mandal, N., & Sarkar, R. (2016, January). Design of a PC based real time mass flow indicator using AD590 as sensor. In *Control, Measurement and Instrumentation (CMI), 2016 IEEE First International Conference on* (pp. 449-453). IEEE.

[5]. Arunaganesan, S., Adhavan, J., Reddy, G. S., & Venkatesan, M. (2013, December). Data acquisition system based on 8051 microcontroller for cutting tool temperature measurement. In *Computational Intelligence and Computing Research (ICCIC), 2013 IEEE International Conference on* (pp. 1-4). IEEE.

[6]. Pease, R. L., Dunham, G. W., Seiler, J. E., Platteter, D. G., & McClure, S. S. (2007). Total dose and dose rate response of an AD590 temperature transducer. *IEEE Transactions on Nuclear Science*, 54(4), 1049-1054.

[7]. Chatterji, S., Shimi, S. L., Singh, A. K., & Gaur, A. (2013, December). Web laboratory in instrumentation engineering for distance education using LabVIEW. In *Innovation and Technology in Education (MITE), 2013 IEEE International Conference in MOOC* (pp. 240-244). IEEE.

[8]. Deshmukh, P. M., Pathan, S. C., Chanvan, S. V., Tilekar, S. K., & Ladgaonkar, B. P. (2016). Wireless sensor network for monitoring of air pollution near industrial sector. *International Journal of Advanced Research in Computer Scienceand Software Engineering*, 6(6), 638-645.

[9]. Luo, R. C., & Su, K. L. (2007). Autonomous fire-detection system using adaptive sensory fusion for intelligent security robot. *Ieee/Asme Transactions on Mechatronics*, 12(3), 274-281.

[10]. S. K. Tilekar and B. P. Ladgaonkar, (2013). "Designing of Mixed Signal Based Programmable System on Chip for Temperature Compensated pH Measurement", *International Journal of Scientific and Engineering Research, France*, Vol. 4, No. 6, pp. 672-678.

[11]. Kumaravel, S., Neelamegam, P., & Vasumathi, R. (2010). Distributed chloride prediction system using neural network and PIC18F452 microcontrollers in water analysis. *Int. J. of computer applications (0975-8887)*, 8(14), 15-20.

[12]. SalehaBegum, B., AshrafAhamed, B., Kumar, A. S., RamaMurthy, B., Thimmaiah, P., & Khan, K. A. (2013). Embedded Based Soil Electrical Conductivity Measurement System. *IOSR Journal of Agriculture and Veterinary Science (IOSR-JAVS)*, 26, 17-20.

[13]. Tamayo, M., Westover, A., & Sun, Y. (2010, March). Microcontroller based pulse oximeter for undergraduate capstone design. In *Bioengineering Conference, Proceedings of the 2010 IEEE 36th Annual Northeast* (pp. 1-2). IEEE.

[14]. Pertijs, M. A., Aita, A. L., Makinwa, K. A., & Huijsing, J. H. (2010). Low-cost calibration techniques for smart temperature sensors. *IEEE Sensors Journal*, 10(6), 1098-1105.

[15]. Frischer, R., Penhaker, M., Krejcar, O., Kacerovsky, M., & Selamat, A. (2014). Precise temperature measurement for increasing the survival of newborn babies in incubator environments. *Sensors*, 14(12), 23563-

23580.

[16]. **Khan, N. A. A., & Sankar, K. J. (2014, October).** User interface design for LPC2138 to configure wireless sensor node parameters. In *Smart Structures and Systems (ICSSS), 2014 International Conference on* (pp. 31-34). IEEE.

[17]. **Che, X., & Xie, Z. (2017).** Development of ReFaST Pyrometer for Measuring Surface Temperature With Unknown Emissivity: Methodology, Implementation, and Validation. *IEEE Transactions on Instrumentation and Measurement*, 66(7), 1845-1855.

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