International Journal of Control and Automation
Vol. 8, No. 7 (2015), pp. 13-24
http://dx.doi.org/10.14257/ijca.2015.8.7.02

User-friendly Calibration Tool for Temperature Measurements of PCR Devices with NTC Thermistors

Wan Yeon Lee[1], Tong Min Kim[2], Min Ja Kim[2], YoungWoong Ko[3] and Jong Dae Kim[4*]

[1]Dept. of Computer Science, Dongduk Women's University,
Seoul 136-714, South Korea
[2]Dept. of Computer Science and Engineering, Korea University,
Seoul 136-713, South Korea
[3]Dept. of Computer Engineering, Hallym University,
Chunchon 200-702, South Korea
[4]Dept. of Convergence Software, Hallym University,
Chunchon 200-702, South Korea
[1]wanlee@dongduk.ac.kr, [2]{dianakim, mjfeel}@korea.ac.kr, [3]yuko@hallym.ac.kr,
[4]kimjd@hallym.ac.kr

Abstract

In this paper, we propose a user-friendly tool that calibrates the coefficient variables of Steinhart-Hart equation used for the temperature measurement of NTC thermistor. The proposed tool provides automatic modification of the coefficient variables only with temperature measurement, whereas the legacy process requires manual modification of the coefficient variables with temperature and resistance measurements. For user convenience, the proposed tool is implemented with a user-friendly GUI program. The tool is applied to 4-points temperature measurements of PCR devices. In accuracy evaluation, the proposed tool yields a precision of ±0.1 ℃.

Keywords: *Calibration, Steinhart-Hart equation, Thermistor, Temperature Measurement*

1. Introduction

For limited range temperature measurement, NTC(Negative Temperature Coefficient) thermistor is favored over other devices due to its many benefits such as high sensitivity, fast thermal response, various shapes and sizes, and low-cost [1]. The thermistor is a thermally sensitive sensor. As the sensing temperature of a thermistor changes, its resistance value is accordingly changed. Measuring the resistance value of a thermistor can be utilized for temperature measurement of the thermistor [2]. The relationship between temperature and resistance of thermistors is nonlinear and almost exponential [3]. The relationship is precisely analyzed by Steinhart-Hart equation [4].

In order to directly derive a temperature from a measured resistance value using the Steinhart-Hart equation, we must know three coefficient values of the Steinhart-Hart equation, called S-H coefficients. Manufactures typically supply the S-H coefficients for thermistors. Manufacturer-applied S-H coefficients are generally

---

[*] Corresponding Author: Jong Dae Kim, email: kimjd@halym.ac.kr
This paper is a revised and expanded version of a paper entitled "GUI Program Design for Convenient Resistance-Temperature Calibration of NTC Thermistors" presented at International Conference on Advanced Science and Technology, February 2015.

ISSN: 2005-4297 IJCA

identical for the same model of thermistors; however, these coefficients may vary for individual thermistor units. Therefore, S-H coefficients of each thermistor unit need to be slightly adjusted for more precise temperature measurement. The procedure to adjust the S-H coefficients of thermistors is referred to as calibration. The calibration procedure of temperature measurement instruments including thermistors is performed by certified institutions equipped with thermally stable environments (circulating liquid bath) [5].

In the legacy scheme [6], the calibration process is performed as follows; (1) Users deliver the temperature measurement instruments to the certified institution. (2) The certified institution finds the modified S-H coefficients suitable for individual temperature measurement instruments by measuring the resistance values of each instrument upon known reference temperatures. (3) The found S-H coefficients are sent back to users and manually stored in memory logger of each temperature measurement instrument. However, this legacy calibration scheme demands a burden of measuring the resistance values of each instrument from the certified institution, and the inconvenient manual memory setting of the found S-H coefficient variables from users.

In this paper, we propose a calibration tool that automatically modifies the default S-H coefficients given by thermistor manufactures. Also the proposed calibration tool provides greater user convenience by simply recording the difference between the measured temperature and the reference temperature, rather than measuring the resistance values of each temperature measurement instrument in legacy calibration scheme. To enhance user convenience, the proposed tool is implemented with user-friendly GUI(graphic user interface) programs. We apply the tool to 4-points temperature measurements of PCR device [7,8], and verify that the tool significantly enhances the temperature measurement accuracy with a precision of ±0.1°C.

The rest of this paper is organized as follows; Section 2 explains the background knowledge to understand the proposed scheme. Section 3 describes the proposed calibration tool in detail. Section 4 shows evaluation results for calibration accuracy of the proposed tool. Section 5 provides concluding remarks.

2. Preliminaries

2.1. Resistance-Temperature Relation of NTC Thermistors

Thermally sensitive resistors (*i.e.*, thermistors) are one of the most commonly used temperature measurement devices because they can be installed in many environments, they have a high degree of accuracy (generally < 0.01°C can be easily attained), and they are relatively inexpensive (< $100) [6]. There are two types of thermistors, negative temperature coefficient (NTC) thermistors and positive temperature coefficient (PTC) thermistors, of which NTC thermistors are the most common. The response of resistance vs. temperature for a thermistor is highly nonlinear and is almost exponential in nature. Figure 1 shows a common resistance-temperature relation curve for a 10kΩ NTC thermistor.

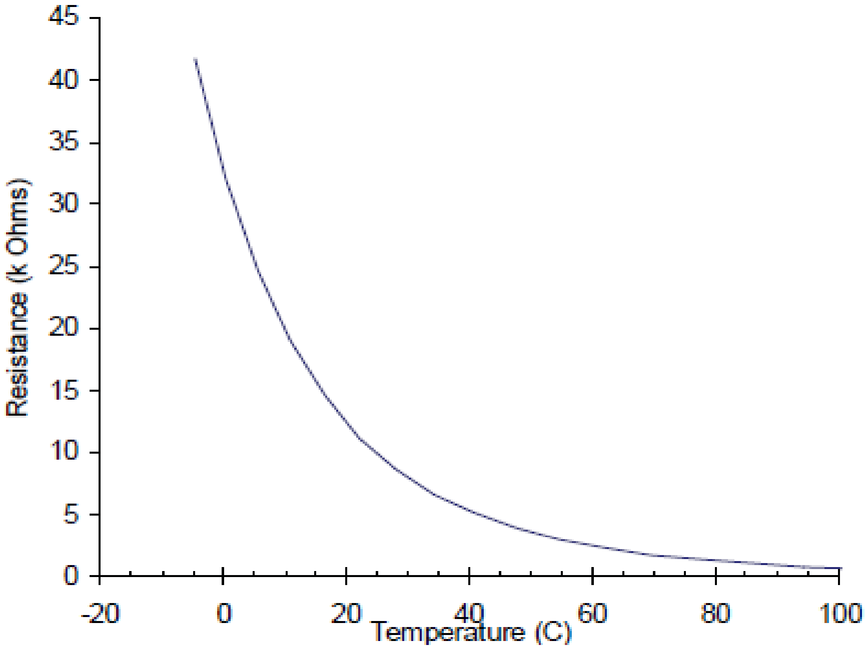


Figure 1. Resistance-Temperature Relation Curve of NTC Thermistors

2.2. Steinhart-Hart Equation

The nonlinear resistance-temperature characteristics of NTC thermistor may be modeled to a high degree of accuracy using mathematical modeling techniques such as Steinhart-Hart equation [4], Lagrange polynomials [9], and other modelling techniques [10]. The Steinhart-Hart equation shown in equation (1) is the mostly favored because it is the most accurate function for fitting proxy data to reference temperature data [11]. The Steinhart-Hart equation is expressed as below:

$$T^{-1} = A + B \cdot \ln R + C \cdot (\ln R)^3 \qquad (1)$$

where A, B, and C are dimensionless variables referred to as S-H coefficients and R is the measured resistance value of the thermistor. This equation generally yields a precision ±0.001°C of over the range of -40°C to +150°C.

Although manufactures of NTC thermistors generally provides identical S-H coefficients for the same model of thermistors, these coefficients need the calibration procedure that slightly adjusts the default coefficients for more precise temperature measurement. The calibration procedure to determine the S-H coefficients involves measuring the thermistor resistance value under a thermally stable environment with a known reference temperature (*i.e.*, circulating liquid bath) [5]. If three resistance values of thermistors (R_1, R_2, R_3) are measured under three known reference temperatures (T_1, T_2, T_3) respectively, the three coefficient variables (A, B, C) can be directly derived by applying the three measured resistance values and the three known temperatures to equation (1) and solving the following three equations.

$$\frac{1}{T_1} = A + B \cdot (\ln R_1) + C \cdot (\ln R_1)^3$$

$$\frac{1}{T_2} = A + B \cdot (\ln R_2) + C \cdot (\ln R_2)^3$$

$$\frac{1}{T_3} = A + B \cdot (\ln R_3) + C \cdot (\ln R_3)^3$$

With R_1, R_2 and R_3 values of resistance at temperatures T_1, T_2 and T_3 respectively, we derive the values of A, B and C according to the following formulas:

$$L_1 = \ln R_1 , \qquad L_2 = \ln R_2 \quad \text{and} \quad L_3 = \ln R_3$$

$$M_1 = \frac{1}{T_1}, \qquad M_2 = \frac{1}{T_2} \quad \text{and} \quad M_3 = \frac{1}{T_3}$$

$$N_2 = \frac{M_2 - M_1}{L_2 - L_1} \quad \text{and} \quad N_3 = \frac{M_3 - M_2}{L_3 - L_2}$$

$$\Rightarrow C = (\frac{N_3 - N_2}{L_3 - L_2})(L_1 + L_2 + L_3)^{-1}$$

$$\Rightarrow B = N_2 - C \cdot \{ (L_1)^2 + L_2 \cdot L_2 + (L_2)^2 \}$$

$$\Rightarrow A = M_1 - \{ B + (L_1)^2 \cdot C\} \cdot L_1$$

The calibration procedure of temperature measurement instruments including thermistors is performed by certified institutions equipped with thermally stable environments (circulating liquid bathes). The legacy calibration scheme [6] demands a burden of measuring the resistance values of each instrument from the certified institution, and the inconvenient manual memory setting of the found S-H coefficient variables from users.

The proposed calibration tool automatically modifies the default S-H coefficients given by thermistor manufactures. Also the proposed calibration tool provides greater user convenience by simply recording the difference between the measured temperature and the reference temperature, rather than measuring the resistance values of each temperature measurement instrument in legacy calibration scheme.

3. Proposed Calibration Tool

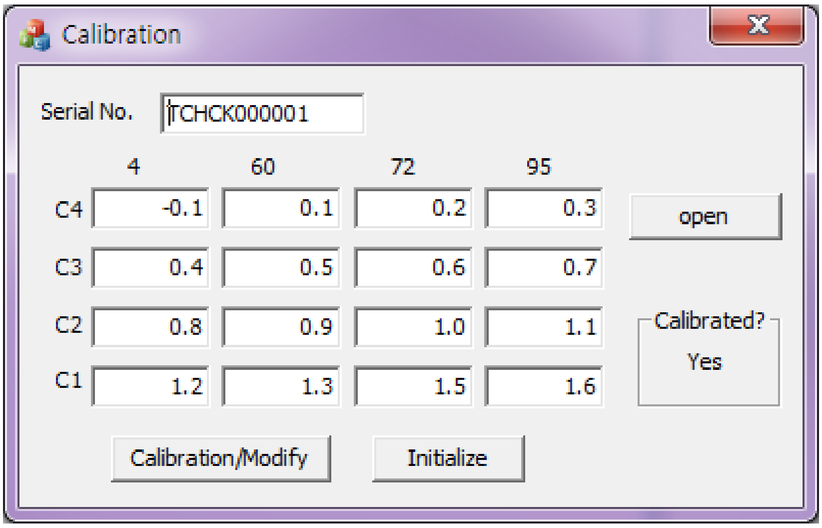
The default S-H coefficients before calibration are denoted as A, B and C. The modified S-H coefficients after calibration are dented as $A^{'}$, $B^{'}$ and $C^{'}$. The measured temperature using the default coefficients is denoted as T. The known reference temperature in thermally stable liquid bath is denoted as T^{R}. When measuring the reference temperature of liquid bath, the measured temperature T might be different from the exactly known reference temperature T^{R} if the default S-H coefficients are not exact. Our goal is to make $T \approx T^{R}$ by modifying the default S-H coefficients.

The proposed calibration tool allows users to omit the resistance measurement procedure. From the default S-H coefficients (A, B and C) and the measured temperature T, the resistance value R of thermistors can be derived by using the inverse equation of equation (1), which is expressed as below:

$$R = \exp\left(\sqrt[3]{\beta - \alpha} - \sqrt[3]{\beta + \alpha} \right) \qquad (2)$$

$$\text{where } \alpha = \frac{A - \frac{1}{T}}{2C} \text{ and } \beta = \sqrt{\left(\frac{B}{3C}\right)^3 + \alpha^2} .$$

For easy calibration handling and one step calibration process, the proposed tool provides a graphic user interface (GUI) such as shown in Figure 1, which handles 4 channels of thermistors from C1 to C4. The GUI runs on Windows XP or Windows 7, and is implemented using Microsoft Visual Studio 2008 and Microsoft Foundation Class (MFC). The user records only the difference of the measured temperature from the reference temperature (*i.e.*, $T - T^R$) in GUI as input parameters. Then its resistance value R is automatically calculated by using equation (2). The modified S-H coefficients A', B' and C' are obtained by applying the automatically calculated resistance R and the reference temperature T^R to equation (1).



Serial No. TCHCK000001

	4	60	72	95
C4	-0.1	0.1	0.2	0.3
C3	0.4	0.5	0.6	0.7
C2	0.8	0.9	1.0	1.1
C1	1.2	1.3	1.5	1.6

Calibrated? Yes

Figure 2. GUI Program

As shown in Figure 2, the proposed tool determines the S-H coefficients based on four known reference temperatures, because the tool is designed for PCR(Polymerase Chain Reaction) devices using four different temperatures such as 4°C, 60°C, 72°C, and 95°C [7,8]. For the calibration of each channel with four temperature points, we apply the least squares fitting method that minimizes the sum of measurement errors. First, we make four equations applying four known temperatures T_1^R, T_2^R, T_3^R and T_4^R, and their corresponding resistance values R_1, R_2, R_3 and R_4 to equation (1):

$$\frac{1}{T_i^R} = A' + B' \cdot \ln R_i + C' \cdot (\ln R_i)^3 \text{ for } i = 1, 2, 3, 4.$$

From the above equation, we derive three matrixes X, Y and Z such that $Z = Y \cdot X$ as below:

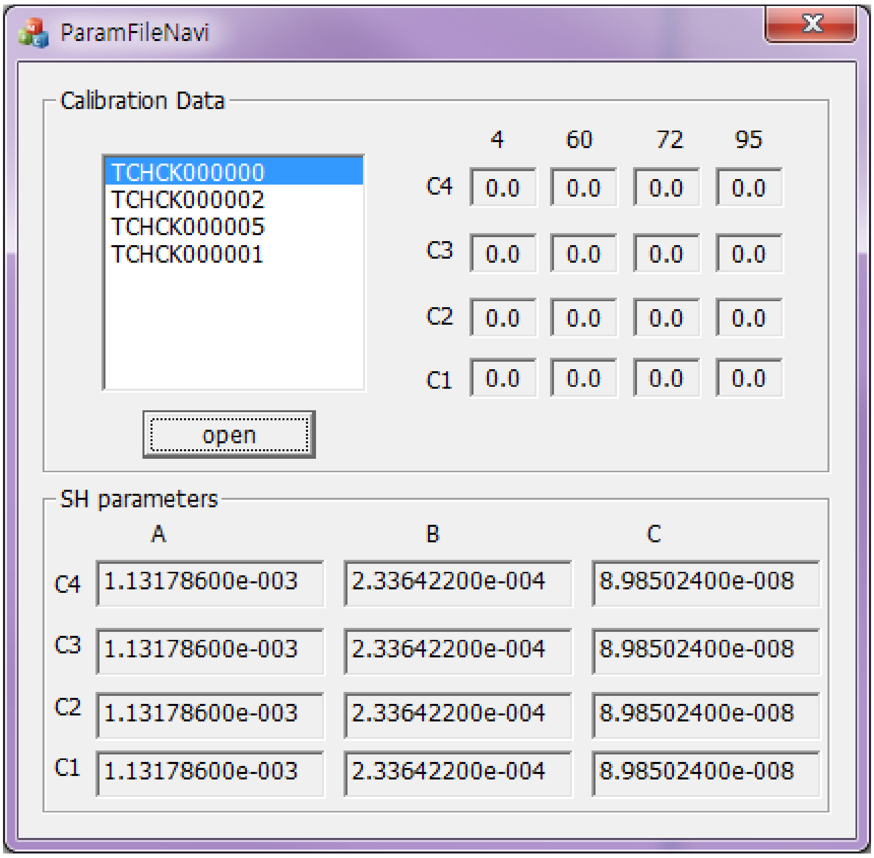
$$Z = \begin{bmatrix} 1/T_1^R \\ 1/T_2^R \\ 1/T_3^R \\ 1/T_4^R \end{bmatrix}, \quad Y = \begin{bmatrix} 1 & \ln R_1 & (\ln R_1)^3 \\ 1 & \ln R_2 & (\ln R_2)^3 \\ 1 & \ln R_3 & (\ln R_3)^3 \\ 1 & \ln R_4 & (\ln R_4)^3 \end{bmatrix}, \quad \text{and} \quad X = \begin{bmatrix} A' \\ B' \\ C' \end{bmatrix}.$$

The matrix X including the modified S-H coefficients can be obtained by applying the following least square solution:

$$Y \cdot X = Z \Rightarrow Y^T \cdot Y \cdot X = Y^T \cdot Z$$

$$\Rightarrow X = (Y^T \cdot Y)^{-1} \cdot Y^T \cdot Z.$$

Finally the tool automatically substitutes the modified S-H coefficients for the default S-H coefficients. Figure 3 shows the modified S-H coefficients values in the GUI program of the proposed tool.

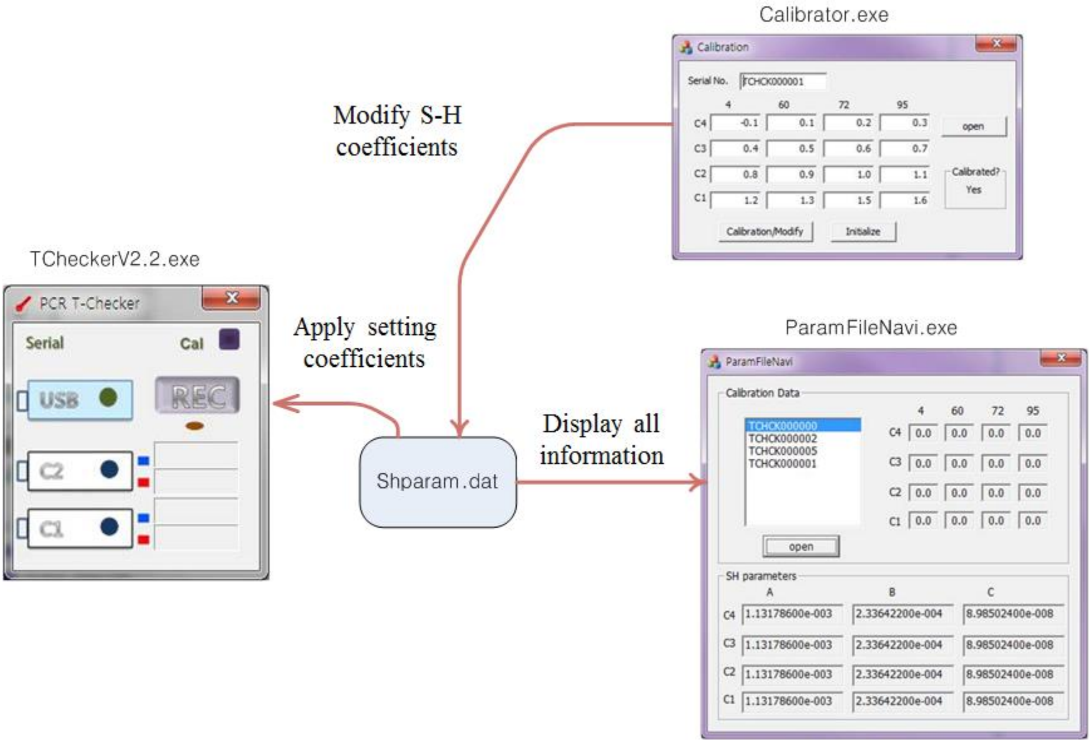


TCHCK000000
TCHCK000002
TCHCK000005
TCHCK000001

	4	60	72	95
C4	0.0	0.0	0.0	0.0
C3	0.0	0.0	0.0	0.0
C2	0.0	0.0	0.0	0.0
C1	0.0	0.0	0.0	0.0

	A	B	C
C4	1.13178600e-003	2.33642200e-004	8.98502400e-008
C3	1.13178600e-003	2.33642200e-004	8.98502400e-008
C2	1.13178600e-003	2.33642200e-004	8.98502400e-008
C1	1.13178600e-003	2.33642200e-004	8.98502400e-008

Figure 3. Modified S-H Coefficients in GUI Program



Serial No. TCHCK000001

	4	60	72	95
C4	-0.1	0.1	0.2	0.3
C3	0.4	0.5	0.6	0.7
C2	0.8	0.9	1.0	1.1
C1	1.2	1.3	1.5	1.6

Calibrated? Yes

TCHCK000000
TCHCK000002
TCHCK000005
TCHCK000001

	4	60	72	95
C4	0.0	0.0	0.0	0.0
C3	0.0	0.0	0.0	0.0
C2	0.0	0.0	0.0	0.0
C1	0.0	0.0	0.0	0.0

	A	B	C
C4	1.13178600e-003	2.33642200e-004	8.98502400e-008
C3	1.13178600e-003	2.33642200e-004	8.98502400e-008
C2	1.13178600e-003	2.33642200e-004	8.98502400e-008
C1	1.13178600e-003	2.33642200e-004	8.98502400e-008

Figure 4. Overall Configuration of GUI Programs

Figure 4 shows the overall configuration of all GUI programs of the proposed tool. The file named with “Shparma.dat” stores the setting S-H coefficient values of each NTC thermistor sensor and the difference between the measured temperature and the reference temperature. The GUI program in the left of Figure 4 is executed by “TCheckerV2.2.exe”. This program applies the modified S-H coefficients if the file “Shparma.dat” stores the modified S-H coefficients of the target measurement instrument. Otherwise, the program applies the default S-H coefficients.

The proposed calibration tool provides greater user convenience by simply recording the difference between the measured temperature and the reference temperature, rather than measuring the resistance values of each temperature measurement instrument in legacy calibration scheme.

4. Calibration Accuracy Evaluation

For evaluation of temperature measurement accuracy, we employ 16 thermistors of the USSENSOR company that have ±0.4°C error range over default S-H coefficients identical for all thermistor sensors. Temperature measurement accuracy before calibration is compared with that after applying the proposed calibration tool. Table 1 shows measured temperatures using the default S-H coefficients before calibration. Table 2 shows measured temperatures using the modified S-H coefficients after calibration.

Table 1. Measured Temperature *before* Calibration

Reference Temperature	**4.0 °C**	**60.0 °C**	**72.0 °C**	**95.0 °C**
Thermistor Number 1	3.9 °C	60.2 °C	72.0 °C	95.1 °C
Thermistor Number 2	3.8 °C	60.2 °C	72.0 °C	95.2 °C
Thermistor Number 3	3.9 °C	60.2 °C	71.9 °C	95.2 °C
Thermistor Number 4	3.8 °C	60.2 °C	71.7 °C	95.2 °C
Thermistor Number 5	3.7 °C	60.2 °C	72.0 °C	95.1 °C
Thermistor Number 6	3.7 °C	60.2 °C	72.0 °C	95.1 °C
Thermistor Number 7	3.7 °C	60.2 °C	72.0 °C	95.1 °C
Thermistor Number 8	3.7 °C	60.2 °C	72.0 °C	95.1 °C
Thermistor Number 9	3.8 °C	60.0 °C	72.3 °C	94.9 °C
Thermistor Number 10	3.8 °C	60.1 °C	72.4 °C	95.0 °C
Thermistor Number 11	3.8 °C	60.0 °C	72.3 °C	94.8 °C
Thermistor Number 12	3.8 °C	60.1 °C	72.4 °C	95.0 °C
Thermistor Number 13	3.7 °C	60.2 °C	72.1 °C	94.9 °C
Thermistor Number 14	3.7 °C	60.2 °C	71.9 °C	95.0 °C
Thermistor Number 15	3.6 °C	60.0 °C	72.2 °C	94.9 °C
Thermistor Number 16	3.6 °C	60.0 °C	72.2 °C	94.9 °C

Table 2. Measured Temperature *after* Calibration

Reference Temperature	4.0 °C	60.0 °C	72.0 °C	95.0 °C
Thermistor Number 1	4.1 °C	60.0 °C	72.0 °C	95.1 °C
Thermistor Number 2	3.9 °C	60.0 °C	72.0 °C	95.0 °C
Thermistor Number 3	4.1 °C	60.0 °C	71.9 °C	95.0 °C
Thermistor Number 4	3.9 °C	60.0 °C	71.9 °C	95.0 °C
Thermistor Number 5	4.0 °C	60.0 °C	72.0 °C	95.1 °C
Thermistor Number 6	4.0 °C	60.0 °C	72.0 °C	95.1 °C
Thermistor Number 7	4.0 °C	60.0 °C	72.0 °C	95.1 °C
Thermistor Number 8	4.0 °C	60.0 °C	72.0 °C	95.1 °C
Thermistor Number 9	4.0 °C	60.1 °C	72.1 °C	95.0 °C
Thermistor Number 10	4.0 °C	60.0 °C	72.1 °C	95.0 °C
Thermistor Number 11	4.0 °C	60.1 °C	72.0 °C	95.0 °C
Thermistor Number 12	4.0 °C	60.0 °C	72.1 °C	95.0 °C
Thermistor Number 13	4.0 °C	60.0 °C	72.1 °C	94.9 °C
Thermistor Number 14	4.0 °C	60.0 °C	72.1 °C	95.0 °C
Thermistor Number 15	4.0 °C	60.0 °C	72.1 °C	94.9 °C
Thermistor Number 16	4.1 °C	60.0 °C	72.1 °C	94.9 °C

In Table 1, the maximum error of temperature measurement is 0.4°C, and the average error of temperature measurement is about 0.161°C. In Table 2, the maximum error of temperature measurement is 0.1°C, and the average error of temperature measurement is about 0.037°C. Table 2 shows that the proposed calibration tool yields a precision of ±0.1°C. Consequently, the proposed calibration tool significantly enhances the temperature measurement accuracy.

5. Conclusions

The proposed calibration tool automatically modifies the default S-H coefficients given by thermistor manufactures. The proposed tool provides greater user convenience by simply recording the difference between the measured temperature and the reference temperature upon a user-friendly GUI program. In the temperature measurement evaluation of PCR devices, the proposed tool significantly enhances the temperature measurement accuracy with a precision of ±0.1°C.

Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology(2011-0009358).

References

[1] C. Chen, “Evaluation of resistance–temperature calibration equations for NTC thermistors”, Measurement, vol. 42, **(2009)**, pp.1103-1111.

[2] H. G. Schweiger, M. Multerer and H. J. Gores, “Fast multichannel precision thermometer”, IEEE Trans. Instrumentation and Measurement, vol.56, **(2007)**, pp.2002-2009.

[3] V. Maric, M. D. Lukovic, L. Zivanov, O. Aleksic and A. Menicanin, “EM simulator analysis of optimal performance thick-film segmented thermistors versus material characteristics selection”, IEEE Trans. Instrumentation and Measurement, vol.57, **(2008)**, pp.2568-2575.

[4] J. S. Steinhart and S. R. Hart, “Calibration curves for thermistors”, Deep Sea Research and Oceanographic Abstracts, vol.15, no.4, **(1968)**, pp.497-503.

[5] J. D. Kim, C. Y. Park, J. M. Kim, Y. S. Kim and H. J. Song, “Calibration of buffer-less system for thermistor temperature measurement”, International Conference on Information and Communication Technology Convergence, **(2012)**.

[6] M. D. Alexander and K. T. B. MacQuarrie, “Toward a standard thermistor calibration method: data correction spreadsheets”, Ground Water Monitoring & Remediation, vol.25, no.5, **(2005)**, pp.75-81.

[7] C. Y. Park, J. D. Kim, Y. S. Kim, H. J. Song, J. M. Kim and J. Kim, “Cost Reduction of PCR Thermal Cycler,” International Journal of Multimedia and Ubiquitous Engineering, vol.7, no.2, **(2012)**, pp.389-394.

[8] J. D. Kim, C. Y. Park, S.Y. Kim, O.D. Gwak, D.J. Lee, Y. S. Kim and H. J. Song, “Chamber Temperature Measurement of Micro PCR Chip Using Thermocouple,” International Journal of Multimedia and Ubiquitous Engineering, vol.7, no.2, **(2012)**, pp.395-402.

[9] D. Luenberger, Linear and Nonlinear Programming, Addison-Wesley, **(1984)**.

[10] BetaTHERM Sensors, Thermistors Applications Notes **(2004)**, available at http://www.betatherm.com.

[11] ILX Lightwave Corporation, Thermistor calibration and the Steinhart-Hart equation, Application Notes: Report no.4 **(2000)**, Bozeman, Montana.

Authors

Wan Yeon Lee, he received the BS, MS, and PhD degrees in computer science and engineering from POSTECH in 1994, 1996, and 2000, respectively. From 2000 to 2003, he was a research engineer in LG electronics. He is an associate professor in the Department of Computer Science, Dongduk Women’s University. His recent interests focus on embedded system, bioinformatics, computer security, and mobile computing.

Tong Min Kim, she received the B.S. degree in Computer Science from Dongduk Women’s University in 2014. She is currently pursuing her M.S. degree in College of Informatics, Korea University, Seoul, Korea. Her research interests include operating system, embedded system and computer security.

Min Ja Kim, she received the B.S. degree in computer engineering from Dongduk Women's University in 2000 and M.S. degree in Computer Science from Korea University in 2002. She is currently pursuing her Ph.D degree in College of Informatics, Korea University, Seoul, Korea. Her research interests include Operating System, File system and multimedia streaming.

Young Woong Ko, he received both a M.S. and Ph.D. in computer science from Korea University, Seoul, Korea, in 1999 and 2003, respectively. He is now a professor in Department of Computer engineering, Hallym University, Korea. His research interests include operating system, embedded system and multimedia system.

Jong Dae Kim, he received the M.S. and the Ph.D. degrees in Electrical Engineering from Korea Advanced Institute of Science and Technology, Seoul, Korea, in 1984 and 1990, respectively. He worked for Samsung Electronics from 1988 to 2000 as an electrical engineer. He is a Professor in Department of Convergence Software, Hallym University. His recent interests focus on biomedical system and bioinformatics.