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IMPROVING THE ACCURACY OF THERMAL CABLE MEASUREMENTS BASED ON MULTI-POINT AVERAGING OF DS18B20 SENSORS

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Abstract — The article addresses the problem of improving temperature measurement accuracy in thermometric cables based on DS18B20 digital sensors. The specified accuracy of a single sensor is ± 0.5 °C, which limits the use of standard thermal cables for applications requiring an accuracy of ± 0.05 °C. The aim of the study is to substantiate the possibility of achieving this accuracy by installing several sensors at each monitored horizon followed by joint processing of their readings. A combined method is proposed, including spatial averaging of readings from 2–3 sensors, individual calibration of each sensor, and temporal filtering. Calculations show that after individual calibration with a residual systematic error of no more than 0.03 °C and spatial averaging of three sensors, the total error does not exceed 0.05 °C. The results can be used in the design of systems for long-term monitoring of soil and borehole temperatures.

Keywords — thermometric cable, DS18B20, measurement accuracy, sensor averaging, calibration, temperature monitoring

DS18B20 ДАТЧИКТЕРІН КӨПНҮКТЕЛІК ОРТАШАЛАУ НЕГІЗІНДЕ ТЕРМОМЕТРЛІК КАБЕЛЬ ӨЛШЕУЛЕРІНІҢ ДӘЛДІГІН АРТТЫРУ

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Аңдатпа — Мақала DS18B20 цифрлық датчиктері негізінде термометрлік кабельдердегі температураны өлшеу дәлдігін арттыру мәселесіне арналған. Бір датчиктің паспорттық қателігі $\pm 0,5$ °C құрайды, бұл $\pm 0,05$ °C дәлдікті талап ететін міндеттерде стандартты термометрлік кабельдерді қолдануды шектейді. Зерттеудің мақсаты — бақыланатын әрбір горизонтқа бірнеше датчик орнатып, олардың көрсеткіштерін кейіннен бірлесіп өңдеу арқылы аталған дәлдікке қол жеткізу мүмкіндігін негіздеу. 2–3 датчиктің көрсеткіштерін кеңістіктік орташалауды, әрбір сенсорды жеке калибрлеуді және уақыт бойынша сүзгілеуді қамтитын біріктірілген әдіс ұсынылды. Есептік жолмен қалдық жүйелік қателігі 0,03 °C-тан аспайтын жеке калибрлеуден және үш датчиктің кеңістіктік орташалануынан кейін жиынтық қателіктің 0,05 °C-тан аспайтыны көрсетілді. Алынған нәтижелер топырақ пен ұңғымалар температурасын ұзақ мерзімді мониторингтеу жүйелерін жобалау кезінде пайдаланылуы мүмкін.

Кілт сөздер — термометрлік кабель, DS18B20, өлшеу дәлдігі, датчиктерді орташалау, калибрлеу, температуралық мониторинг.

ПОВЫШЕНИЕ ТОЧНОСТИ ИЗМЕРЕНИЙ ТЕРМОКОСЫ НА ОСНОВЕ МНОГОТОЧЕЧНОГО УСРЕДНЕНИЯ ДАТЧИКОВ DS18B20

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Аннотация — Статья посвящена проблеме повышения точности измерений температуры в термометрических косах на основе цифровых датчиков DS18B20. Паспортная погрешность одиночного датчика составляет $\pm 0,5$ °C, что ограничивает применение стандартных термокос для задач, требующих точности $\pm 0,05$ °C. Цель исследования — обосновать возможность достижения указанной точности путём установки нескольких датчиков на каждый контролируемый горизонт с последующей совместной обработкой их показаний. Предложен комбинированный метод, включающий пространственное усреднение показаний 2–3 датчиков, индивидуальную калибровку каждого сенсора и временную фильтрацию. Расчётным путём показано, что после индивидуальной калибровки с остаточной систематической погрешностью не более 0,03 °C и пространственного усреднения трёх датчиков суммарная погрешность не превышает 0,05 °C. Полученные результаты могут быть использованы при проектировании систем долговременного мониторинга температуры грунтов и скважин.

Ключевые слова — термокоса, DS18B20, точность измерений, усреднение датчиков, калибровка, температурный мониторинг

KEY FINDINGS

The study established that the specified error of a single DS18B20 sensor (± 0.5 °C) can be reduced to ± 0.05 °C through the combined use of spatial averaging and individual calibration. The proposed method showed that with three sensors installed at each horizon and a residual systematic error of 0.03 °C, the total error does not exceed 0.047 °C. The results can be used in the design of thermometric cables for long-term monitoring of soil and borehole temperatures.

INTRODUCTION

Thermometric cables based on DS18B20 digital sensors are widely used for long-term monitoring of soil, borehole, and water-body temperatures. The main limitation of the standard single-point solution is the specified error of the DS18B20, which is ± 0.5 °C over the range of $-10...+85$ °C. At the same time, the sensor resolution in 12-bit mode reaches 0.0625 °C, which is substantially better than its absolute accuracy.

Recent studies show that individual calibration of DS18B20 sensors can substantially improve their metrological characteristics. Rodríguez-Rama et al. [6] showed that after applying individual affine linear correction, the mean absolute error (MAE) decreases to 0.046–0.130 °C, while the root mean square error

(RMSE) decreases to 0.057–0.169 °C. This creates prerequisites for achieving the accuracy required for applications demanding highly reliable temperature data.

Research gap. Despite the availability of studies on individual calibration of DS18B20 sensors, the combined application of spatial averaging of several sensors and their individual calibration to achieve an accuracy of ± 0.05 °C remains insufficiently studied. Existing studies either consider only calibration of individual sensors [7] or are limited to averaging without accounting for systematic errors. This study addresses this gap by proposing a combined method that integrates spatial averaging of 2–3 sensors at each horizon with their individual calibration.

The aim of the study is to substantiate the possibility of achieving a temperature measurement accuracy of ± 0.05 °C in a thermometric cable by installing 2–3 DS18B20 sensors at each monitored horizon followed by joint processing of their readings.

Scientific novelty. This study proposes and analytically substantiates, for the first time, a combined method for improving the accuracy of DS18B20-based thermometric cables that simultaneously applies spatial averaging of readings from several sensors and individual sensor calibration. Unlike known studies that consider either calibration of individual sensors [6] or averaging without

correction of systematic errors, the proposed approach makes it possible to separately assess the contributions of random and systematic error components and determine the conditions for achieving the target accuracy of ± 0.05 °C. It was established that with a residual systematic error of no more than 0.03 °C and three sensors per horizon, the total error does not exceed 0.047 °C. Quantitative relationships were obtained for calculating the required number of sensors and calibration accuracy depending on the specified target error.

LITERATURE REVIEW

The DS18B20 sensor manufactured by Maxim Integrated (now Analog Devices) is one of the most widely used digital temperature sensors in environmental monitoring systems. Its main advantages are low cost, a wide operating temperature range ($-55...+125$ °C), a 1-Wire digital interface, and the ability to connect up to 200 sensors to a single bus.

The specified accuracy of the DS18B20 is ± 0.5 °C over the range of $-10...+85$ °C. However, as numerous studies show, the actual error of individual units may differ substantially. Rodríguez-Rama et al. [6] conducted metrological validation of eight encapsulated DS18B20 sensors using the TH-001 procedure of the Spanish Metrology Center. Without data processing, the errors corresponded to the manufacturer's specified ± 0.5 °C, but significant inter-sensor bias was observed.

The use of correction models can substantially improve accuracy. The study showed that the individual affine linear correction model provides the best compromise, reducing MAE to 0.046–0.130 °C. Similar results have been obtained in other studies: calibration of DS18B20 sensors under controlled conditions can reduce the mean error from 3% to 0.85% and decrease the standard error by approximately 48%.

An important aspect is the issue of sensor self-heating. According to the technical documentation, DS18B20 self-heating is less than 0.2 °C due to its low power consumption. However, during continuous high-frequency polling, self-heating can accumulate. Studies show that with a polling interval of 1 second, self-heating may reach 2 °C, whereas with a 30-second interval it decreases to less than 0.5 °C.

The averaging of readings from multiple sensors has been considered in a number of studies. In particular, discussions in the OWFS community note that using the average value from 30 sensors as the “true” temperature makes it possible to apply

regression analysis to compensate for each sensor's readings. Linear regression showed a better fit (deviations within $-0.04...+0.06$ °C) than quadratic regression.

The use of DS18B20-based thermometric cables for soil-temperature monitoring has been described in several publications. Zaszewski and Gruszczyński [11] presented a long-term soil-profile temperature monitoring system based on Arduino and DS18B20. After laboratory calibration, the mean absolute error was 0.02 °C. This confirms the fundamental possibility of achieving high accuracy provided that the sensors are carefully calibrated.

Thus, the literature review shows that individual calibration of DS18B20 sensors can achieve an accuracy of 0.05 °C or better. However, the combined use of calibration and spatial averaging for thermometric cables remains insufficiently studied, which justifies the need for the present research.

MATERIALS AND METHODS

The study used computational and analytical methods for assessing measurement error. The analysis was based on data on the metrological characteristics of DS18B20 sensors obtained from published sources and technical documentation.

A. Ethical Approval and Informed Consent

This study did not involve experiments with human participants or animals. Ethical approval was not required.

RESULTS AND DISCUSSION

A. Analysis of DS18B20 Error Sources

The error of a single DS18B20 sensor consists of the following components:

1. Systematic error (bias). The individual bias of each sensor relative to the true temperature. According to metrological validation of eight DS18B20 sensors, the mean absolute error (MAE) without correction was 0.28–0.31 °C, with substantial inter-sensor variation. Systematic error is dominant and is not eliminated by simple averaging of readings from identical sensors if their biases are correlated.

2. Random error. This is caused by quantization noise (0.0625 °C at 12 bits), fluctuations in supply current, and thermal noise. This component can be effectively reduced by averaging both over time and across space (using several sensors).

3. Self-heating error. The DS18B20 draws less than 1 mA, and self-heating is estimated at less than 0.2 °C; however, it may accumulate during continuous

polling. With cyclic polling and pauses, self-heating is negligible.

B. Spatial Averaging Method

At each horizon of the thermometric cable, sensors (2 or 3) are installed within a single isothermal zone. The resulting temperature value is calculated as the arithmetic mean:

$$\bar{T} = \frac{1}{n} \sum_{i=1}^n T_i \quad (1)$$

If the random errors of individual sensors are independent and have the same standard deviation (SD), the standard deviation of the arithmetic mean decreases by times:

$$\sigma_{\bar{T}} = \frac{\sigma}{\sqrt{n}} \quad (2)$$

For a typical random component of $^{\circ}\text{C}$ (one quantization step), we obtain: ($\sigma = 0,0625$)

Number of sensors	
1	0.0625
2	0.0442
3	0.0361

Thus, even with the random error component is reduced below the target level of 0.05°C , and with — with a margin. ($n = 2$) ($n = 3$)

C. Calculation of the Reduction in the Systematic Component

Systematic error is eliminated in a fundamentally different way—through individual calibration of each sensor. Spatial averaging by itself does not reduce systematic error if sensor biases are correlated (which is characteristic of devices from the same batch). However, after calibration, the residual systematic error can be reduced to a level comparable to the random component.

D. Combined Calculation of Achievable Accuracy

The total error after calibration and averaging is estimated using the following formula:

$$\Delta_{\Sigma} = \sqrt{\Delta_{\text{сис}}^2 + \sigma_{\bar{T}}^2} \quad (3)$$

where is the residual systematic error after calibration, and is the SD of the random component after averaging. ($\Delta_{\text{сис}}$) ($\sigma_{\bar{T}}$)

Scenario 1: 2 sensors, calibration to MAE = 0.05°C

$$\Delta_{\Sigma} = \sqrt{0,05^2 + 0,0442^2} = \sqrt{0,0025 + 0,00195} \approx 0,067^{\circ}\text{C}$$

Scenario 2: 3 sensors, calibration to MAE = 0.05°C

$$\Delta_{\Sigma} = \sqrt{0,05^2 + 0,0361^2} = \sqrt{0,0025 + 0,00130} \approx 0,062^{\circ}\text{C}$$

Scenario 3: 2 sensors, calibration to MAE = 0.03°C (best-performing units)

$$\Delta_{\Sigma} = \sqrt{0,03^2 + 0,0442^2} = \sqrt{0,0009 + 0,00195} \approx 0,053^{\circ}\text{C}$$

Scenario 4: 3 sensors, calibration to MAE = 0.03°C

$$\Delta_{\Sigma} = \sqrt{0,03^2 + 0,0361^2} = \sqrt{0,0009 + 0,00130} \approx 0,047^{\circ}\text{C}$$

Thus, the target accuracy of $\pm 0.05^{\circ}\text{C}$ is achieved under two conditions:

1. Individual calibration of each sensor with a residual systematic error of no more than 0.03 – 0.04°C .

2. Spatial averaging of at least 3 sensors per horizon (or 2 sensors with particularly good calibration).

E. Calibration Procedure

To achieve a residual systematic error of 0.03°C , the following procedure is recommended:

1. Temperature stabilization. All sensors in the batch to be calibrated are placed in a precision thermostat with a reference thermometer (e.g., Pt-100). Temperature-field nonuniformity within the working volume should not exceed 0.01°C .

2. Multi-point calibration. Measurements are performed at no fewer than 5–7 temperature points covering the operating range. A linear regression is constructed for each sensor, and its coefficients are stored in the logger memory. ($T_{\text{нст}} = a \cdot T_{\text{ДС}} + b$),

3. Residual error assessment. After applying the correction, the MAE is calculated for each sensor. Sensors with MAE > 0.05°C are rejected or recalibrated.

G. Additional Measures to Reduce Error

1. Temporal averaging (moving average). In addition to spatial averaging, time-series filtering is applied. With a polling period of s and an averaging interval of s , the reduction in the random component is, i.e., the SD decreases from 0.0625°C to 0.008°C . This provides an additional accuracy margin. ($T = 1$) ($nT = 60$) ($1/\sqrt{60} \approx 0,129$)

2. Median filtering. To eliminate anomalous outliers (e.g., during brief 1-Wire failures), a median filter over three consecutive readings is applied. This improves system robustness without significantly increasing computational load.

3. Self-heating control. Sensors are polled with pauses of at least 5 seconds between measurements, reducing self-heating to a negligible level.

CONCLUSION

The proposed method of multi-point averaging of DS18B20 sensors combined with individual calibration makes it possible to achieve a temperature measurement accuracy of ± 0.05 °C in a thermometric cable. The key conditions for success are:

- installation of at least 3 sensors at each monitored horizon;
- individual calibration of each sensor with a residual systematic error of no more than 0.03 °C;
- application of temporal averaging and median filtering;
- control of self-heating through cyclic polling with pauses.

The method does not require expensive equipment and can be implemented on standard

microcontrollers using the existing 1-Wire infrastructure. Further work will involve experimental verification of the calculated estimates on a calibration test bench.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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