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Water temperature measurement in an automated terrarium using a Pt1000 sensor

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Abstract: *The article considers the application of a platinum resistance thermometer Pt1000 for accurate measurement of water temperature in an automated terrarium. A mathematical model of the resistance-temperature dependence R(T) based on the Callendar–Van Dusen equations is presented. The static and dynamic characteristics of the sensor are analyzed, and the influence of lead wire resistance and measurement channel noise is evaluated. An experiment was conducted to investigate the response of the Pt1000 sensor to a rapid temperature change in a water environment. The obtained curves demonstrate a fast initial temperature jump in the sensor contact zone with hot water, followed by a transient mixing of layers with damped oscillations and gradual establishment of thermal equilibrium. The experimental results confirm a first-order dynamic model with an effective thermal time constant τ and are consistent with analytical estimates of thermal inertia. The obtained dependencies make it possible to improve calibration accuracy and optimize digital filtering algorithms in terrarium microclimate control systems.*

Keywords: *Pt1000, Callendar–Van Dusen, terrarium, temperature measurement, RTD, thermal inertia, automated system.*

1. INTRODUCTION

Temperature control is an important component of automated microclimate monitoring systems in technical and biological facilities. This task is especially relevant in conditions where stable environmental parameters must be maintained, in terrariums, laboratory installations, and animal housing facilities. Violation of the temperature regime can negatively affect both biological processes and the efficiency of technical systems [1–3].

Among modern temperature measurement instruments, platinum resistance thermometers of the Pt100 and Pt1000 types are widely used due to their high stability, repeatability of readings, and wide measurement range. Their main characteristics and accuracy requirements are regulated by the international standard IEC 60751, which defines the dependence of electrical resistance on temperature and sensor accuracy classes [4]. The use of platinum thermometers is also consistent with the International Temperature Scale ITS-90, which confirms their metrological reliability [5].

At the same time, in practical applications of resistance thermometers, a number of factors affect measurement accuracy. These include lead wire resistance, contact instability, sensor self-heating, and errors of the measurement circuitry. To reduce the influence of these factors, various connection schemes and compensation methods are used, as confirmed by modern studies in the field of measurement technology [6–8].

With the development of microcontroller technologies, intelligent measurement systems have become widespread, providing digital signal processing, sensor characteristic linearization, and integration with automated control systems [9–11]. This makes it possible to increase measurement accuracy and reliability of microclimate control systems.

Modern approaches to environmental monitoring involve the use of multisensor systems and remote data acquisition technologies, which are especially important for facilities with increased requirements for environmental stability. In such systems, temperature measurement accuracy is a determining factor for the effectiveness of control algorithms.

The aim of this work is to develop a model of the water temperature measurement channel based on a Pt1000 sensor, analyze its static and dynamic characteristics, and quantitatively assess the main sources of error in the context of application in an automated terrarium.

2. MODELING OF THE PT1000 THERMORESISTOR USING THE CALLENDAR–VAN DUSEN EQUATIONS

Platinum resistance thermometers of the Pt1000 type are widely used in measurement systems due to the stability of their characteristics and the predictable dependence of electrical resistance on temperature. The nominal resistance of the sensor at 0 °C is 1000 Ω, and a change in temperature causes a proportional change in the resistance of the sensing element.

To mathematically describe this dependence, the Callendar–Van Dusen equation is used, which allows determining the resistance of the thermoresistor as a function of temperature.

For positive temperatures (t ≥ 0 °C), the dependence has the form:

$$R_t = R_0(1 + At + Bt^2) \tag{1}$$

where: R_t– resistance of the thermoresistor at temperature t, Ω;
R_0– nominal resistance at 0°C;
A, B – coefficients depending on the properties of platinum.

For negative temperatures (t < 0 °C), the equation is supplemented with a cubic term:

$$R_t = R_0[1 + At + Bt^2 + C(t - 100)t^3] \tag{2}$$

where C – an additional coefficient that accounts for nonlinearity at low temperatures.

The standard values of the coefficients for platinum resistance thermometers are:

$$A = 3.9083 \times 10^{-3}\ °\mathrm{C}^{-1},$$

$$B = -5.775 \times 10^{-7}\ °\mathrm{C}^{-2}, \tag{3}$$

$$C = -4.183 \times 10^{-12}\ °\mathrm{C}^{-3}.$$

The mathematical model based on these equations makes it possible to convert the measured resistance into the corresponding temperature and analyze sensor sensitivity in a given range. The sensitivity of the thermoresistor is determined as the derivative of resistance with respect to temperature:

$$S = \frac{dR_t}{dt} \tag{4}$$

which allows estimating resistance variation for small temperature changes.

In practical measurement systems, this model is implemented in the form of an algorithm that can be embedded in a microcontroller or software. This increases measurement accuracy and allows correction of results during sensor calibration.

B Based on these equations, the R(T) dependence for Pt1000 was developed in the range from −20 to 120°C. The resulting curve is shown in Fig. 1. Fig. 2 shows the temperature sensitivity dR/dT calculated by numerical differentiation of R(T), which is a nonlinear function of temperature according to the Callendar–Van Dusen equations, and the total deviation of the sensor sensitivity in the entire studied temperature range is quite small, which simplifies the implementation of the measuring channel and ensures stable resolution of the system. The most noticeable change in sensitivity is observed outside the operating range of terrarium temperatures, while in the range of 20–35 °C it changes slightly and is about 4 Ohm/°C, which provides good resolution even for ADCs with a limited number of bits.

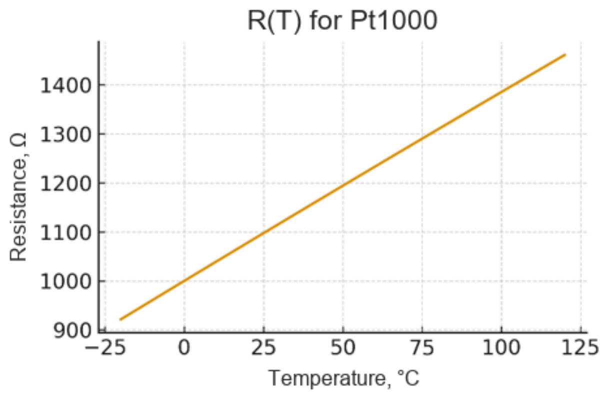

Figure 1. Resistance-temperature dependence R(T) of the Pt1000 sensor.

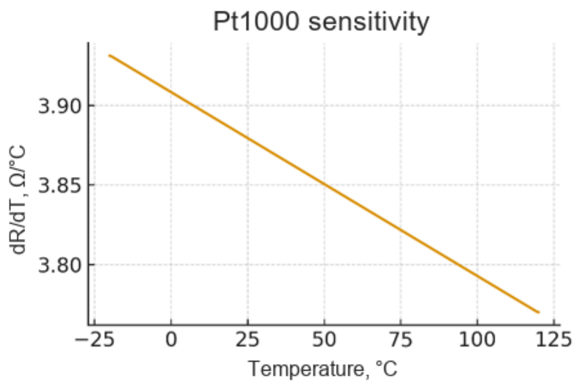

Figure 2. Temperature sensitivity of the Pt1000 sensor, dR/dT.

3. ARCHITECTURE OF THE AUTOMATED TERRARIUM

An automated terrarium is a complex system designed to maintain stable microclimate parameters through continuous temperature monitoring and control of actuators. The main purpose of the system is to ensure a задане temperature regime in accordance with the biological needs of the organisms being kept.

The architecture of the automated terrarium includes the following main components:

– primary temperature sensors;
– data acquisition and processing module;
– actuator control system;
– user interface.

A platinum resistance thermometer of the Pt1000 type is used as the primary temperature sensor. It is installed in the water zone of the terrarium and connected to the controller via a 3- or 4-wire scheme, which allows compensation of cable resistance [12]. The sensor signal is fed to the measurement module, where resistance is converted into a digital code using an analog-to-digital converter [13].

Functionally, the system structure can be represented as a closed control loop, where the ambient temperature is the controlled variable. The measured temperature value is compared with the setpoint, after which a control action is generated for the actuators.

The main control equation has the form:

$$e(t) = T_{set} - T_{meas} \tag{5}$$

where: $e(t)$ – control error;
T_{set} – set temperature value;
T_{meas}– measured temperature value.

Based on the error, the control signal is formed:

$$u(t) = K \cdot e(t) \tag{6}$$

where: $u(t)$– control action applied to the actuator;
K – system gain coefficient.

The actuators include heating elements, ventilation, and humidification systems that provide correction of microclimate parameters. The system operates on the principle of periodic sensor polling followed by data processing in a microcontroller.

An important part of the architecture is the software module that implements signal processing algorithms, measurement filtering, and control command generation. To reduce the influence of random disturbances, averaging of measurement results is used:

$$T_{avg} = \frac{1}{n}\sum_{i=1}^{n} T_i \tag{7}$$

where: T_i – individual measured temperature values;
n – number of measurements.

The use of digital signal processing increases system stability and reduces the probability of false actuator triggering.

The structural diagram of the information and measuring system for controlling the microclimate of an automated terrarium used in this study is shown in Fig. 3. The system was implemented as a multi-channel platform for collecting measuring information and controlling actuators and was used both for experimental research of the characteristics of the Pt1000 sensor and for practical maintenance of the specified microclimate parameters [14].

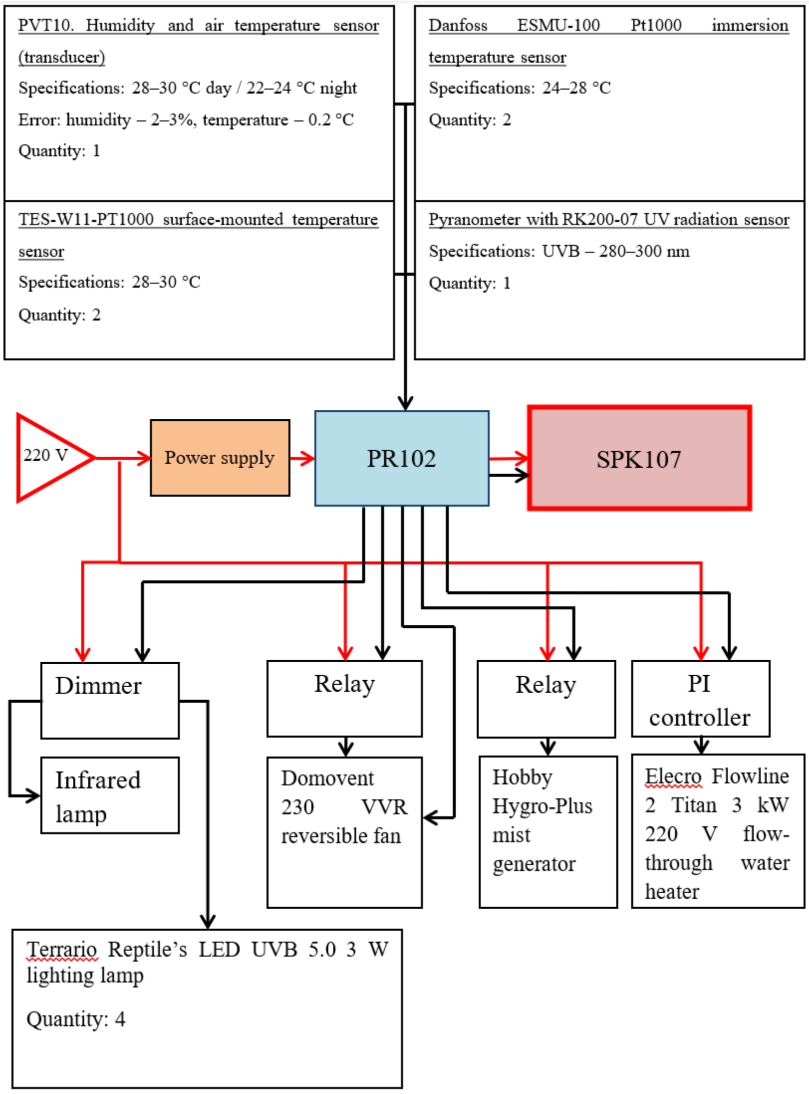

Figure 3. Structural diagram of the information and measuring system for controlling the microclimate in the terrarium.

The system includes air temperature and humidity sensors, immersion and surface-mounted Pt1000 temperature sensors, and an ultraviolet radiation sensor. The primary converters generate analog signals that are fed to the PR102 programmable relay, which performs the functions of collecting and primary processing of measurement information.

The AQTeck touch panel controller SPK107 was used as the central element of interaction with the operator and visualization of microclimate parameters, which provides indication of current temperature values, settings and displaying the status of actuators. The PR102 programmable relay from the same manufacturer performed the functions of logical control, processing signals from sensors and generating control actions.

The terrarium actuators, in particular heating elements, fans, humidification and lighting systems, are controlled via power modules, relays and power regulators connected to PR102. This architecture allows you to separate the information-measuring and power levels of the system, increasing its reliability and electrical safety.

The use of this structural diagram provided the opportunity to study the static and dynamic characteristics of the Pt1000 sensor in conditions as close as possible to real operation, as well as to assess the impact of signal processing and control algorithms on the accuracy of measuring the temperature of the water environment.

4. MODELING AND EXPERIMENTAL METHODOLOGY

To evaluate the influence of cable resistance, a sequential addition of 1–10 Ω to the nominal resistance of the Pt1000 was modeled. The equivalent temperature error was calculated by dividing the additional resistance by the local sensitivity dR/dT at 25 °C. The results are presented in Table 1.

Table 1. Temperature measurement error caused by cable resistance.

Cable resistance, Ω	Error, °C	Relative error, % of range 0–120 °C
0.0	0.000	0.000
1.0	0.258	0.215
2.0	0.516	0.430
5.0	1.289	1.074
10.0	2.578	2.148

Calibration of the measurement channel was modeled as a series of measurements at known reference temperatures in the range 0–60 °C. A constant offset and random noise simulating amplifier error and ADC quantization were added to the true temperature value. Based on the obtained «true–measured» temperature pairs, the mean bias and root mean square error (RMSE) were calculated [15] (Table 2).

Table 2. Calibration results of the Pt1000 measurement channel.

Reference temperature, °C	Measured temperature, °C	Error, °C
0.0	0.23	+0.23
10.0	9.86	-0.14
20.0	20.18	+0.18
30.0	29.75	-0.25
40.0	39.77	-0.23
50.0	50.06	0.06
60.0	60.18	0.18
RMSE / bias		0.191 / 0.004

To analyze the dynamic properties of the sensor, a first-order model with a time constant τ was adopted. The response to temperature change is described by the expression $T(t) = T_{end} + (T_{start} - T_{end})\cdot\exp(-t/\tau)$. Fig. 4 shows the normalized transient response for τ = 8 s, which is a typical value for an immersed sensor in stationary water.

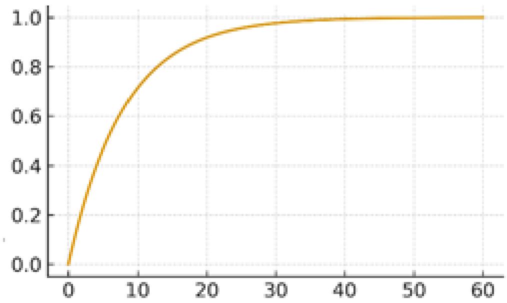

Figure 4. Normalized transient response of the Pt1000 sensor for a temperature step.

The time parameters t_{10}, t_{50} and t_{90} were defined as the times when the sensor output reaches 10%, 50% and 90% of the total temperature change, respectively. For different environments (stationary water, running water, air) these parameters differ due to different heat transfer coefficients and heat capacity of the surrounding medium. The smaller value of the time constant in flowing water is explained by a more intensive heat transfer due to forced convection, while in stationary water the formation of a local temperature layer near the sensor surface reduces the heat transfer rate [16] (Table 3).

Table 3. Dynamic parameters of the Pt1000 sensor in different media.

Environment	t_{10}, c	t_{50}, c	t_{90}, c	τ, c
Stationary water	2.0	6.0	18.0	8.0
Running water	0.8	2.5	7.5	3.5
Air in the terrarium	5.0	15.0	45.0	18.0

5. EXPERIMENTAL STUDIES

As part of the study, an experiment was conducted to evaluate the dynamic response of the Pt1000 sensor during sudden changes in water temperature. For this experiment, a SCADA system was developed to record the measurement signals from the temperature sensor and present them in the form of graphs and numerical values. In the first stage, the sensor was in a stable state at a temperature of about 12–14°C (Figure 5).

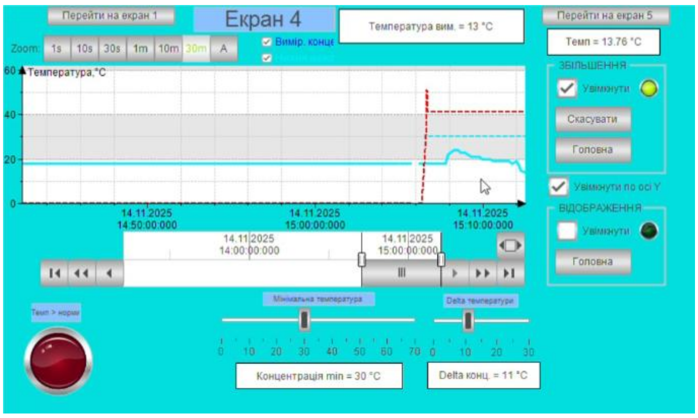

Figure 5. Initial response of the sensor in cold water.

Adding a portion of hot water caused a rapid increase in temperature in the local area near the sensor, as shown in Figure 6. This corresponds to the phase when the thermal conductivity of water provides rapid heat transfer to the sensing element. Then the temperature gradually decreased. This is explained by the fact that hot water, having a lower density, rises and mixes with the bulk of the colder water. Convection flows form a complex structure of recirculation movements, due to which the temperature value does not decrease monotonically, but changes according to a complex dependence.

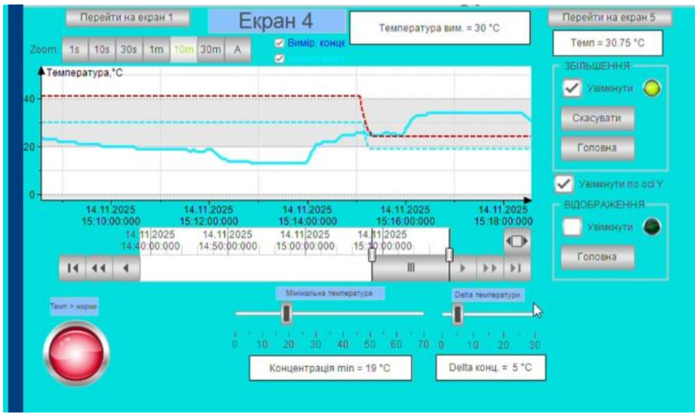

Figure 6. Transient process: sensor response to a sharp thermal shock and mixing of water layers.

In the final phase (Fig. 7), the system approaches thermal equilibrium. The rate of temperature change decreases, and the water mass approaches a stable value determined by the ratio of hot and cold water volumes. At this stage, the thermal balance is described by an exponential law with effective heat capacity and heat transfer coefficient [17].

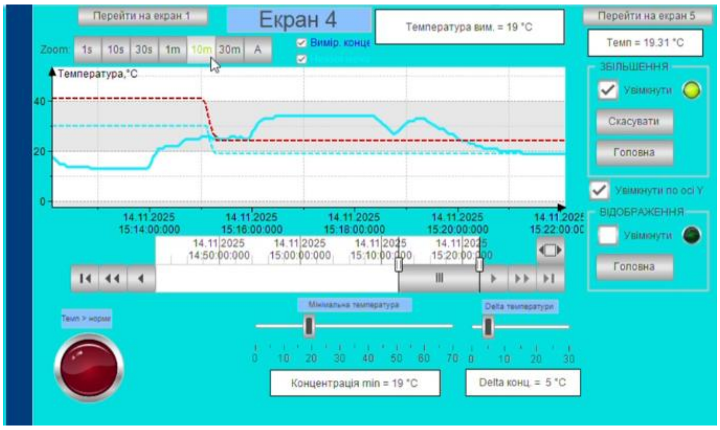

Figure 7. Final stage: slow establishment of thermal equilibrium.

6. ERROR AND NOISE ANALYSIS

The total temperature measurement error consists of several components: the error of the Pt1000 sensor itself (accuracy class), the error from the resistance of the connecting conductors, the error of the calibration of the measuring path, the noise of the amplifier and the quantization noise of the ADC. As can be seen from Table 1, even an additional resistance of 5 Ohm can lead to an equivalent error of about 1.3 °C, which is unacceptable for high-precision control. Therefore, in practical implementations, it is advisable to use a 3- or 4-wire connection scheme, as well as to make a correction for the measured line resistance. The simulation results

(Table 2) show that in the presence of constant bias and small random noise, the root mean square error RMSE is about 0.19 °C, and the average bias is 0.18 °C. In a real system, these values can be reduced by multipoint calibration, matching the Callendar–Van Dusen coefficients with the passport data of a particular sensor, and using low-noise amplifiers.

The noise of the measurement path, as a rule, has a close to white spectrum in the operating frequency band. The use of digital low-pass filters (for example, moving average or exponential smoothing) allows you to reduce the standard deviation of the readings without a significant increase in the delay, especially if the filter time constant is chosen significantly less than the thermal time constant of the sensor τ.

The quantization noise of the ADC can become significant in the case of inefficient use of the input range of the converter or insufficient signal amplitude on the measuring resistor. For example, for a 12-bit ADC with a range of 0–3.3 V, one quantum corresponds to approximately 0.8 mV. With a sensitivity of the measuring circuit of about 10 mV/°C, this corresponds to a temperature quantization step of about 0.08 °C, which is acceptable in the conditions of this system. Further reduction of the influence of this source of error can be achieved by increasing the resolution of the ADC to 16 bits or using signal preamplification.

7. CONCLUSIONS

The article discusses the use of a Pt1000 platinum resistance thermometer to measure water temperature in an automated terrarium. Based on the Callendar–Van Dusen equations, the R(T) dependence was constructed and temperature sensitivity in the operating range of 20–35°C was evaluated. The analysis of lead wire resistance influence, as well as modeling of calibration errors and measurement channel noise, showed that measurement accuracy strongly depends on correct line resistance compensation, amplifier selection, and ADC resolution.

Experimental studies performed by abrupt temperature changes in the aquatic environment confirmed the dynamic properties of the Pt1000 sensor obtained during the simulation. The experiment demonstrated the presence of a rapid temperature increase due to local heating and a subsequent damped thermal equalization process, which is in good agreement with the first-order model with a time constant τ. The results obtained indicate the predictability of data from the sensor in real-world conditions and confirm the possibility of an accurate description of its thermal inertia by means of analytical simulation.

Thus, the combination of theoretical analysis, modeling, and experimental verification provides a comprehensive understanding of Pt1000 operation in terrarium water environments. With proper calibration and consideration of environmental physical properties, the Pt1000 sensor ensures temperature measurement accuracy at the level of 0.2 °C, making it an effective tool for automated terrarium water temperature control systems.

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