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INCREASING ACCURACY OF TEMPERATURE MEASUREMENT BASED ON ADAPTIVE ALGORITHM FOR MICROCONTROLLER TRANSMITTER

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Original scientific paper

The article compares the most common methods for converting measured resistance of platinum sensor to a temperature value in relation to the new adaptive algorithm applied in a compact temperature transmitter. The hardware of the temperature transducer is based on a microcontroller with input/output circuits that generate an output signal proportional to the measured temperature. The compact temperature transmitter has size constraints because it is required to be installed in the head of an industrial thermometer. The microcontroller is limited by the available power supply and memory resources. The platinum temperature sensors should conform to industry standards and fit a mathematical curve known as the Callendar-Van Dusen equation with nominal values of constants *A*, *B* and *C*. The increase in the total accuracy of temperature measurement is possible by matching the sensor characteristics with the connected temperature transducer. After calibration of the platinum sensor, corresponding new constants are calculated and written into the temperature transmitter. The presented new software method enables the use of the Callendar-Van Dusen constants retaining or even increasing the accuracy of the resistance to temperature conversion.

Keywords: *adaptive algorithm, microcontroller, sensor, temperature measuring, temperature transmitter*

Povećanje točnosti mjerenja temperature primjenom adaptivnog algoritma mikroupravljača u pretvorniku

Izvorni znanstveni članak

U članku su uspoređene najčešće metode pretvorbe izmjerenog otpora platinskog senzora u vrijednost temperature u odnosu na novi adaptivni algoritam u kompaktnom pretvorniku temperature. Hardverska osnova pretvornika temperature je mikroupravljač s ulazno-izlaznim sklopovima koji generiraju izlazni signal proporcionalan izmjerenoj temperaturi. Kompaktni pretvornik temperature ima dimenzijska ograničenja kako bi se mogao montirati u glavu industrijskog termometra, a mikroupravljač je ograničen glede raspoložive struje napajanja te memorijskih resursa. Platinski temperaturni senzori normirani su Callendar-Van Dusenovom jednadžbom s definiranim koeficijentima *A*, *B* i *C*. Povećanje ukupne točnosti mjerenja temperature moguće je usklađivanjem karakteristika senzora s pretvornikom temperature na koji se priključuje. Kalibracijom platinskog senzora odrede se pripadni koeficijenti CvD jednadžbe koji se mogu upisati u pretvornik temperature. Prikazana nova programska metoda omogućuje korištenje navedenih koeficijenata uz zadržanu ili čak i povećanu točnost pretvorbe otpora u temperaturu.

Ključne riječi: *adaptivni algoritam, mikroupravljač, mjerenje temperature, pretvornik temperature, senzor*

1
Introduction
Uvod

A temperature transmitter is an electronic device that converts the temperature measured by a sensor to the proportional electrical or digital value. It is necessary to measure the resistance of a sensor with high accuracy (at the input terminals of the transmitter) for platinum sensors applications. The temperature calculation depends on the functional relationship to the measured resistance. The generated electrical signal is linearly proportional to the calculated temperature. NAMUR-Recommendations for the use of temperature transmitters with digital signal processing in the chemical industry NE89 [1] precisely define the properties that such a device must have. The recommendations describe the dimensions of the device (to be inserted into the thermometer head or on the rail) and the value of the output signal, which must be proportional to the measured temperature, or in the case of the error it must show the alarm condition. The values of the output signal are given in the recommendation NE43 [2], and the behavior in the event of electromagnetic interference is governed by the recommendation NE21 [3]. The recommendation NE53 [4] deals with the issue of identification, version control and stability of the software, and the recommendation NE79 [5] regulates the behavior, use and verification of microprocessor-temperature transducers in the safety instrumentation systems (SIL).

The aim of this study is to compare the effects caused by different calculation methods on the accuracy of temperature measurement. The measurement error of the sensor resistance is equal in all tested methods. This result is caused by the use of the fixed input structure (hardware) and the same resistance measurement software. There are several methods/algorithms used for conversion of the measured resistance R_t into the temperature ϑ. The dependence of resistance R_t on temperature value ϑ is defined in the standard [6] and based on Callendar-van Dusen equation:

$$R_\mathrm{t} = R_0\left[1 + A\cdot\vartheta + B\cdot\vartheta^2 + C\cdot(t-100)\cdot\vartheta^3\right]. \tag{1}$$

The value of the constants *A*, *B* and *C* is defined by the standard. In reality, since platinum sensors have minute variations in chemical composition and deviate from the perfect temperature-resistance relationship [7], it is necessary, with an additional calibration, to determine the precise values of the constants [8]. With the matching between the temperature transmitter and the connected sensor, it is possible to reduce the total error of the temperature measurement up to three times [9]. Of course the most important precondition for this is that the resistance-temperature conversion method can benefit from the corrected constants *A*, *B* and *C*. The new method based on adaptive algorithm uses this approach.

2
Compact temperature transmitter
Kompaktni pretvornik temperature

The hardware complexity and compact temperature transmitter software are limited by space and physical limits deriving from its application. Each applied conversion method of Platinum sensor resistance to temperature should take care of physical limits such as microcontroller memory and processing speed of program code execution in real time [14].

The temperature measurement transmitters have some limits that are not so important by similar electronic instruments:

1. Small available space or volume, limited by request to put the transmitter to the industrial thermometer head;
2. Small available power for transmitter operation (<3 mA from current loop, or < 10 mA by Profibus or similar industrial bus);
3. Limited dimensions of electronic circuit board and the fact that the sensor (measuring inlet) terminals are going throughout the central whole on this board.

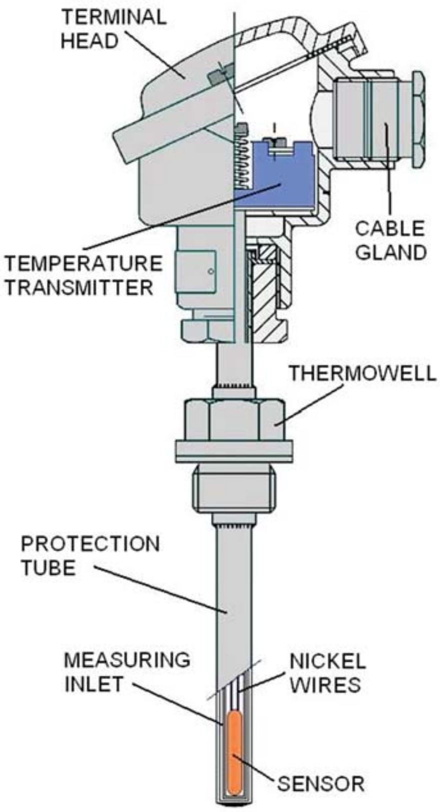

Figure 1 *Temperature transmitter position inside thermometer*
Slika 1. *Smještaj pretvornika temperature u termometru*

The temperature transmitter that is placed in a casing intended to be built into the thermometer head has a limited volume, as it should be suitable by dimensions to be incorporated to a B-type head with shallow cover (presented in Fig.1 in the cross-section of industrial thermometer). This type of head is most commonly used in practice. This is due to the fact that an older plants temperature transmitter was installed in the instrumentation racks (like cards or modules to be installed in the frame). The industrial thermometers had terminals in the head (terminal block on the ceramic body). The function of converting a measurement signal is transferred closer to the sensor by decentralization of measurement system, i.e. measuring transducers are mounted directly to the sensor head. In this way the weak signal from the sensor input passing through the long lines is prevented from being exposed to unwanted interference from the environment. At the beginning of the measurement transducers were performed in analog electronics hardware, discrete electronic circuits, which required a relatively small volume, though there was also some problem. By adapting to digital technology, galvanic isolated circuits and multiprocessor control using microcontroller, the requirements for small volume have become a limiting factor.

Measuring temperature transducers with current output are fed from the current loop. In relation to digital converters with digital bus (Profibus or Fieldbus) they are more limited by the energy they can receive from the monitoring system. They have limited current for their own consumption to a maximum of 3 mA. The current of 3,6 mA is a signal current for the alarm by the standard [2]. Transmitter must function properly with the voltage in the range from 8 to 10 V (specifications vary from manufacturer to manufacturer). These both together give a maximum power of about 30 mW, which is available to the circuits of the measuring temperature transmitter.

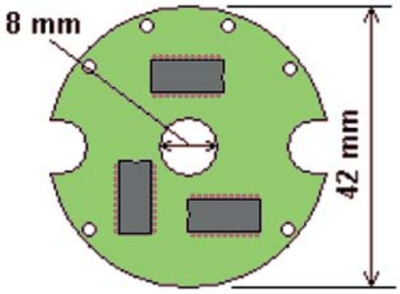

Figure 2 *Layout of printed circuit board of temperature transmitter*
Slika 2. *Tlocrt tiskane pločice pretvornika temperature*

Fig. 2 shows the printed circuit board layout, and the available surface area to accommodate electronic circuits of the measuring transducer temperature. The irregular shape of the surface can be observed making it difficult to place larger integrated circuits, microcontroller of higher power, or the available program and RAM memory. The space that is available for the microcontroller is less than the square size of 12×12 mm so the microcontroller selection is limited to a smaller range of types.

More complex temperature transmitters use 2 or more microcontrollers, utilize different types of sensors, and communicate via digital bus. To compare methods for the resistance-temperature conversion software, it is sufficient to take as the basis a compact temperature transmitter with a single microcontroller.

The platinum sensor resistance is measured by comparing the voltage drop across the sense resistor Pt100 and reference resistor R_{ref} while keeping a constant current flow in the circuit. This principle is called the Anderson current loop [10]. The current loop (see Fig. 3) consists of a current source and the following resistors connected in series: resistance of the temperature sensor (Pt100), R1, R2 and the highly precise, and most importantly, temperature-stable reference resistor R_{ref}. The resistors R1 and R2 limit the current in the loop and lift the differential voltages in the voltage domain of A/D converter. The ideal circuit should have a regulated constant current source. The measurements of the differential voltages on Pt100 and R_{ref} should be taken simultaneously [11]. In the simplified version a constant current source is not used, but stabilized power supply (V_{cc}=3,5 VDC). It is assumed that the current is constant during the measurement of the differential voltages ΔU_{Pt100} and ΔU_{Rref}.

$$I_k = \frac{V_{cc}}{R_1 + R_{Pt100} + R_{ref} + R_2}. \tag{2}$$

The accuracy of resistance measurement is affected by changes of amplifier and A/D converters offsets, therefore they must be taken into account if the measurement is not performed under conditions of constant ambient temperature [12].

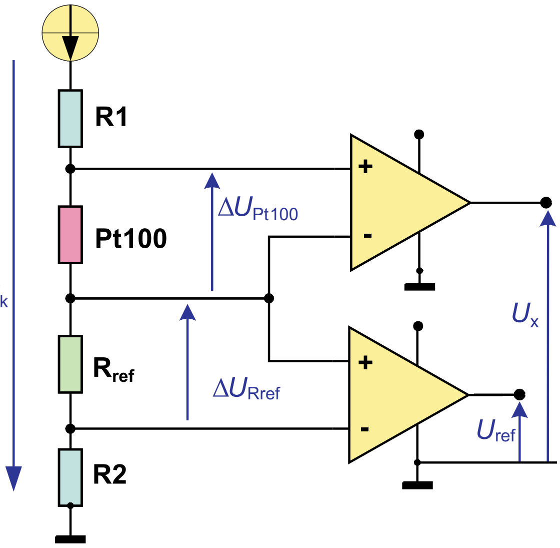

Figure 3 *The input circuit on the principle of Anderson current loop*
Slika 3. *Ulazni sklop na principu Andersonove strujne petlje*

Fig. 4 shows a block diagram of the compact temperature transmitter. Platinum sensor with four-wire connection is connected to the transmitter input, thus directing the excitation current flow through terminals 3 and 6 and the reference resistor R_{ref}. Voltage drop across the sensor is measured at terminals 4 and 5. A two-channel A/D converter [13] with integrated differential amplifiers is used for the analog-digital conversion. A microcontroller from TI's MSP430 series is selected because of its relatively low energy consumption [14]. The output circuit consists of a voltage-current converter. The converter is controlled by "pulse width" modulation from the microcontroller. The 4-20 mA loop, which is modulated by the transmitter, is connected at terminal 1 and 2. The information about the measured temperature is transmitted by output current signal.

There is also a possibility to input the digital parameters to the transmitter by applying an amplitude modulation to serial ports R×D and T×D. The energy supply of the transmitter is derived from the voltage of the output current loop, with a limitation that the total current of all circuits is less than 3 mA. Through the JTAG interface the microcontroller offers both the capability for entering a program and checking the program execution.

3
Temperature conversion methods
Metode proračuna temperature

There are several well-known software methods for resistance-temperature conversion, which consider the relationship according to equation (1) that can be used with the described hardware structure, i.e., a temperature transducer based on microcontroller. The execution of the program code is performed on a microprocessor platform of ultra-low power 16-bit RISC mixed-signal microcontroller. The program design is influenced by limiting factors such as the available code memory, the amount of available EEPROM, speed of execution and the general properties of the selected microcontroller [18].

The fact that the physical limitation of available microcontroller power supply will result in a decreased frequency of its oscillator clock should also be considered. In addition to descriptions of the known temperature conversion methods, a new method of gradual approach will be described. Each method has its respective advantages or disadvantages that are based on the criteria used for the method evaluation. The precision of measurements is one of the most important parameters. Increasing the accuracy of measurements by modifying the software on the same hardware platform is one of the biggest challenges of this research.

Three basic methods for temperature calculation are often applied in practice:

- Lookup table method
- Equation method
- Polynomials method.

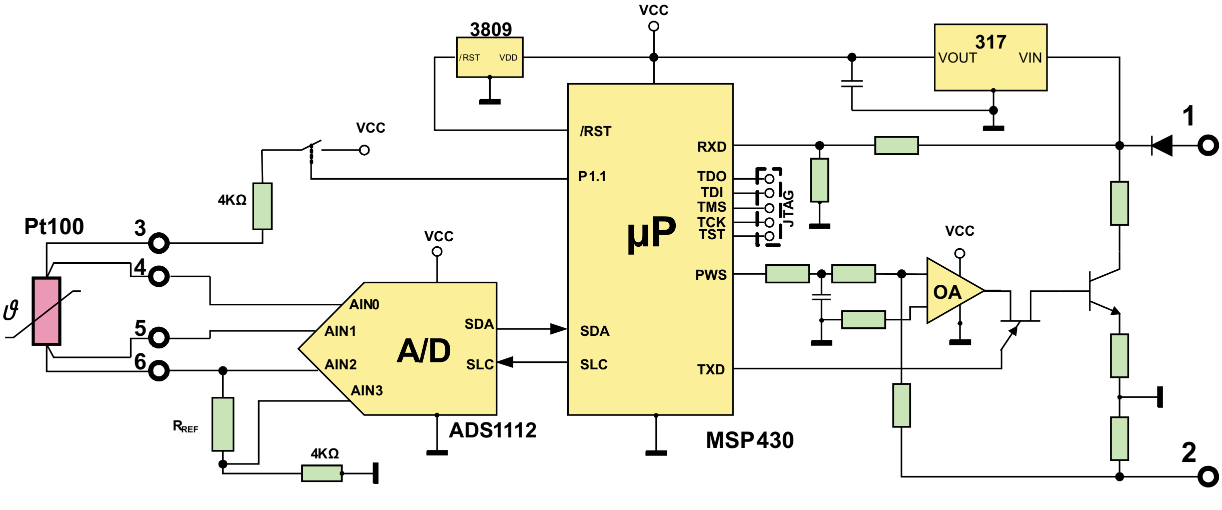

Figure 4 *Block scheme of a compact temperature transmitter*
Slika 4. *Blok shema jednostavnog pretvornika temperature*

3.1
Lookup table method (Points22 and Points43)
Tablična metoda (Points22 and Points43)

The microcontroller used in the temperature transmitter has limited resources. The available code memory leaves space for only up to 50 pairs in the temperature – resistance lookup table. If the value of the resistance falls between two values in the lookup table linear approximation of equation through two points should be calculated. Table elements can be equidistantly positioned or they can have higher density in the defined range [15]. To show the impact of number of points on measurement precision, two variants are implemented: the shorter with the smaller pair number (Points22) and longer (Points43). The temperature value is calculated by interpolation between two pairs of points in the table where the R_{meas} is the measured value of sensor resistance:

$$T=\frac{(R_{\text{meas}}-R_{\text{first low}})\cdot\Delta T_{\text{tab}}+T_{\text{first low}}}{R_{\text{first high}}-R_{\text{first low}}}. \tag{3}$$

3.2
Calculations by equations method
Metoda proračuna preko formule

The calculation by equations method is based on solving the equation (1), which describes the resistance as a function of temperature T:

$$T_R=\frac{-R_0\cdot A+\sqrt{R_0^2\cdot A^2-4\cdot R_0\cdot B\cdot(R_0-R_T)}}{2\cdot R_0\cdot B}. \tag{4}$$

For the evaluation of temperature under 0 °C it is necessary to use iterative calculation. The initial approximation is the result of the equation:

$$t_1=\frac{\frac{R_{\text{t}}}{R_0}-1}{A+100\cdot B}. \tag{5}$$

The second step is calculated by substituting results obtained in the first step in the expression shown in (6).

$$t_{n+1}=t_n-\frac{1+A\cdot t_n+B\cdot t_n^2+C\cdot t_n^3(t_n-100)-\frac{R_{\text{t}}}{R_0}}{A+2\cdot B\cdot t_n-300\cdot C\cdot t_n^2+4\cdot C\cdot t_n^3}. \tag{6}$$

In general two step calculation is sufficient to achieve the satisfactory accuracy. This method is realized by software module named "Formula".

3.3
Polynomials with constant coefficients method
Metoda proračuna preko polinoma s fiksnim koeficijentima

The most commonly applied method for calculating the temperature is a method that uses polynomials with fixed coefficients. This method is used for the resistance sensors as well as for thermocouples [39] with very non-linear characteristics.

The basic form of the polynomial is:

$$T(R)=c(n)_0+c(n)_1\cdot R+...+c(n)_m\cdot R^m \tag{7}$$

where c_0, c_1, ... c_m are the polynomial coefficients of degree m. Polynomial function approximates the temperature dependence of the measured resistance. A higher polynomial degree gives more accurate result. The actual polynomial degree that can be used is limited by the speed of the microcontroller, the real-time in which the calculation must be executed, and the size of the program memory where the coefficients are stored (usually as double precision numbers). If we want to achieve a greater precision using the lower degree of polynomials, the measurement range must be divided into several segments. Every segment uses a distinctive polynomial.

The practical application of this method is realized by dividing measurement range in two or maximum three segments covered with polynomial of degree n. The polynomial coefficients are previously calculated and recorded in the memory for each segment. The microcontroller performs the measurement of platinum sensor resistance at the measuring cycle initialization. The measured value is the base for determining inside what segment is the requested temperature, i.e. it is checked where the value of resistance is in relation to the supporting points of polynomial (n). For the chosen polynomial (n) the coefficient field indicators are obtained and calculation (7) is performed.

With the prepared polynomial coefficients a fast calculation of temperature is possible because the mathematical operations are just iterative additions and multiplications [16]. The main problem of this method is the lack of capability for platinum sensor characteristic corrections in 4 reference temperatures. This is because the polynomial coefficients are based on standard, predefined values of equation (1) constants A, B and C. This method was created and tested under name "Standard".

A similar method is based on the measurement of sensors at certain temperatures. Step by step, the calibration method builds up a polynomial transfer correction. A step calibration of sensors is carried out, resulting in the calculation of coefficients of the polynomial [17].

3.4
Method of gradual approach
Metoda postupnog približavanja

The temperature – resistance dependence of the platinum sensor in a narrow part of the measurement range can be represented with a straight line through two points. The first is the beginning and the other is the end of the selected measuring range. If we assume that the segment of the measuring range is shorter, the difference between the beginning and end of range tends to zero:

$$\Delta T=(T_{\text{end}}-T_{\text{start}})\to 0. \tag{8}$$

In this case the straight line passing through the boundary points of the range will become a tangent with a slope S_{p} defined in point (T, R). The function $T=f(R)$ is replaced by a tangent in very narrow domain (Fig. 5). This represents an inverse function of the formula (1), which will be used to develop the calculation by the method of gradual approach.

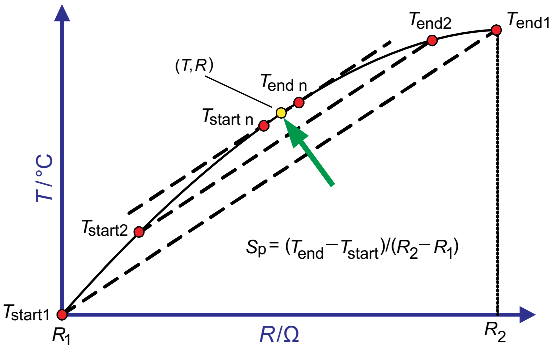

Figure 5 *The tangent to the point (T, R)*
Slika 5*. Tangenta u točki (T, R)*

An example of the calculation according to the new method is shown in Fig. 6. Based on the assumed initial temperature (or the temperature calculated in the previous measurement cycle), the resistance R_{calc} is calculated by equation (1) and compared with the value of the resistance R_{meas} which is measured in a new measurement cycle. The difference of resistance values is the basis for calculating the new temperature:

$$\Delta T = \Delta R \cdot S_p , \tag{9}$$

$$T_{new} = T_{old} + \Delta T , \tag{10}$$

where S_p is the slope coefficient at the tangent point (T, R).

In the variant of new method called "Const" the tangent slope coefficient $S_p = T/R$ is constant with a value of 2,596 (slope in point 100 °C). In another similar variant of the new method, called "Adapt", S_p coefficient is calculated at each new iteration step in the calculation loop (value of S_p slightly increases with the rising temperature).

The calculation of the temperature corresponding to the measured sensor resistance in the new measurement cycle is performed in a loop of n steps, until the difference between the new and the input temperature is less than the defined value. Since the measurement accuracy of the temperature transmitter is usually expressed in °C, we can set a criterion to continue with the program loop, until the following condition is satisfied:

$$\Delta T < \frac{digerr}{10} , \tag{11}$$

where *digerr* is the default digital measurement uncertainty of temperature transmitter in °C.

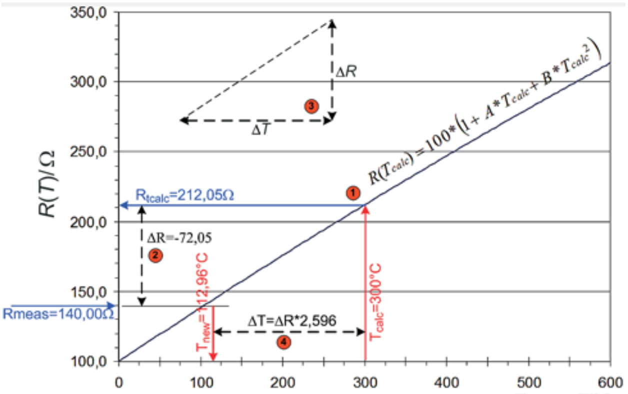

Figure 6 *Gradual approach example*
Slika 6. *Primjer stupnjevitog pristupa*

The comparison of methods "Const" and "Adapt" shows that the method with the dynamic calculation of coefficient S_p converges faster. For these variants, both simulations on the mathematical model and software module written in C are made. The flowchart of gradual approach method is presented in Fig. 7.

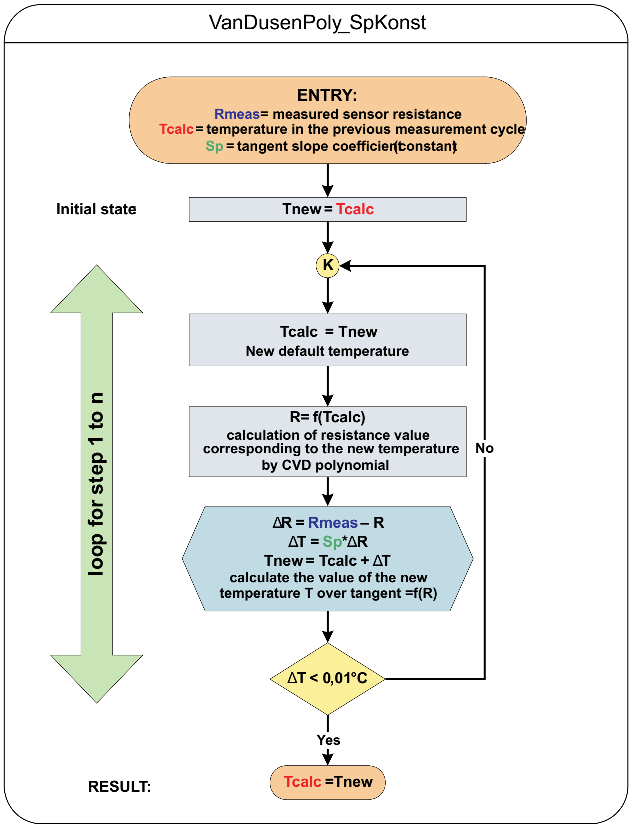

Figure 7 *The flowchart of gradual approach method*
Slika 7. *Dijagram toka metode postupnog približavanja*

4
Accuracy comparison of temperature measurements
Usporedba točnosti mjerenja temperature

4.1
Measuring and testing
Mjerenje i ispitivanje

To accomplish the estimation of the calculated temperature deviation in relation to the ideal value resulting from the standard [4], the span of platinum sensor (–200 to 850 °C) was divided in steps of 40 °C, which gave us 27 measuring points. This division was chosen to have a more realistic estimation by avoiding, if possible, the temperature points, which were used as the value pairs in the methods of Points22 and Points43. The nominal values of the resistance sensor that match the requested temperature were taken according to the standard.

The real Pt100 sensor is replaced by resistance decade, connected to the input of the temperature transmitter. The temperature transmitter is programmed to measure in the four-wire sensor configuration, with electrical damping of 0,5 s and the measuring range from 0 to 800 °C. The measurements are always done using the same differential amplifier gain in front of the A/D converter. This way we have avoided the situation that happens at lower temperature ranges at which the transmitter works with higher gain. Therefore, the results obtained throughout the whole range, are comparable. Although the variable which is read out from the transmitter is the digital temperature value, rather than the transmitter output current, it is important to know that this value is obtained with a constant amplification factor.

Digital value of the measured resistance and the calculated temperature and based on this value, can be read in two ways:

1) via JTAG emulator by reading the values of resistance and temperature in the table after stopping the execution following the time longer than 10 × t_{dump} periods (specifically 5 s), which corresponds to about 25 full measuring cycles
2) via modem communication with the temperature transmitter by reading under the same conditions the variables in the table.

The first method has an advantage because downloading digital values from IAR emulator to an Excel compatible software is a very simple task. Values are transferred from the source application to the target by copying the data using a clipboard operation supported by the operating system. Another advantage of this method has to do with the fact the microcontroller does not need to communicate with the modem, and thus there are no interrupts (*Rx*, *Tx*) that would disturb the continuous stream of measurements and the conversions of resistance to temperature.

The method described under (2) has an advantage in the case when continuous monitoring of the stability of the sensor resistance measurements at transmitter input circuit is required. Another advantage is the ability to automate the entire measurement process. However, in our case the focus was on testing computational methods, rather than ensuring stability of resistance measurements. Therefore, the JTAG emulator method was chosen (Fig. 8).

Figure 8 *Communication with the target prototype using JTAG tool*
Slika 8. *Komuniciranje s ciljnim prototipom pomoću JTAG alata*

4.2
Analysis of the comparison results
Analiza rezultata usporedbe

We have analyzed the results of six different methods presented in this paper using the same hardware prototype (temperature transmitter).

When comparing two variations of the method tables of pairs of points (Points22 and Points43 on Fig. 9), the conclusion is clear. The more pairs of points exist, the error in calculation of the temperature is smaller. Also, the size of the error varies with the position of the measured resistance value to the fixed pair (*R*, *T*).

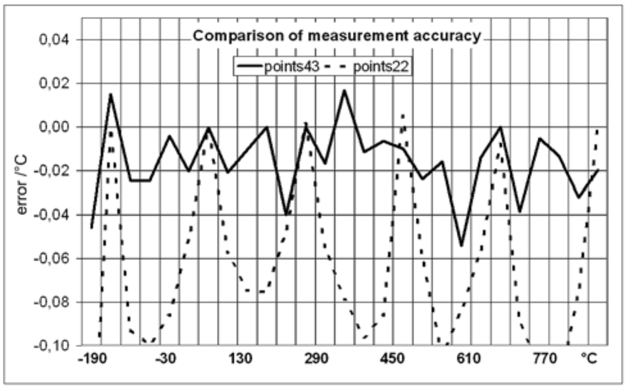

Figure 9 *Measurement accuracy of Points43 vs. Points22 methods*
Slika 9. *Točnost mjerenja metode Points43 naspram metode Points22*

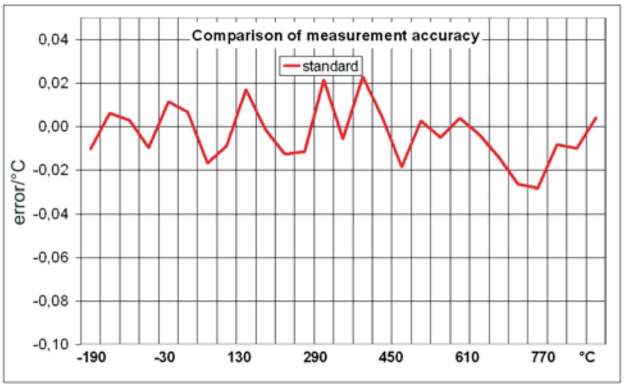

Figure 10 *Measurement accuracy of Standard method*
Slika 10. *Točnost mjerenja metode Standard*

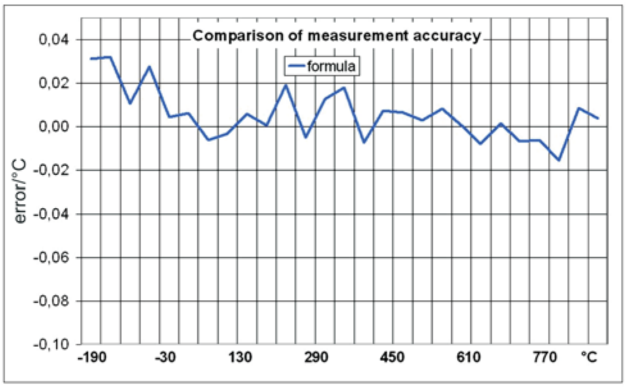

Figure 11 *Measurement accuracy of Formula method*
Slika 11. *Točnost mjerenja metode Formula*

Fig. 10 and Fig. 11 show the graphs of measurement accuracy for nominal temperature for method "Standard" and "Formula" respectively. The measurement errors are similar, but smaller than in the method "Pointsxx". The maximum deviation is approximately ±0,02 °C.

It is obvious that the methods "Adapt" and "Const" have a small deviation in comparison to the methods "Standard" and "Formula", and that the "Points" methods have significantly worse results. In Fig. 12 there is a comparison of these two variants of gradual approach method. The graphic representation of measurement error does not show noticeable differences. The maximum deviation in this case is approximately ±0,015 °C.

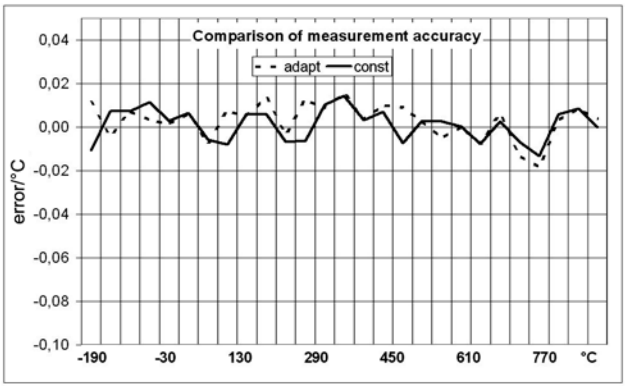

Figure12 *Comparison of accuracy of Adapt and Const method*
Slika 12. *Usporedba točnosti metoda Adapt i Const*

The right evaluation of the results and their quality can be obtained using statistical data processing. A better numerical accuracy assessment method is the calculation of standard and absolute deviation of temperature errors. The obtained results of statistical processing are shown in Fig. 13. It is evident that the highest accuracy of computation has the method "Const" (standard deviation) and method "Adapt" (absolute deviation).

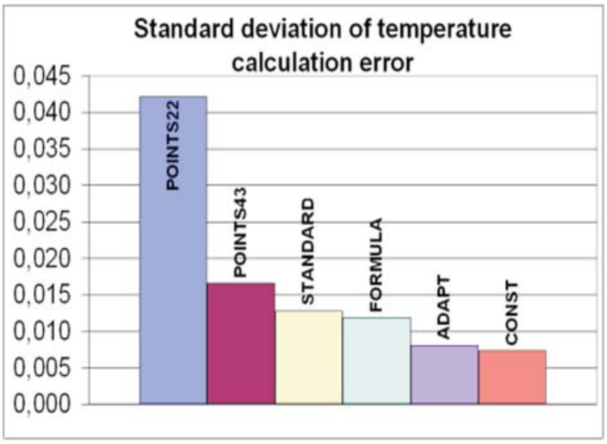

Figure 13 *Standard deviation of temperature calculation error*
Slika 13. *Standardno odstupanje pogreške izračunavanja temperature*

The difference between "Const" and "Adapt" versions is very small or negligible in measuring precision. If the dynamic behavior of one version is in case (response to fast change in input temperature), then the "Adapt" version has an advantage, because it is faster to this temperature step. Normally, the version "Adapt" requires more program code due to the need of gradient coefficient S_p calculation.

5
Conclusion
Zaključak

For reviewing of the applied methods a criterion of accuracy of temperature calculation is extremely important. There are also other criteria, like response time [1], cycle time, program code length, etc. The assessment can already be done using simulation tools (eg. Excel, Visual Basic). But, the de facto situation is proven only after applying the theoretical thesis to the real model of temperature transmitter.

As already noted, the application of microcontroller platform, even with all the limitations that are specific for it, shows some advantages when using the gradual approach algorithm compared to other known methods. Relatively large errors in the accuracy of methods such as "Points" are derived from theoretical reasons and were visible already on simulation models. Methods "Standard" and "Formula" have shown that accuracy could be assessed with the mark "good", with some slight advantage on the side of second method. This advantage would be even greater, but the method shows an increased inaccuracy in the area of negative temperatures, where the double-passing iterative calculation is applied.

The accuracy of method "Standard" is associated with the number of segments that cover the span of the sensors and with the polynomial order in these segments. The increasing the number of segments or order polynomial would require additional resources of microcontroller.

If the assessment of the accuracy of the temperature calculation could be limited to the area of positive temperature values ($T_{calc} > 0$ °C), which in industry practice is not so often the case, there could be some changes in the relationship of standard deviation of temperature measurement errors. In relation to the displayed values in Fig. 10, we would get some improvement in the methods of "Formula" and "Const" and the deterioration in the method "Standard". Error value in "Adapt" method would remain on the same level.

6
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