# Laboratory experiment No. 1: Temperature

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This laboratory experiment is designed to support the master course Maritime Systems. Processing all chapters will cover five to six sessions in the laboratory. The preparation of the experiment before the visit is an important basis for effective work and shared success. For the first session chapter 1 and chapter 2 have to be covered.

## 1. Introduction

In this experiment you are supposed to assemble a circuit for temperature measurements using a platinum resistor. The handling with a platinum resistor and its use in a Wheatstone bridge circuit are important details of the exercise. This bridge circuit is operated by means of a Zener diode with a constant voltage. The temperature dependent output voltage of the measuring bridge shall by means of an instrumentation amplifier be amplified to a suitable and easily to be measured voltage. After dimensioning and assembling of the measuring circuit you will conduct a calibration and determine the temperature of a water bath.

A SPICE simulation will help to understand the circuit designed. This simulation ensures that the output signal of the bridge circuit suites the input conditions of the instrumentation amplifier.

Based on these experiences the calibration and calculation to temperature values is to be programmed on a microcontroller. The output of all data should be available via a serial interface. The calibration should be started with push buttons.

In case you prepare the experiment thoroughly in advance (including the calculation of the necessary components, simulating the circuit with SPICE and program the microcontroller) you may not need to perform follow-up course work. This will be decided by the teaching assistant.

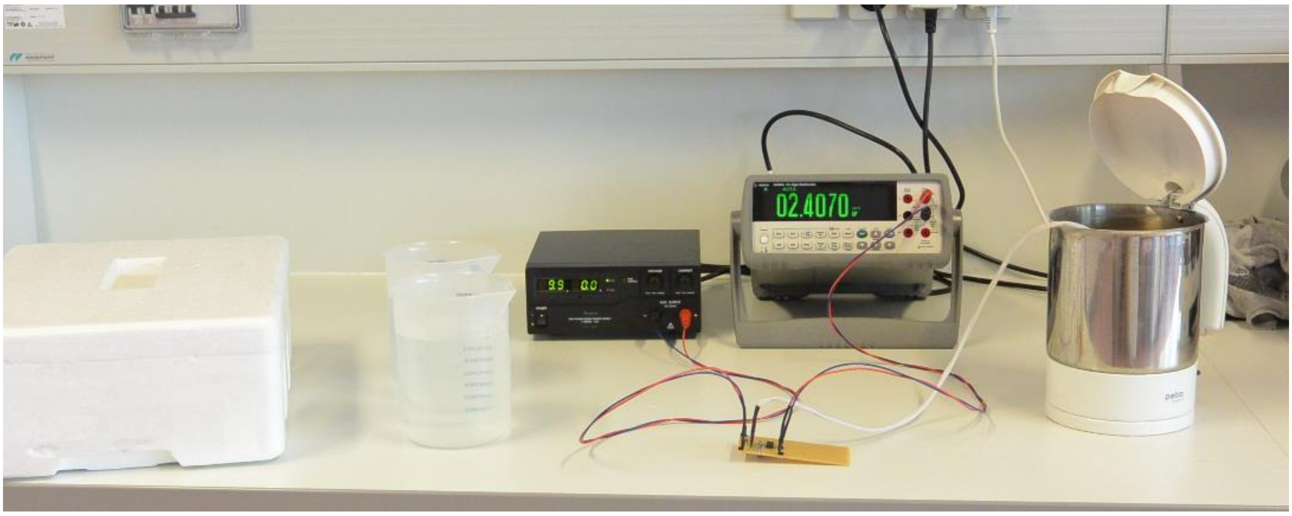



*Figure 1: Measuring circuit operated during calibration with ice and boiling water.*

## 1.1 Temperature sensor

The electrical resistance of metals increases as temperature rises. Thus, metals have positive temperature coefficients. Platinum is the most common metal for temperature measurements. Used as a temperature sensor the resistance is specified by $R_0$ at a temperature of $\vartheta = 0°\text{C}$. Normally the value of $R_0 = 100\ \Omega$; we speak about a $\text{PT100}$. The resistance value $R_\vartheta$ of a $\text{PT100}$ will follow the temperature $\vartheta$ according the following formula:

$$R_\vartheta = R_0\,(1 + \alpha\,\vartheta + \beta\,\vartheta^2) \tag{1}$$

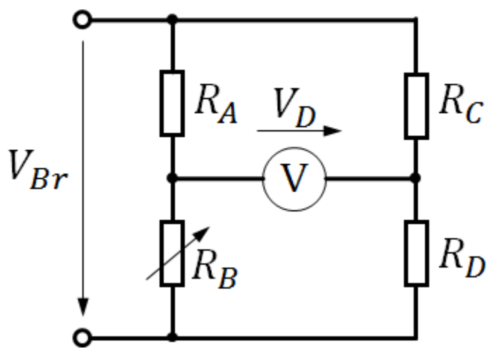
The two coefficients are:

$$\alpha = 3.9083 \cdot 10^{-3}\ \frac{1}{°\text{C}} \qquad \text{and} \qquad \beta = -0.5775 \cdot 10^{-6}\ \left(\frac{1}{°\text{C}}\right)^2 \tag{2}$$

In the experiment a $\text{PT100}$ shall be used for measurement of temperatures within the range of $\vartheta_{min} = -15°\text{C}$ to $\vartheta_{max} = 110°\text{C}$.

## 1.2 Wheatstone measuring bridge

A bridge circuit consisting of two voltage dividers is often used for resistance measurements. The advantage of this circuit is that the output of the bridge has an adjusted voltage of $V_D = 0\ \text{V}$ and supplies an approximate linear voltage for small resistance changes of one of the resistors.




$$V_D = 0\ \text{V} \quad \text{for} \quad \frac{R_A}{R_B} = \frac{R_C}{R_D} \tag{3}$$

$$V_D \sim \Delta R_B \quad \text{for} \quad \Delta R_B \ll R_B \tag{4}$$

*Figure 2: Wheatstone measuring bridge with condition for adjustment.*

## 1.3 Zener diode

Exceeding the breakthrough voltage the reverse current increases steeply for all diodes. For Zener diodes the breakthrough voltage, when the steep increase occurs, is precisely specified. It is described as Zener voltage $V_Z$. You can use such a diode to stabilize direct-current (d.c.) voltages. The Zener diode BZX85C6V8 used in the experiment has a breakthrough voltage of $V_Z = 6.8\ \mathrm{V}$. In the diagram (figure 3, to the right), which is taken from data specification [11], you can see that this voltage is rather stable at a current of $I_Z = 50\ \mathrm{mA}$. Abbreviated Zener diodes are described as Z-diodes

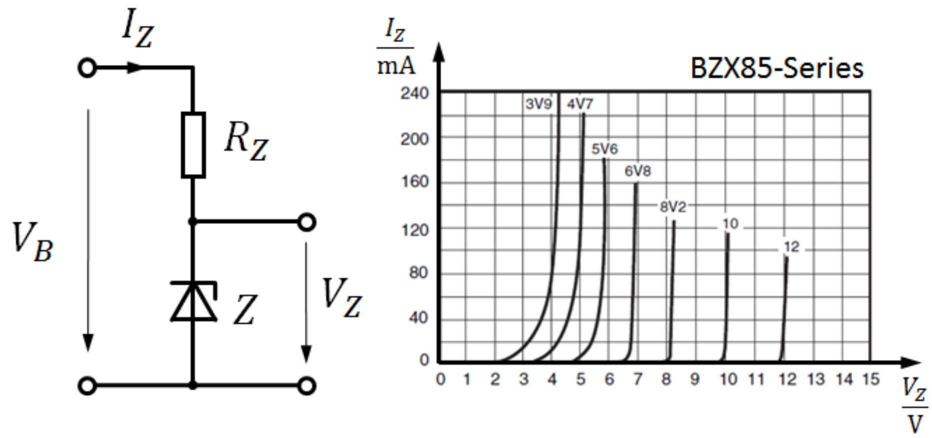



*Figure 3: Z-diode to stabilize the voltage with breakthrough voltage and current.*

## 1.4 Instrumentation amplifier

Instrumentation amplifiers are designed to measure potential differences with the advantage of a high input resistance. Figure 4a shows the inner assembly of this integrated component. It consists of three operational amplifiers. In principle, the substractor $OA_3$ can be used to measure potential differences. Amplifying impedance converters are placed in front of the operational amplifier $OA_3$, to increase the input resistance of both the negative and positive input. The advantage of this circuit is that you can adjust the differential gain varying only one resistor. In the experiment we use the instrumentation amplifier AD623 from *Analog Devices.* As to [2] the gain or amplification $A$ results in:

$$A = \frac{V_{out}}{V_{in}} = 1 + \frac{2 \cdot R}{R_G} \qquad \text{with} \quad R = 50\ \mathrm{k\Omega} \tag{5}$$

In practice, instrumentation amplifiers are easy to use. Figure 4b shows that a suitable resistor $R_G$ is sufficient as wiring. Additionally you will only need to connect the power supply and a reference voltage.

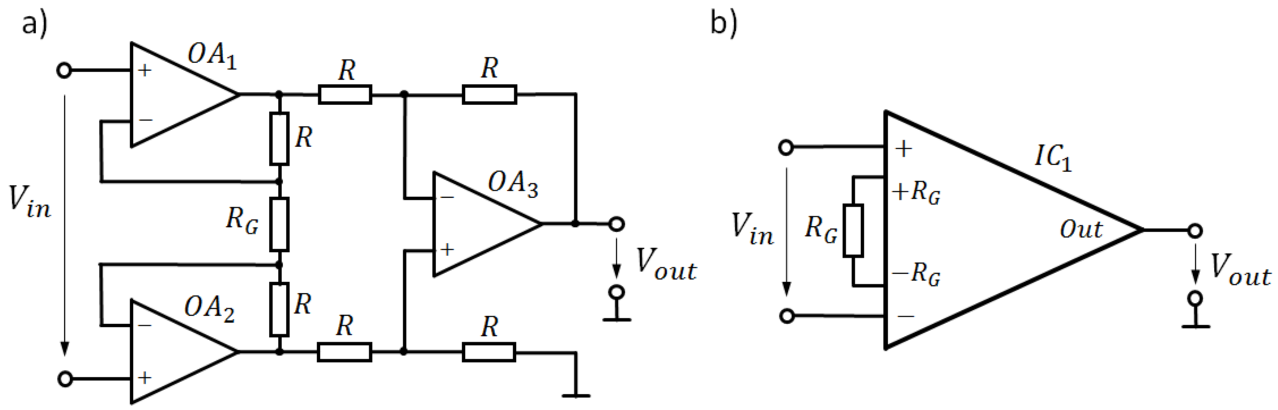



*Figure 4: Instrumentation amplifier, inner design (a) and integrated circuit (b).*

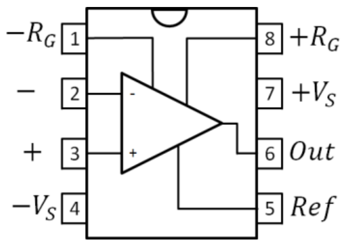



*Figure 5: Connection diagram of the integrated instrumentation amplifier AD623.*

The connection diagram of the instrumentation amplifier AD623 from *Analog Devices* [2] is shown in figure 5. Additional to the connections defined in figure 4, the positive and the negative supply voltage are provided by $+V_S$ and $-V_S$.

Specific characteristics of the AD623 are that it is possible to be operated with only one supply voltage ($-V_S = 0\ \mathrm{V}$). As well as the necessity that the common-mode input voltage must be about $V_{CM} = 2\ \mathrm{V}$ to ground ($0\ \mathrm{V}$) (Common-mode input; see [2], page 11). The reference voltage $Ref$ in the present case may be connected with pin 4 ($-V_S = 0\ \mathrm{V}$).

## 1.5 Resistors

We need different resistors for the circuit design. Metal film resistors with a tolerance of 1% are provided. Metal film resistors are characterized by high precision. We use the series of standards E12 consisting of following leading digits: $10,\ 12,\ 15,\ 18,\ 22,\ 27,\ 33,\ 39,\ 47,\ 56,\ 68,\ 82$. The calculated resistors must be adapted to the existing values. If, e.g., a value of $R_2 = 1902.0\ \Omega$ is calculated, we can use a resistor with $R_2 = 1.8\ \mathrm{k\Omega}$. In case no convenient value exists we can generate values by series or parallel connection of two resistors.

For Wheatstone measuring bridge you would choose resistors made of other, highly temperature-independent materials. As these are quite expensive we also use metal film resistors in this circuit during our laboratory experiment.

## 1.6 Test circuit

Figure 6 shows the test circuit, where you partly need to calculate the components. After assembly of the circuit on a laboratory experimental printed circuit board we want to measure temperatures.

The resistance of the temperature-dependent PT100 ($R_\vartheta$) increases according to the temperature to be measured. The resistor is integrated in a measuring bridge, which is continuously operated with constant voltage by means of the Zener diode. For measurement applications you would choose more precise references voltage. As these are quite expensive we use a Zener diode in this circuit during our laboratory experiment.

If the resistance $R_\vartheta$ increases, the difference voltage $V_D$ increases too. This difference voltage is amplified to output voltage $V_\vartheta$ by the instrumentation amplifier. This output voltage is now proportional to the temperature $\vartheta$.

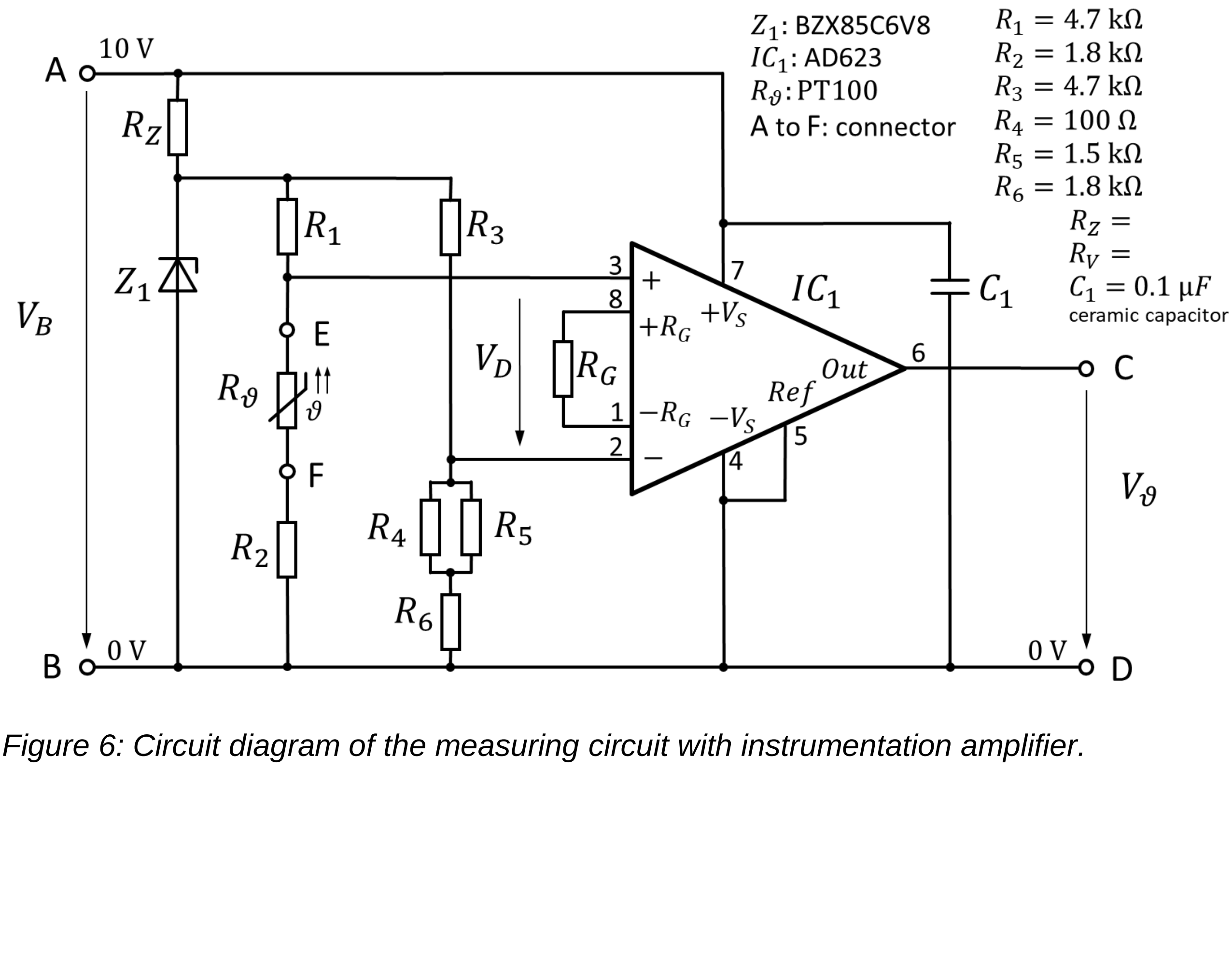



*Figure 6: Circuit diagram of the measuring circuit with instrumentation amplifier.*

# 2. Preparation prior to attending the laboratory

Make yourself acquainted with the experimental circuit shown in figure 6 and calculate the resistor $R_Z$ as series resistance of the Zener diode and the resistor $R_G$ for gain adjustment prior to attending the laboratory. The procedure is explained below. The calculation process be documented handwritten.

## 2.1 Calculation of the measuring bridge

As mentioned at the beginning, the circuit shall support a lowest temperature to be measured $\vartheta_{min} = -15°\mathrm{C}$. At this temperature the measuring bridge should be adjusted, providing an output voltage of $V_D \approx 0\ \mathrm{V}$ (see figure 2). The resistor $R_{\vartheta min}$ of the $\mathrm{PT100}$ will according to equation (1) with the coefficients (2) be:

$$R_{\vartheta min} = R_0 \left(1 + \alpha\, \vartheta_{min} + \beta\, {\vartheta_{min}}^2\right)$$

$$R_{\vartheta min} = 100\ \Omega \left[1 + 3.9083 \cdot 10^{-3}\ \frac{1}{°\mathrm{C}} \cdot (-15°\mathrm{C}) - 0.5775 \cdot 10^{-6} \left(\frac{1}{°\mathrm{C}}\right)^2 (-15°\mathrm{C})^2\right] = 94.125\ \Omega$$

To avoid that the current, flowing through the $\mathrm{PT100}$, will heat the device too much and, thus, bias the temperature measurement, the current should be low. A measurement current $I_{PT100} = 1\ \mathrm{mA}$ is suitable. According to [2] the common mode input voltage should correspond to approx. $V_{CM} = 2\ \mathrm{V}$ in relation to ground ($CM$ – Common Mode). Thus, $R_2$ is to be calculated.

$$R_2 + R_{\vartheta min} = \frac{V_{CM}}{I_{PT100}} \quad \text{or} \quad R_2 = \frac{V_{CM}}{I_{PT100}} - R_{\vartheta min} = \frac{2\ \mathrm{V}}{1\ \mathrm{mA}} - 94.125\ \ \Omega = 1905.9\ \Omega$$

selected from E12 standard: $R_2 = \underline{\underline{1.8\ \mathrm{k\Omega}}}$

With a supply voltage for the measurement bridge of $V_{Br} = 6.8\ \mathrm{V}$ (see figure 2 and figure 3) this results in:

$$R_1 + R_2 + R_{\vartheta min} = \frac{V_{Br}}{I_{PT100}} \quad \text{or}$$

$$R_1 = \frac{V_{Br}}{I_{PT100}} - R_{\vartheta min} - R_2 = \frac{6.8\ \mathrm{V}}{1\ \mathrm{mA}} - 94.125\ \ \Omega - 1.8\ \mathrm{k\Omega} = 4905.9\ \Omega$$

selected from E12 standard: $R_1 = \underline{\underline{4.7\ \mathrm{k\Omega}}}$

The second voltage divider of the bridge must be set symmetrically to the first. According to this specification the resistors $R_3$ and $R_6$ result in:

$$R_3 = R_1 = \underline{\underline{4.7\ \mathrm{k\Omega}}} \quad \text{and} \quad R_6 = R_2 = \underline{\underline{1.8\ \mathrm{k\Omega}}}$$

The bride shall be adjusted at $\vartheta_{min} = -15°\mathrm{C}$. According to equation (3) this will be the case if the parallel circuit of $R_4$ and $R_5$ results in the value of $R_{\vartheta min}$. To realize this as precisely as possible a parallel connection was planned.

$$\frac{R_4 \cdot R_5}{R_4 + R_5} = R_{\vartheta min}$$

With the selection of $R_4 = \underline{\underline{100\ \Omega}}$ this formula can be transposed to calculate $R_5$:

$$R_5 = \frac{R_4 \cdot R_{\vartheta min}}{R_4 - R_{\vartheta min}} = \frac{100\ \Omega \cdot 94.125\ \Omega}{100\ \Omega - 94.125\ \Omega} = 1602.1\ \Omega$$

selected from E12 standard : $R_5 = \underline{\underline{1.5\ \mathrm{k}\Omega}}$

The determined values are recorded in figure 6.

### 2.2 Calculating the series resistor of the Zener diode

As mentioned the Wheatstone bridge shall be operated with a voltage of $V_{Br} = V_Z = 6.8\ \mathrm{V}$. As you may read in the diagram of figure 3 the breakthrough voltage $V_Z$ is rather stable at a current of $I_Z = 50\ \mathrm{mA}$. In this case and with a voltage equal to $V_B = 10\ \mathrm{V}$ the series resistor $R_Z$ shall be calculated (figure 6). Please, select a value from the E12 standard.

### 2.3 Calculating the resistor for the amplification

You will need some interim results for the calculation of the resistor $R_G$ using equation (5).

a) Calculate the resistor $R_{\vartheta max}$ of the $\mathrm{PT100}$ according to equation (1) using the coefficients (2) for the maximum temperature to be measured $\vartheta_{max} = 110°\mathrm{C}$.
b) Calculate the maximum voltage difference $V_{Dmax}$ for the temperature $\vartheta_{max} = 110°\mathrm{C}$, which is present at the input of the instrumentation amplifier.
c) Calculate the required amplification $A$, according to equation (5) in this case the maximum output voltage of the instrumentation amplifier should to be $V_{\vartheta max} = 3\ \mathrm{V}$.
d) Calculate the resistor $R_G$ with the conversion of equation (5) to realize the required amplification $A$. The internal resistors of the instrumentation amplifier have a value $R = 50\ \mathrm{k}\Omega$. Please, select a value from the E12 standard.

## 3. Assembly of the circuit

Starting in the laboratory, please, collect the components, required for the circuit shown in figure 6. Then place the components on the experimental printed circuit board in a way that you may easily connect the circuit points by soldering. Please pay attention to the orientation of the Zener diode and of the instrumentation amplifier. The Zener diode has a black ring at the cathode. Between pin 1 and pin 8 of the instrumentation amplifier there is a round denting. Figure 7 shows a convenient positioning.

Connect all necessary circuit points by soldering on the rear of the printed circuit board. Figure 8 shows a measuring circuit, wired with silver wire.

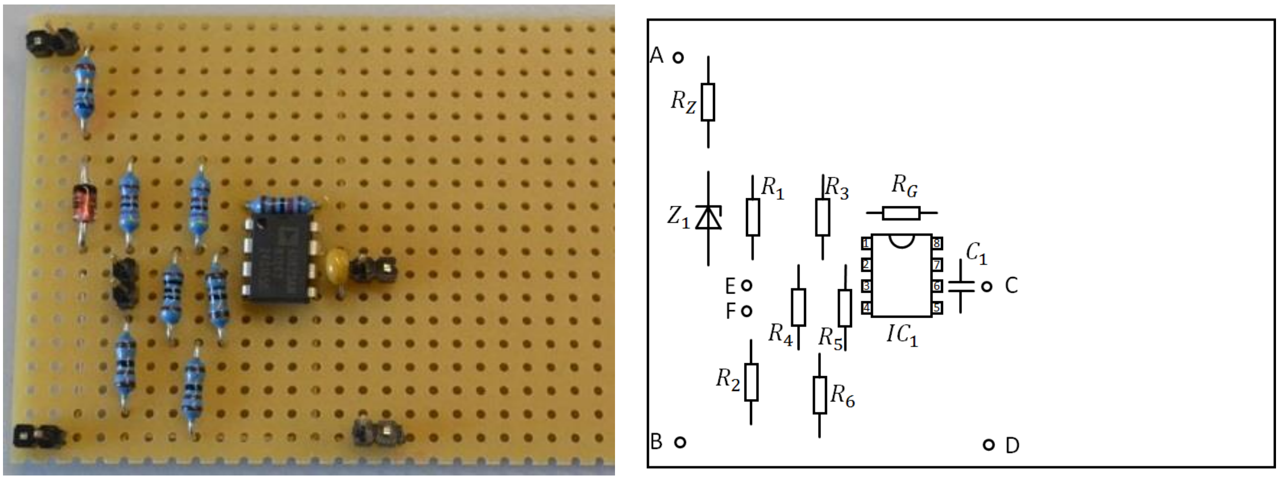



*Figure 7: Positioning of the components on the experimental printed circuit board.*

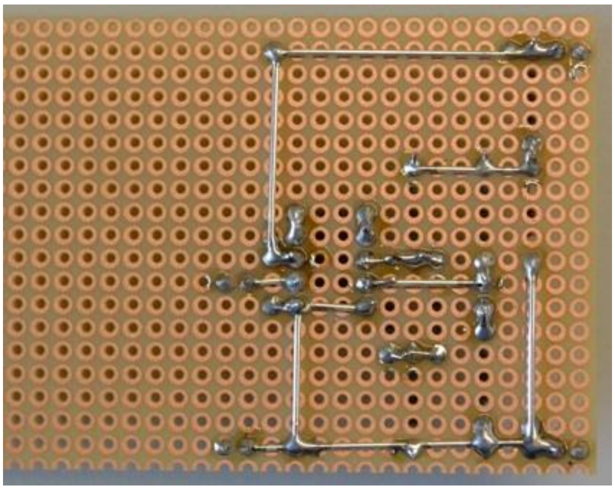


*Figure 8: Wired experimental circuit on the soldering side.*

## 3.1 Setting-up operation of the measuring circuit

Please, calculate the expected output voltage $V_\vartheta$ for the measuring temperatures $\vartheta_0 = 0°\text{C}$, $\vartheta_{20} = 20°\text{C}$ and $\vartheta_{100} = 100°\text{C}$. You may proceed as described in chapter 1.3 a and b. The input voltage of the instrumentation amplifier is calculated and then the output voltage is determined with the amplification according to equation (5). Thus, the output voltages will be $V_\vartheta$ as $V_0$, $V_{20}$ and $V_{100}$.

a) For the set-up you may operate the circuit using a laboratory power supply of $V_B = 10\ \text{V}$, shown in figure 6. You can measure the output voltage $V_\vartheta$ with a multimeter. If you set-up the circuit at ambient temperature you will receive an output voltage of approx. $V_{20}$. In case you heat up the $\text{PT100}$ with your hands, the output voltage should increase slightly.

b) Measure the output voltage $V_\vartheta$ placing the $\text{PT100}$ in a mixture of ice and water of $\vartheta = 0°\text{C}$ and compare it to the calculated value $V_0$. In case the measured value deviates from this, it should at least exceed $20\ \text{mV}$.

c) Measure the output voltage $V_\vartheta$ placing the $\text{PT100}$ in boiling water, where $\vartheta = 100°\text{C}$ and compare it to the calculated value $V_{100}$.

# 4. Simulation with SPICE

SPICE (Simulating Program with Integrated Circuit Emphasis) is a circuit simulator for the simulation of analog, digital, and mixed analog/digital circuits. The circuit displayed in figure 6 should be simulated with a SPICE of your choice. The output voltage is to be displayed according to the resistance of the $\mathrm{PT100}$ from $R_\vartheta = 93\ \Omega$ to $R_\vartheta = 143\ \Omega$.

LTspice from *Linear Technology* is a software package from the SPICE family with a graphical input of circuit diagrams and a graphical output representing the simulation results. LTspice is available for free; see [7] for a download and course material.

## 4.1 Simulating the measuring bridge

Start with the input of the circuit displayed in figure 6 except the instrumentation amplifier. After studying basic course material for circuit input and simulation you will be able to display the output voltage of the Wheatstone measuring bridge $V_D$ according to the resistance of the $\mathrm{PT100}$. It might be a problem to simulate the variable resistor $R_\vartheta$. See [9] for help.

## 4.2 Simulating the measuring circuit

Before implementing the instrumentation amplifier AD623 you have to add the appropriate SPICE model into the library of LTspice. See [1] for the SPICE macro-model and [6] how to add third-party models. Make sure to start your LTspice program as administrator (start program with right mouse button) to automatically generate a symbol for the graphical editor.

Display the output according to the resistance of the $\mathrm{PT100}$ from $R_\vartheta = 93\ \Omega$ to $R_\vartheta = 143\ \Omega$.

# 5. Calibration and temperature measurement

If the circuit works, you may use it for temperature measurements. In case of small resistance changes of the $\mathrm{PT100}$, we assume a linear relation between temperature $\vartheta$ and output voltage $V_\vartheta$, and, thus, you may calculate the temperature $\vartheta$ using following equation:

$$\vartheta = a_1 \cdot V_\vartheta + a_0 \qquad (6)$$

## 5.1 Calibration

Think about, how you can define the coefficient of equation (6) via calibration by means of a mixture of ice and water where $\vartheta = 0°\mathrm{C}$ and boiling water where $\vartheta = 100°\mathrm{C}$.

## 5.2 Temperature measurement

The task is to measure the temperature of a water basin of approx. ambient temperature. Measure the output voltage $V_\vartheta$ while the $\mathrm{PT100}$ is in the water basin. Calculate the water temperature with help of equation (6).

# 6. Data acquisition with ATmega32

The experimental microcontroller board provided in the laboratory hosts the 8-bit microcontroller ATmega32 [3] from Microchip. This board enables data acquisition of analog signals with an analog to digital converter, communication via a serial RS232 interface and digital input and output. The circuit diagram of the experimental microcontroller board is shown in figure 9. Note that the circuit and the shown units are only partially drawn. Only components relevant for the experiment are shown.

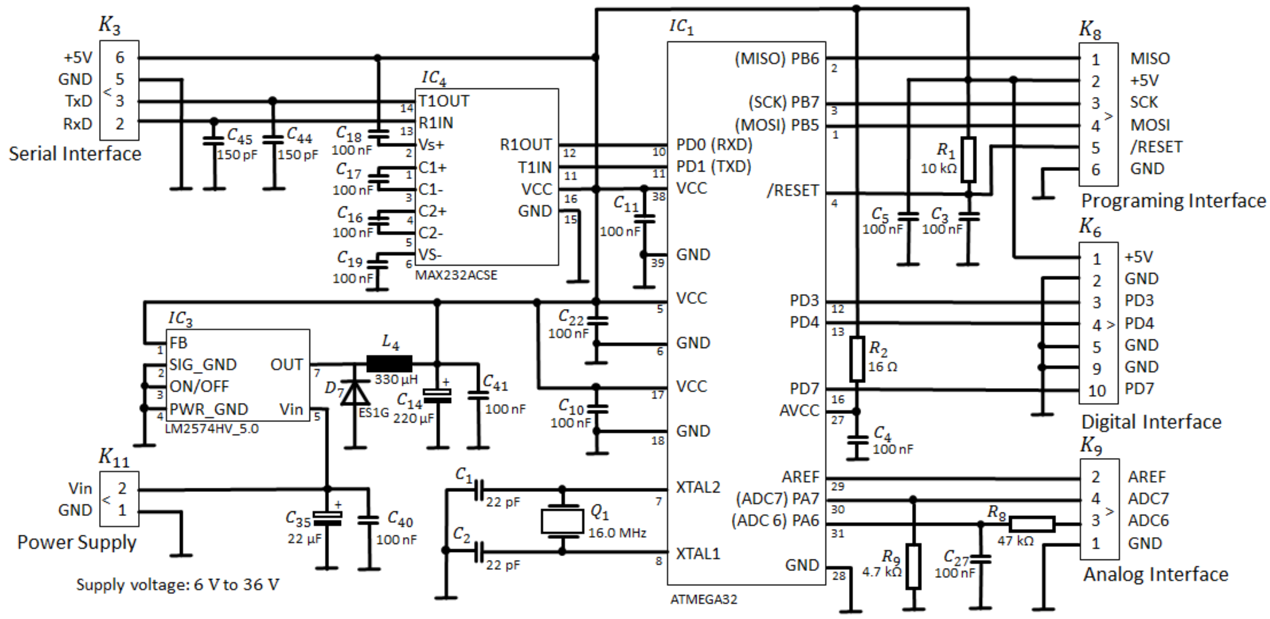



*Figure 9: Experimental microcontroller board. Note: circuit and units are partially drawn.*

The task is to program the ATmega32 to read the analog output voltage of the measuring circuit (figure 6) and to send the calculated temperature value as ASCII text via the serial port. For calculation equation (6) with your own coefficients must be used.

The ATmega32 will be programmed with Microchip Studio [8]. Microchip Studio is an integrated development platform for developing microcontroller applications. Microchip Studio gives you a seamless and easy-to-use environment to write, build and debug your applications written in C code. The microcontroller will be programmed in-circuit to allow a fast developing process.

## 6.1 Getting started

Get familiar with the Microchip Studio and the communication to the experimental micro-controller board. Use the skeleton program provided and get it running on the ATmega32. Connect the serial interface to the computer and start HTerm [4] or another terminal program. Choose “Build/Rebuild DataAcquisition” to compile and link the sources. After succession choose “Tools/Device Programming” to prepare for programming. Select “Tool/AVRISP mkII” and press “Apply” to connect to the programmer. “Memories” and “Program” will finish the programming and will activate a reset of the microcontroller.

Change the program to an output text announcing the temperature readings.

## 6.2 Data acquisition

Read the analog input channel ADC6 from the ATmega32 connected to the output of the measuring circuit. Send the calculated temperature value as ASCII text via the serial port. For calculation equation (6) with your own coefficients must be used. Use integer arithmetic but with a temperature resolution of $0.1°\mathrm{C}$.

A simulation circuit providing a manually adjustable voltage via a potentiometer will be supplied.

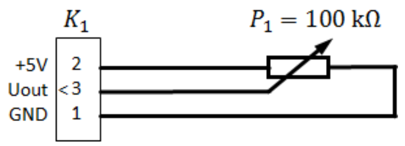



*Figure 10: Simulation circuit of analog input voltage.*

## 6.3 Automatic calibration with ATmega32

Expand the program with the ability for an automatic calibration. A push button will be connected to the microcontroller board. This button is connected to PORTD3 of the ATmega32.

If the button is pushed the program should guide the user through the calibration process. After the $\mathrm{PT100}$ is placed in water at $0°\mathrm{C}$ the button must be pushed again. Subsequent after the $\mathrm{PT100}$ is placed in water at $100°\mathrm{C}$ the button must be pushed a third time. According to the calibration the following temperature readings must be send to the serial port.

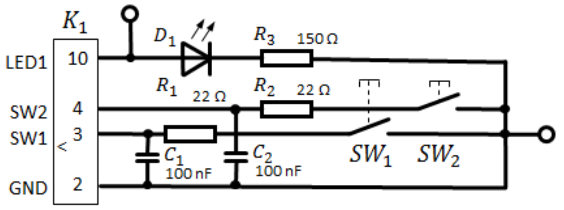



*Figure 11: Push buttons and indicator to control the automatic calibration process.*

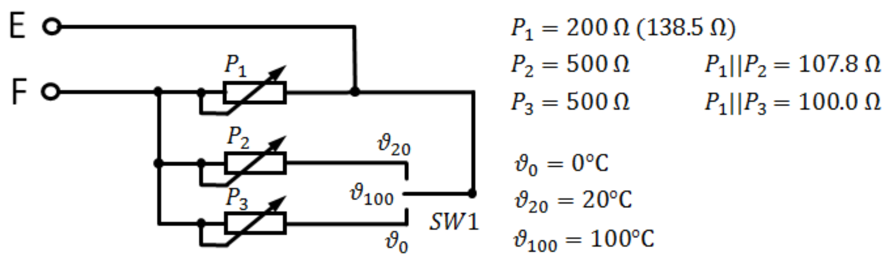



*Figure 12: Simulation circuit of the* $\mathrm{PT100}$ *providing resistances of* $0°\mathrm{C}$, $20°\mathrm{C}$, *and* $100°\mathrm{C}$.

A simulation circuit of the $\mathrm{PT100}$ providing resistances of $0°\mathrm{C}$, $20°\mathrm{C}$, and $100°\mathrm{C}$ will be supplied.

What temperature resolution can be achieved with the measurement circuit in combination with the experimental microcontroller board?

# 7. Evaluation

Complete following tasks after finishing the laboratory. If you have already finished all tasks prior to or during the laboratory experiment, a report is not absolutely necessary. In case we need your report, you must submit it, as PDF, two weeks after the experiment, at the latest.

## 7.1 Circuit calculation

If you haven‘t already documented the circuit calculation prior to the laboratory experiment, please, execute all tasks from chapter 2. Every single calculation must be evident.

## 7.2 Simulation of the measuring circuit

If not carried out with the set-up of the measuring circuit, simulate the circuit displayed in figure 6 with a SPICE program of your choice. Chapter 4 will provide hints for the implementation of LTspice from *Linear Technology*. The output voltage of the measuring circuit is to be displayed according to the resistance of the $\mathrm{PT100}$ from $R_\vartheta = 93\ \Omega$ to $R_\vartheta = 143\ \Omega$.

## 7.3 Calibration and temperature measurement

For the measurements conducted in chapter 5, please, calculate the respective coefficients for equation (6) and, thus, calculate the measured temperature of the water basin.

## 7.4 Data acquisition with experimental microcontroller board

Deliver the program for the ATmega32 to read the analog output voltage of the measuring circuit and to send the calculated temperature value as ASCII text via the serial port. This program must support an automatic calibration as described in chapter 6. Make sure that the program is documented with helpful comments included in the source code.

## Questions:

What must be improved concerning the supply voltage of the bridge to use the circuit of figure 6 for more precise measurements?

What must be improved concerning the resistors of the bridge ($R_1$ to $R_6$) to use the circuit of figure 6 for more precise measurements?

What temperature resolution can be achieved with the measurement circuit in combination with the experimental microcontroller board?

What is the reason of the resistors $R_2$ and $R_6$ in the circuit in figure 6? Which diagram in the data sheet of the instrumentation amplifiers must be consulted to calculate these resistors?

# 8. Literature

[1] Analog Devices: AD623 SPICE macro-model; “www.analog.com/en/license/spice-models?mediaPath=media/en/simulation-models/spice-models/ad623.cir&modelType=spice-models”, access on September 24, 2022.

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