REFERENCE THERMOMETER

The task

1. According to the presented wiring diagram, design a circuit board motif.
2. Transfer the designed printed circuit motif to the printed circuit board.
3. Make a flat joint.
4. Install the parts.
5. Reboot the device.

Introduction

In the practical part of ZENIT in electronics, you will build the so-called reference thermometer. It is a precision analog circuit that is able to propagate the signal from two platinum resistance temperature sensors (RTD) and two thermocouples (TC). The circuit of precise and stable components, advanced measurement methods and the resulting calculation of the temperature value is realized according to the ITS-90 resistance for primary sensors (SPRT - Standard Platinum Resistance Thermometer) and for secondary industrial sensors (IPRT - Industrial Platinum Resistance Thermometer). With the correct design of the circuit board, the accuracy of the measurement will be defined only by the quality and accuracy of the sensors used and their calibration. A device controlled by a microcontroller and communicating with SCPI commands over a serial line. It can therefore also be used in automated measuring devices.

Constructions from ZENIT are very popular among students, for example, as practical maturity. We would like to inform you that this is a copyrighted work and based on its part in a pre-graduation or other work, it is necessary to agree with the author (contact at the end of the document) and the work must be correctly cited with the full reference of the source.

The use of unauthorized assistance is prohibited for the competition. Violation of the regulation will be penalized by disqualification.

Rating

A maximum of 80 points can be obtained for the practical part. The evaluation of the practical part is as follows:

- Printed circuit design maximum 20 points
- Soldering and mounting quality maximum 15 points
- Cleanliness of execution maximum 5 points
- The function of the completed connection is a maximum of 40 points, of which:
  - o microcontroller with screen board 5 points
  - o voltage reference and AD converter 5
  - o current source 10 points
  - o measurement of RTD sensors 10 points

o measuring thermocouples 10 points
• Bonus: a fully functional design on a 100x120 mm board, which is integrated into a 3D printed box (special hardware and accessories for the thermometer, calibration. The offer is valid while stocks last.)

The overall quality of the board design (layout of components, electrical quality of the boards, motif design, number and placement of jumpers, overall size of the boards, use of polygons even if not allowed...) is evaluated under the "PCB Design" parameter.

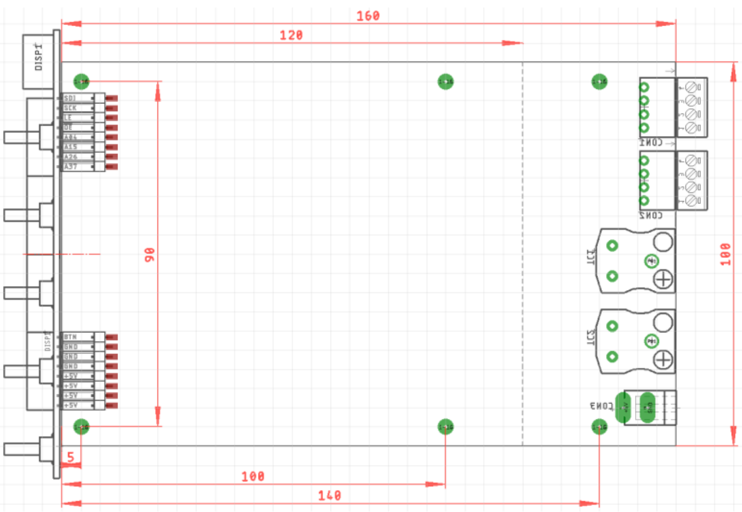
PCB design

The following important take care and understanding. The right proposal has a direct impact on the overall performance, your success and evaluation.

You have at your disposal double-sided printed circuit boards coated with a photosensitive layer of size 160x100 mm. The exact size of your PCB design is not given, use as much of the material as you need. Cut the board to the required size before exposure, while the protective film is still attached.

You are designing a circuit board for a measuring device with a user interface. Therefore, the display module goes on the front panel. All measured signals and power are connected to the device via the rear panel. Place the microcontroller on the board as needed. But take into account access to the USB connector (serial port). The recommended connector layout is shown in Figure 1.

In case of interest, two models of the 3D printed box are prepared for the device. The first for a 100x160 mm board and the second for a more compact 100x120 mm board. If you want to use a box, the size of the boards is fixed and the layout of the connectors and mounting holes must be observed. The USB port will be connected using an extension cable mounted on the rear panel above the TC2 and CON3 connectors.



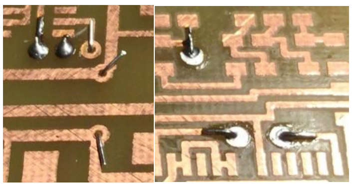


fig. 2: Implementation of transitions between layers

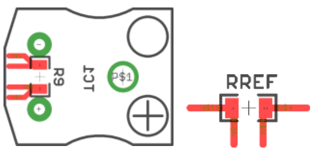


fig. 3: Placement of the R9 sensor on the thermocouple connector and an example of a four-wire connection to measuring resistors

fig. 1: Recommended layout of important parts. Display on the front panel, all connectors on the back panel

All components and all wire jumpers must be mounted on the top side of the board. The connectors CON1, CON2, CON3, TC1, TC2 are placed on the underside of the board. In the Eagle/KiCAD files you received, the parts are already divided into layers where they belong. Do not change the assignment of components to the layer!

In the files, there is also a preset grid of 0.635 mm, do not change this either.

The entire underside of the board is a continuous ground plane, no connector required. The polygon is already prepared in the file you received. The connection to the ground is made with wire jumpers, the recommended method of transition between the layers of the double-sided board is a "metalled" hole (in Eagle Via), drill diameter 0.6-0.8 mm, surface diameter min. 2.2 mm. A short wire is inserted into the hole from both sides, fixed and ignited, see figure 2.

To make it easier to distinguish the soldering surfaces, we recommend using a different shape (e.g. square) for ground jumpers, which are drilled, and a different shape for wire jumpers (e.g. circle), which are not drilled.

Pass the polygons.

In order to correctly attach the film to the board, always insert a long enough legible text in the design. We recommend "COMPONENTS PAGE" to the Top layer. This text must also be legible on the attached foil.

The recommended joint and gap width for common signals is at least 0.6 mm. Very short connections can also be supplied in 0.4 mm. The wider the wires, the easier it will be to make boards.

The use of autorouter is prohibited. Violation of the regulation will be penalized by disqualification.

Save the PCB design at regular intervals.

Production of printed circuit boards

Name the finished project with your competition number and upload it to the central storage, which you can open via the line https://cernbox.cern.ch/s/Id2EuB9DaS1Dc3S

If you are using Eagle, upload the .brd and .sch files (eg A01.brd, A01.sch). If you use KiCad, zip the contents of the entire project directory without the -backups subdirectory (eg A01.zip) and upload to the repository.

Production of boards begins in the Electro room no. 4B, where an exposure film is printed from the common repeat. Subsequently, they are called up and improved. You are working with chemicals, therefore the designated protective work equipment (goggles and gloves).

Once upgraded, you move to your competition room to drill and finish. Components with thick leads or large holes have 1 mm pads created to make the initial hole easy to drill. After drilling with a small drill bit (exactly in the center of the pad), enlarge the holes as follows:

•holes for the flat pins of the power connector (CON3) 2-3 holes ø 1.3 mm next to each other, make an oval groove
• connectors for thermocouples (TC1, TC2) and RTD sensors (CON1, CON2) ø 1.3 mm
• mounting holes in the box ø 3.0 mm

All drilled holes must have clean edges on the ground plane side to prevent shorting. Use a larger diameter drill bit and remove the excess me by hand.

Embedding

All components and wire jumpers are mounted on the top side of the boards. The connectors for connecting the sensors (CON1, CON2, TC1, TC2) and the power connector (CON3) are mounted on the bottom of the board.

For correct alignment of the control panel connectors, we recommend soldering the connectors (female pin strip) with the display installed.

The reference voltage source IC8 is in a very small package SOT23-6. find out whether the circuit board is properly etched (e.g. microscopic shorts...) and then use microscope. Pin no. 1 is marked with a + sign, see Fig. 4. If you are unable to fit IC8, ask the supervisor for help.

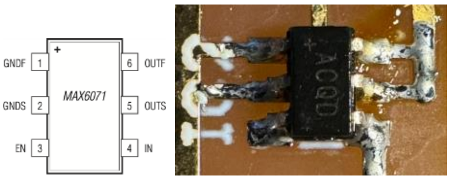


fig. 4: Designation of pin No. 1 on reference MAX6071

Reviving and handing over the structure

Competitors have at their disposal a revival workplace where they can test their product before submission. Problems that competitors find and fix before the official handover of the product are not included in the evaluation. Problems that are detected during the official submission to the evaluation committee are included in the final evaluation.

The connection is active modular and the individual blocks can also be animated. In the case of time binding, you do not need to design or install a complete circuit board. It will be possible to revive it in parts. The competitor will still be awarded a body for completed and functional work according to the degree of development.

Description of the connection

The thermometer consists of four functional blocks - circuits for measuring resistive temperature sensors, circuits for measuring thermocouples, a multiplexer and an analog-to-digital converter and a microcontroller with a display unit.

Resistive temperature sensors based on platinum resistors are widely used, from measurements in industrial processes to the most precise metrological applications. The most commonly used models are PT100, with a nominal value of 100 Ω at a temperature of 0 °C, and PT1000 with a nominal value of 1000 Ω at a temperature of 0 °C. The temperature coefficient of resistance of platinum alloys used in industrial sensors is 0.385%/°C and its course is very accurately mapped throughout the entire range of applicability. Platinum sensors can be used in the temperature range of -200 to +850 °C, the most common applications of conventional sensors are in the range from -50 to +250 °C. In this range, the resistance value of the PT100 sensor reaches approximately 80 to 200 Ω. Measuring temperature with RTD sensors is the task of measuring the resistance of medium values and then converting it to temperature.

We know many methods of resistance measurement. We chose the comparative method for the reference thermometer. The measured resistors are connected in series and powered by a constant current source. Using multiple analog-to-digital channels, we measure the voltage drop across each resistor. If one of the resistors will have exactly

value that does not change with time or active (the so-called reference resistor, in the RREF circuit), and the current source will maintain a constant current, the value of which will not change during the measurement, we can directly compare the voltage drops on each resistor and calculate their values. The main advantage of this method is that we only need one element, the value of which we know exactly (RREF) and the current, the value of which we do not need to know, just must not change. When analyzing the equations in detail, we find that we do not need to know the reference or the exact voltage value of the AD converter, again it will be enough if it does not change.

The source is operational amplifier IC1A. With the help of transistor T2, the latter tries to have the same voltage (UREF) on resistors R1-R4 as it has on the non-inverting input. The value of UREF R1-R4 does not change, so a constant current will flow through the load regardless of its size. The recommended excitation current sensor PT100 is <1 mA. For accurate measurement, where self-heating of the sensor can cause an unacceptable error, we can reduce the measuring current to 250 μA by switching the resistor combination R1-R4 (16x lower power loss, at the price of 4x lower distance/noise).

The current source is fed by the reference resistor RREF, two external sensors RTD1/RTD2, and another temperature sensor R9, which is used to measure the temperature of the so-called of the cold end of the thermocouple. If the RTD1 or RTD2 sensor is not connected, the current flows around the terminals through anti-parallel connected diodes.

To achieve maximum accuracy, all resistive sensors are four-wire connected. If we use two-wire PT100 sensors, they will be connected to the current terminals (between -2 and -3). The sensor connection also includes a filter for common and differential mode (10 nF capacitors).

Next, we use maximum precision with inverse polarity excitation current. The AD converter always takes two samples. The first with the positive polarity of the excitation current and the second with the opposite polarity. the resulting measured voltage is the average of these measurements, which suppresses the effect of static errors in the circuit, especially the zero error of the AD converter and thermoelectric voltages at the transitions of different metals in the measuring chain.

Measurement of thermocouples

A thermocouple used for temperature measurement uses a different principle, namely until the end of the thermoelectric voltage at the junction of two metals, if they have different temperatures (Seebeck phenomenon). Typical values of the thermoelectric voltage are in the order of tens of μV/°C depending on the metals used. The materials used also represent a certain range of temperatures that they can measure. From cryogenic temperatures up to around 2700 °C.

Temperature measurement with a thermocouple is the task of measuring very low voltages, so it tries to eliminate various parasitic thermal voltages (e.g. on connectors or printed circuit boards) and electromagnetic interference, with subsequent conversion to temperature. Our thermometer is designed for K-type thermocouples in the range of approx. -200 °C to 400 °C. It can be easily modified for measuring in a wider range, or with a different type of thermocouple.

The thermocouple is connected with a special connector, which is different for each type of thermocouple (eg type J, K). For correct and accurate measurement, it is necessary to ensure that the connector is located outside the heat source and that there is no temperature gradient on the board. The entire circuit for processing the signal from the thermocouple must have the same temperature.

The small DC voltage is filtered by the low-pass filter R5-R6-C4 and amplified by the operational amplifier IC3. The gain (17x) is restored by feedback resistors of the same type and value to achieve a stable and temperature-independent value. The operating system used is one of the best, "zero drift" type with a single offset voltage of 5 μV. Nevertheless, the offset after OZ amplification can cause a measurement error of 1-2 °C. Offset calibration is therefore implemented in the program. The maximum value (full scale) for the AD converter is ±250 mV. To extend the measurement range, the gain of IC3 is simply adjusted.

The thermoelectric voltage at the output of the thermocouple is proportional to the temperature difference between the hot and cold ends. Historically (and currently for the most accurate measurements), the cold, reference end of the thermocouple was kept in a water bath at exactly 0°C. For measurements in the field or industry, it is not very practical to operate a reference bath with a temperature of exactly 0 °C. Therefore, an alternative procedure was introduced, where another, very accurate thermometer is used to measure the temperature of the cold end and this is used to equalize the difference between the actual temperature of the cold end and 0 °C. In our thermometer, this function is provided by the PT100 R9 platinum sensor. The sensor must be in close thermal contact with the thermocouple connector pins (TC1, TC2). For accuracy, it should be covered with a heat-protective layer. The air flow around the plates can also adversely affect the accuracy of the measurement. It is very important that the electronics of the thermometer are equipped in a box

Multiplexer and analog-to-digital conversion

Only one analog-to-digital converter IC6 is used in the circuit. It is a MCP3553-3 type, a resolution of 22 bits and a maximum sampling rate of 60 seconds per second. Temperature measurement too high sampling frequency. In intelligent processing, the advantage of using the same transducer for all measurements is that most static transmission and transducer errors are automatically compensated.

The converter used has a differential input and supports a wide range of input voltages. Therefore, using solid state switches, it is very easy to measure the voltage of all channels - reference resistor, voltage on RTD1, voltage on RTD2, PT100 thermocouple cold end sensor, amplified voltage of thermocouple 1 and thermocouple 2.

The reference voltage of the AD converter is obtained from an external reference IC8 with a typical temperature coefficient of 1.5 ppm/°C. An accurate reference voltage value is not necessary for resistive sensor measurements, but is critical for thermocouple measurements. The output voltage of 2.5 V is divided to a value of 250 mV using resistors R37-R42. AD also supports lower values of the reference voltage (at the cost of a slightly reduced signal/noise ratio), which greatly simplifies the connection of the thermometer. All resistance sensors can be obtained directly, without additional operational amplifiers and amplifiers for thermocouples, with only a low gain (17).

Microcontroller and display unit

The ATMega328P microcontroller in the form of an Arduino Nano module is soldered directly onto the thermometer board. If you want to use the communication of the thermometer with the computer, it is necessary to place the microcontroller module so that you do not have to use a serial cable (USB port/extension).

The display unit is a separate module equipped with two pin strips. The display board is connected to the main board of the thermometer with two pin sockets. For correct integration, it is necessary to keep the exact position of these connectors as indicated in the documentation. Also, solder the pin sockets to the thermometer board with the display attached to get the exact mechanical position in the box.

Details of the microcontroller program and the installation plan of the unit are shown in the second part of the documentation.

Box and mechanical thermometer integration

Procedure for mounting the electronics in the box:
Connect the display board (1) to the thermometer board (2). Slide the display filter (3) onto the front side.
The assembly is inserted into the grooves in the lower part of the box (4), ensuring that the display and the circuit board are placed in their groove.
The assembly is screwed to the bottom of the box with four short screws (5).
A back wall (6) and an extension for the USB port are required.
The top half of the box (7) stands next to it. The upper and lower halves of the box are connected by four long screws (8).

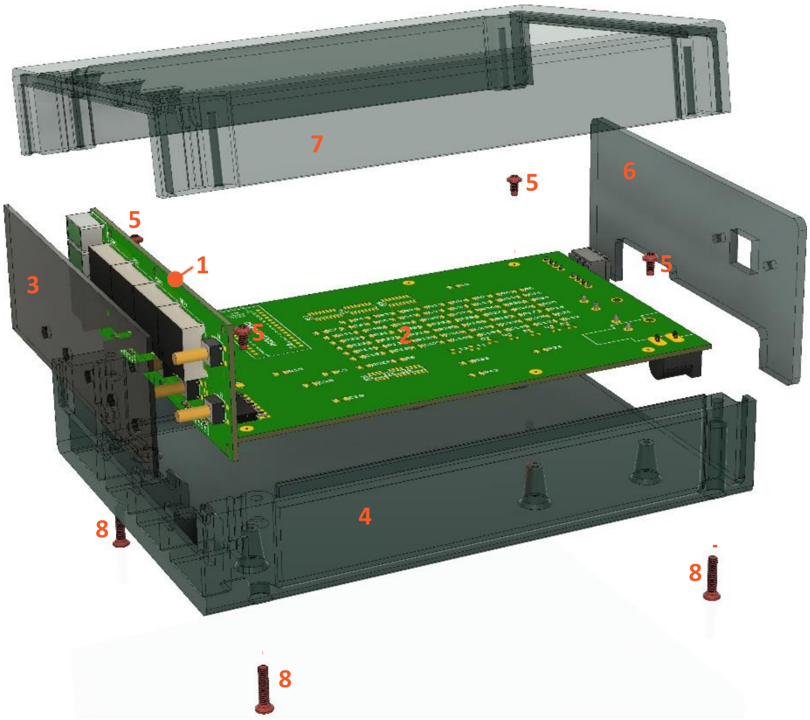
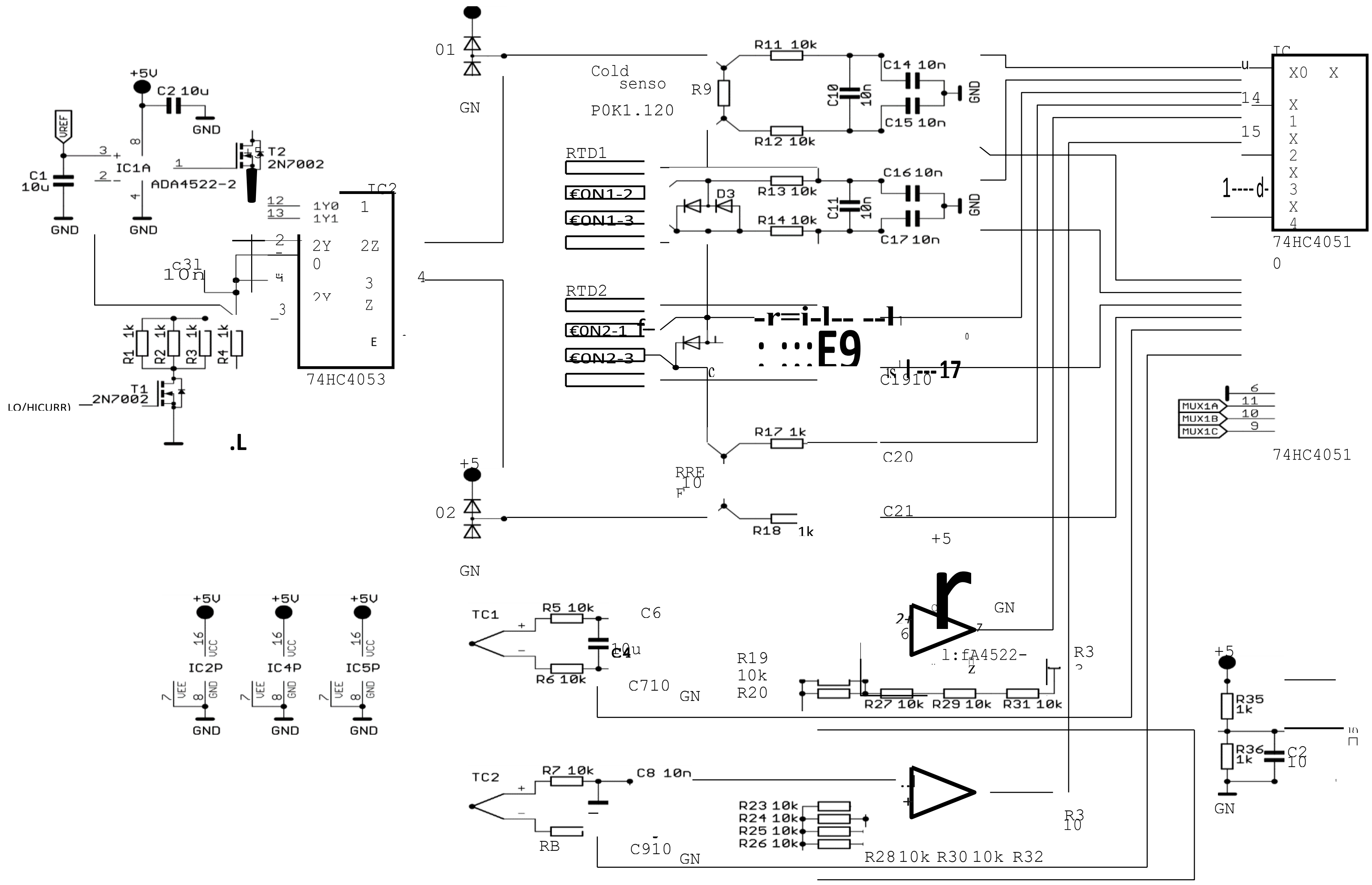


fig. 5: Completing the box

Parts list

Number	Part	Value	Note
8	C1, C2, C4, C5, C22, C23, C24, C26	10 uF, ceramic 1206	Tape marked in red
1	C25	100 uF, tantal	
17	C3, C6, C7, C8, C9, C10, C11, C12, C13, C14, C15, C16, C17, C18, C19, C20, C21	10 nF, ceramic 1206	
2	CON1, CON2	OQ0412510000G+15EDG K-3.5/4P	Install from the bottom side
1	CON3	C9743-CCRNB001R	Power connector 2.1 mm. Install from the bottom side
5	D1, D2, D3, D4, D5	BAV199	
1	DISP1	DISPLEJ 2x 8-pin socket SMD	Display module for thermometer. Connect the pin sockets with the connected display. The exact location is important
2	IC1, IC3	ADA4522-2	
1	IC2	74HC4053D	
2	IC4, IC5	74HC4051D	
1	IC6	MCP3553-E/SN	
1	IC7	Arduino Nano	It is installed without drilling on the side of the components
1	IC8	MAX6071AAUT25+T	Very small case, see. chapter embedding

8	R1, R2, R3, R4, R17, R18, R35, R36	1k, 0,1%	Tape marked in blue. Not to be confused with ordinary 1k 1% resistors from the display board!
32	R5, R6, R7, R8, R11, R12, R13, R14, R15, R16, R19, R20, R21, R22, R23, R24, R25, R26, R27, R28, R29, R30, R31, R32, R33, R34, R37, R38, R39, R40, R41, R42	10k, 0,1%	
1	R9	P0K1.1206.2P.B	Temperature sensor PT100, housing 1206. ***Solder very carefully, do not overheat.***
1	RREF	100 Ω, 10 ppm/°C	Reference resistance. For the most suitable, we recommend measuring the value with an accurate multimeter before installation. ***Solder very carefully, do not overheat.***
2	T1, T2	2N7002	
2	TC1, TC2	IM-K-PCB	Socket for thermocouple. **Install from the bottom side.**
	Circuit board 100x160 mm		
	Connector for USB cable		



+5V
C2 10u
GND
VREF
C1 10u
IC1A
ADA4522-2
T2 2N7002
R1 1k
R2 1k
R3 1k
R4 1k
T1 2N7002
LO/HICURR)
IC2
1Y0
1Y1
2Y 0
74HC4053
01
02
GN
Cold senso
P0K1.120
R9
R11 10k
R12 10k
C10 10n
C14 10n
C15 10n
RTD1
CON1-2
CON1-3
D3
R13 10k
R14 10k
C11 10n
C16 10n
C17 10n
RTD2
CON2-1
CON2-3
R17 1k
R18 1k
C20
C21
74HC4051
MUX1A
MUX1B
MUX1C
TC1
R5 10k
R6 10k
C6
C4
C710
R19 10k
R20
R27 10k
R29 10k
R31 10k
TC2
R7 10k
C8 10n
RB
C910
R23 10k
R24 10k
R25 10k
R26 10k
R28 10k
R30 10k
R32
R35 1k
R36 1k
IC2P
IC4P
IC5P
VCC
VEE
GND

User interface and display

Assembly plan and parts list

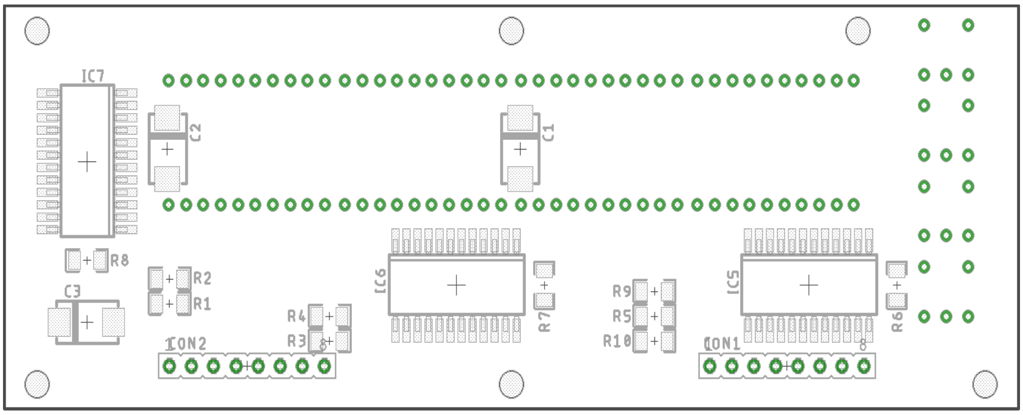


fig. 5: Fitting plan side of connections

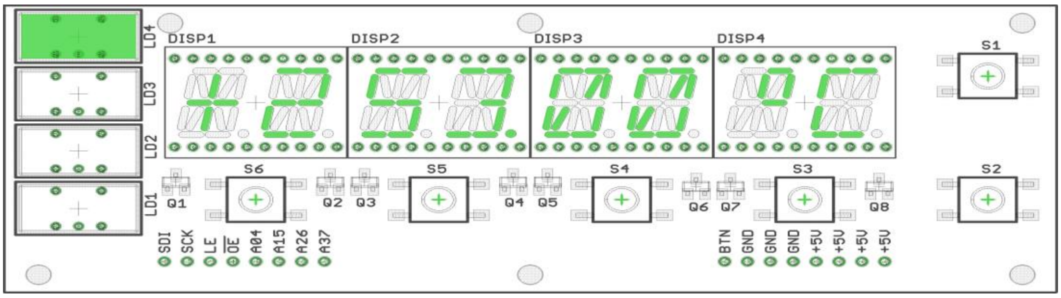


fig. 6: Assembly plan parts side

Nuber	Part	Value	Note
3	C1, C2, C3	100uF	Tantalum electrolytic capacitor
2	CON1, CON2	Pinová lišta 8p	Bar, male
4	DISP1, DISP2, DISP3, DISP4	LTP-4823JD	
3	IC5, IC6, IC7	STP16CPC26MTR	
4	LD1, LD2, LD3, LD4	DE/2GD	
8	Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8	BSS84	Not to be confused with precision resistors 1k 0.1% for measuring board!
9	R1, R2, R3, R4, R5, R6, R7, R8, R9	1k	
1	R10	56k	
6	S1, S2, S3, S4, S5, S6	DTSM-66S-V-B	

Control and indicator elements

S1 selection of physical unit. For RTD sensors °C – °F – K – Ω, for thermocouples °C – °F – K – mV

S2 selection of averaging value 2 – 4 – 8 – 16 – 32 measurements
S3 selection of measurement using thermocouple TC2. Indicates LD1.
S4 selection of measurement using thermocouple TC1. Indicates LD2.
S5 selection of measurement using resistance sensor RTD2. Indicates LD3.
S6 selection of measurement using resistance sensor RTD1. Indicates LD4.

Serial line communication

The device can be controlled via a serial line of text commands in SCPI format.
Communication speed 115200 baud.

The implemented commands are:
IDN?

Device identification. Returns the text "Reference thermometer ZENIT 2023-24"
TEMP?

Returns the value of the measured temperature from the active sensor in the selected unit
UNIT?

I use the active measurement unit °C|K|°F|Ω|µV
UNIT C|K|F|O

Setting the unit of measurement. You can choose °C, K, °F and Ω
SENS?

Returns the name of the active sensor (RTD1, RTD2, TC1, TC2)
SENS RTD1|RTD2|TC1|TC2

We set the active sensor
SENS 1|2|3|4

We will set the active sensor, alternative name
CURR?

Return active measurement current for measuring RTD sensors (high/low)
CURR HIGH|LOW

We set the measuring current for RTD sensors. Values are HIGH (1 mA) or LOW (250 µA)
C+|-

The switching of the excitation current polarity of the RTD sensors is activated. Switching active C+, without switching C-
AVRG?

Return the number of measurements used to calculate the value (averaging)
AVRG 2|4|8|16|32

Sets the number of samples used to calculate the value (averaging)

TCJ?

Returns the measured temperature of the cold end of the thermocouple (the sensor is under the TC1 connector)

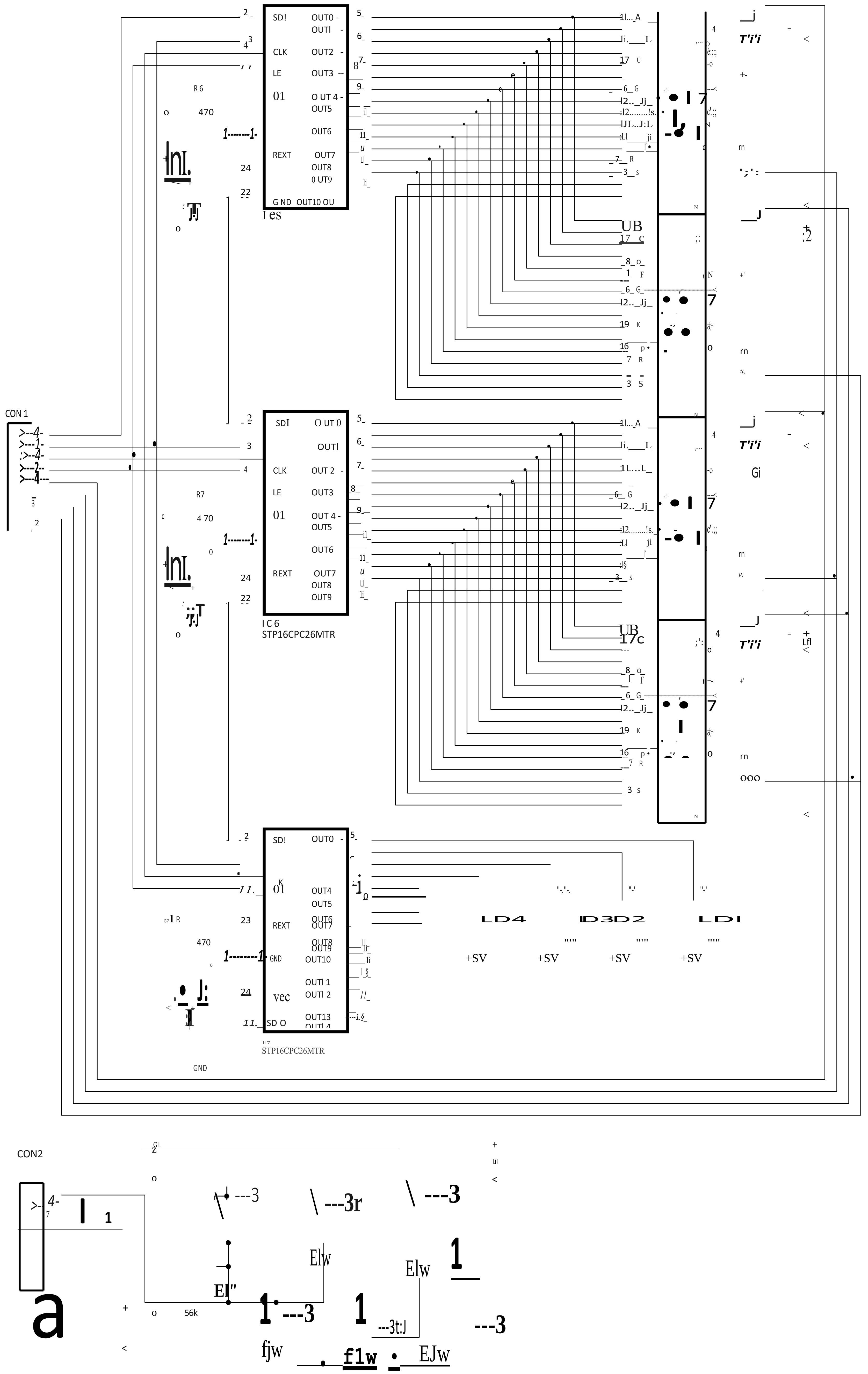
VTC?

Returns the value of the uncompensated thermocouple voltage (directly measured ADC voltage, without cold end compensation)

AUTO ON|OFF

Automatic publication of measured values along the serial line. Units and the same sensors as on the display

Authors: Ing. Peter Adamec, Adam Lassák, Bc. Martin Petrek, Ing. Jaromír Sukuba, Bc. Juraj Tvarožek, doc. Ing. Daniel Valúch, PhD.


CON 1
R6
470
R7
IC 6
STP16CPC26MTR
CLK
LE
REXT
GND
LD4
LDI
+SV
CON2
56k