The Device for Low-Cost Measurement of 2D Thermal Distribution

Jiří Minář, Kamil Říha

Abstract—The article describes a specialized device for measurement of thermal distribution of two dimensional surfaces for some applications in medical industry, and mechanical or civil engineering. The device is a substitution of expensive device for this kind of measurement is thermal camera which can be expensive for some application or should have the limitation of non-possibility to read temperature behind a barrier (wall, bandage).

The main goal of this work was to design a device for measurement of thermal distribution on 2D surface for low-cost measuring processes with slow change of temperature and for processes, which do not require high resolution of collected data. The next advantage of presented device is a possibility of temperature measurement behind the barrier.

Keywords— 2D Sensor Field, NTC, Temperature Measurement, Thermistor.

I. INTRODUCTION

Nowadays, there are many methods of field temperature measurement available on the market. Most of these methods are designed for a non-contact measurement e.g. two-dimensional infrared spectroscopy [1], three-dimensional temperature measurement of water using two-color laser-induced fluorescence (LIF) [2] or CCD (Charge-Coupled Device) or ICCD (Intensified Charge-Coupled Device) sensors [3]. Nevertheless, this kind of measurement device could be expensive for some application or there could be also disadvantage of impossibility of measurement temperature behind the barriers. The most common device, which is used for 2D temperature field measurement is infrared thermo camera, which can be bought from $2000. This can be expensive for some application. Therefore, a low-cost device for these types of measurement is sought. As a basic element for such device simple and cheap sensor: NTC thermistor (Negative Temperature Coefficient) was selected. This sensor is passive electronic component based on conversion of temperature to resistance [4]. The dependence of the resistance of typical thermistor is

$$R_T = Ae^{\frac{B}{T}},\qquad(1)$$

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where R_T is resistance, A is a constant based on geometrical shape and material of thermistor, B is temperature constant based on material of thermistor, and T is thermodynamic temperature.

NTC thermistor has exponential temperature/resistance characteristic. And measurement results can be very imprecise without elimination of this non-linearity. This can be solved with a lookup table (see Chapter IV.) or by inversion function.

As a minimal size of the 2D temperature field is used sensors matrix with 8 x 8 sensors. This size should be sufficient for practical verification of the solution.

II. SENSOR CHARACTERISTICS

A. Thermistor

There is a big variety of NTC thermistors on the market with different size, different toleration or mounting technology, and the price range is from $0.1 to $5 per sensor.

For experimental device NTC thermistor, form company Betatherm with type number SMD110KJ375J was chosen. Its parameters are described in Table I. This thermistor is built for SMT - Surface Mount Technology. The size of the thermistor is very small (3.2 mm × 1.6 mm) therefore is suitable for building big sensors array and the price of this sensor is suitable for low cost application. It is about $0.3 per sensor.

TABLE I
BETATHERM SMD110KJ375J

Parameter	Value
Operation temperature	- 40°C to + 120°C
Max. load	400mW
Resistance at 25°C	10kΩ
Tolerance	5%
Dissipation Constant	3mW/°C

B. Thermistor Characteristic

All the sensors used in the two-dimensional field should have the same exponential characteristic. Same exponential characteristic is expected for all thermistors of the same type. The only error in offset is expected, which is given by 5% tolerance of the thermistor, which can be easily removed only adding or subtracting offset value. This can be solved by implementation into look up table together with linearization of exponential characteristic of thermistor. The shapes of exponential functions of thermistors are same on

considered temperature operation range (25°C to 50°C). As is seen in Fig. 1, where is the example of two NTC thermistors used in measurement device.
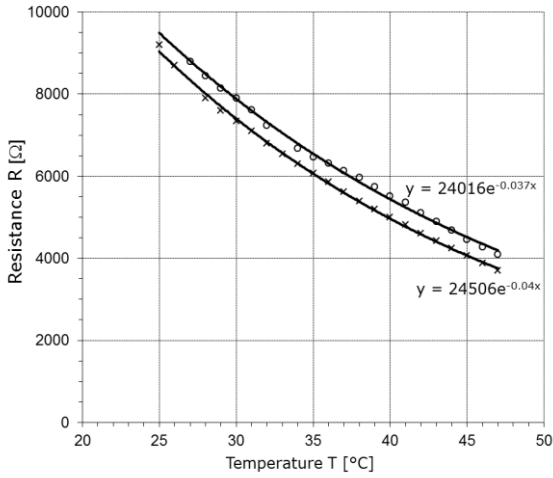

Fig. 1. Example of two NTC thermistors characteristic $R = f$ (T) with constant current 50μA

Measurements of two thermistors were performed in oil fluid, where oil was heat up to 50°C and then temperature decrease from 50°C to 25°C. Cool down of thermistor was approximately 1°C per 15 seconds. As can be seen from Fig. 1, that temperature is out of tolerance in 25°C, but this is cause by thermal accumulation of thermistor. Resistance was in tolerance after approx. two minutes. And the values of thermistor were stabilized on values 10100 Ω and 10180 Ω, which is 5% tolerance.

III. DEVICE REALIZATION

A. Wheatstone Bridge

Value of Temperature on sensor is value of resistance of thermistor; therefore temperature is measured indirectly by measuring of voltage. Very good application of this type of measurement is connection of thermistor into Whetstone bridge with differential amplifier (Fig. 2).
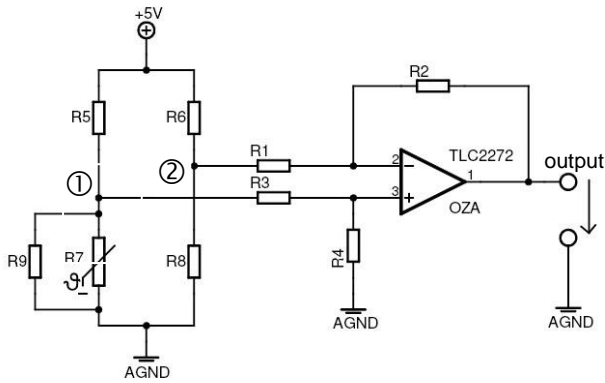

Fig. 2. Wheatstone bridge with parallel connection of thermistor

Device was designed for precision 0.1°C and for measuring temperature range from 25°C to 45°C. These parameters were chosen specifically for one of possible use of this device; measuring of skin temperature.

Values of resistance of Wheatstone bridge were designed for mentioned parameters ($R_7 = 5$ kΩ – 10 kΩ parameters of thermistor from Fig. 1) and for precision 0.1°C (max. current $I_{max} = 300$ μA).

Bridge is balanced in measurement points' ① a ② in Fig. 2. Values of resistors R_5, R_9 are designed to reflect maximum of value of measurement current. Then there are $R_5 = R_6 = 50$ kΩ, and $R_8 = (R_7$ in parallel combination with $R_9) = 2200$ Ω. Resistance R_9 is added for linearization exponential characteristic of thermistor [4].

Amplifier was chosen TLC2272 from company Linear Technology. This amplifier is of rail-to-rail type (can produce output voltage V_{out} very close to supply voltage V_{cc}. Resistances for setting of differential amplifier were set on these values: $R_1 = R_2 = 5$ kΩ a $R_3 = 26$ kΩ.

Values of resistors were verified in program PSpice that current through thermistor is not higher the I_{max} (Fig. 3).

Based on toleration analysis of resistors in program PSpise, possible influence of toleration of resistors on temperature error was verified. Resistors R_1 - R_4 are not too sensitive to precise value of resistors (Fig. 4).
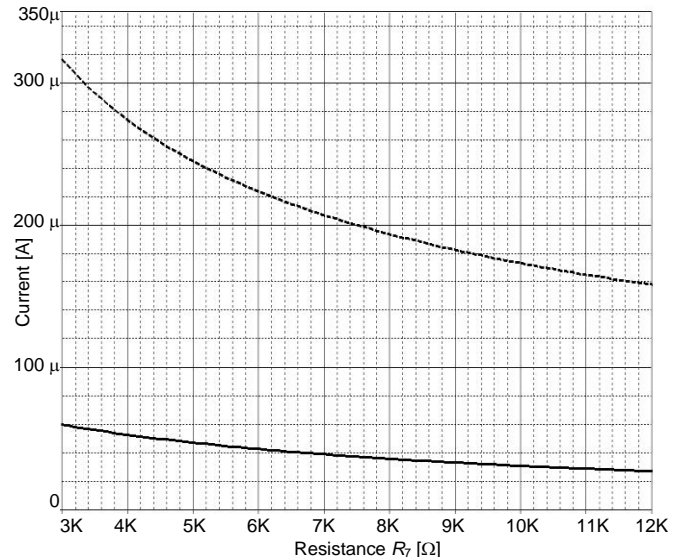

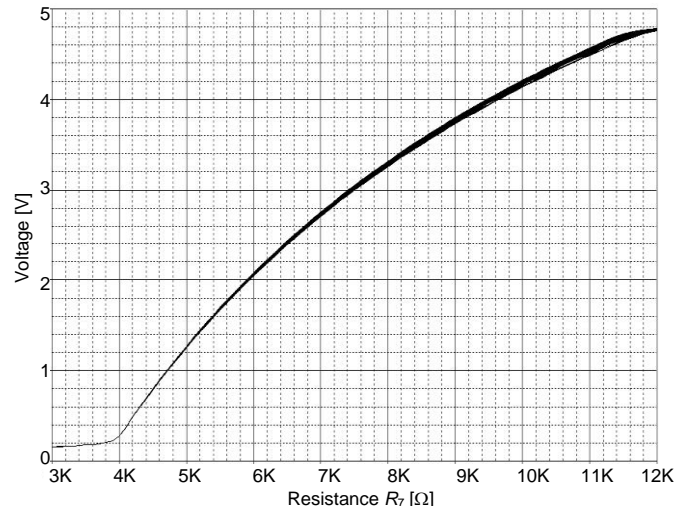Fig. 3. Current through thermistor R_7

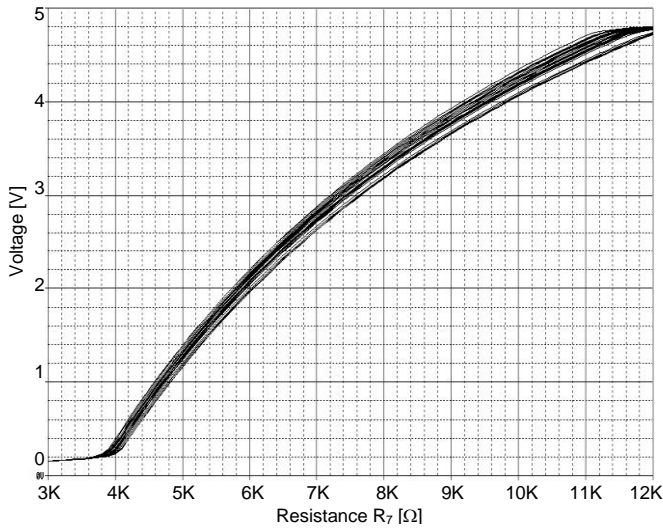Fig. 4. Toleration analysis for resistors R_1-R_4 with tolerance 1 %

Fig. 5. Toleration analysis for resistors R_5-R_7 and R_9 with tolerance 1% - 25 runs

But resistors $R_5 – R_7$ inside the Wheatstone bridge have to be selected from series with very low tolerance (Fig. 5). Because resistors with 1 % tolerance can cause additional offset error, this means 8°C error. For practical realization should be selected resistor from series with tolerance 0.5 % or better or instead of resistor R5 use trimmer for weighting of Wheatstone bridge.

B. Controlling of Sensor matrix

Matrix of sensors has been designed as square matrix with 8 x 8 sensors, therefore switching method was chosen for 64 sensors as an individual connection of thermistors into differential amplifier by multiplexer MC14067B from company ON Semiconductor. This connection ensures that current measurement goes through single switched thermistor (Fig. 6). All thermistors are connected to the ground and only one thermistor is selected. Used multiplexer handle serve 16 sensors, therefore 4 multiplexers have to be used.
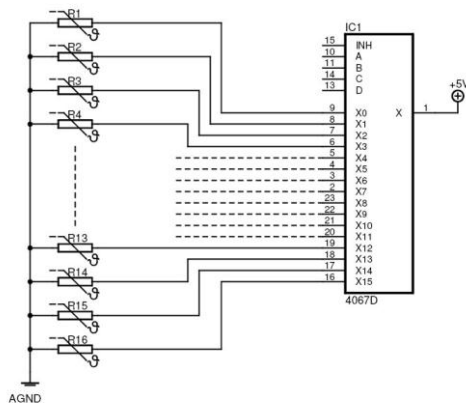

Fig. 6. Switching of thermistor by multiplexer

For controlling and communication with PC microcontroller ATMEL ATmega16 was used. This controller provides necessary functionality for A/D conversion and communication. A/D convertor used in ATmega16 has 10-bits resolution and this is enough for temperature range 25°C – 45°C with toleration 0.1°C,

because change of one bit means that this range is change of 0.02°C.

IV. EXPERIMENTAL RESULTS

Due to exponential characteristic of thermistor and offset of thermistor by 5 % toleration, it is essential to calibrate every sensor at whole range of temperature. Exponential characteristic can be linearized by inversion function from eq. (1) or by lookup table. Lookup table was selected due to its modesty to compute power and also for calibration of offset.

For 0.1°C precision on all temperature range it is necessary to divide whole range at least to 20 intervals, as is seen in Fig. 7. Each interval is considered as linear.

Calibration should be essential, because non-calibrated sensors can have temperature up to 1°C. Fig. 8 shows a situation for 3 examples of calibration. First curve considers only 3 calibration points and due to this the temperature error between two these points can be up to 0.9°C. Second curve demonstrates 5 points calibration with temperature error up to 0.4°C. And the third curve demonstrates sufficient calibration with 23 points and there is temperature error below 0.1°C. This calibration should be done in temperature chamber with suitable temperature range and with step 1°C per 2 minutes to ensure sufficient heat of thermistor.
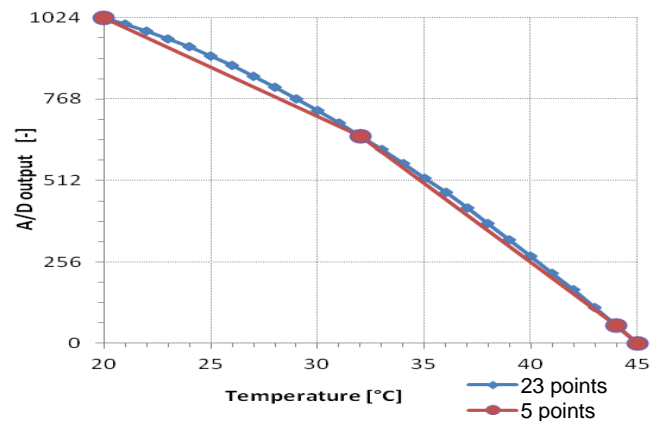

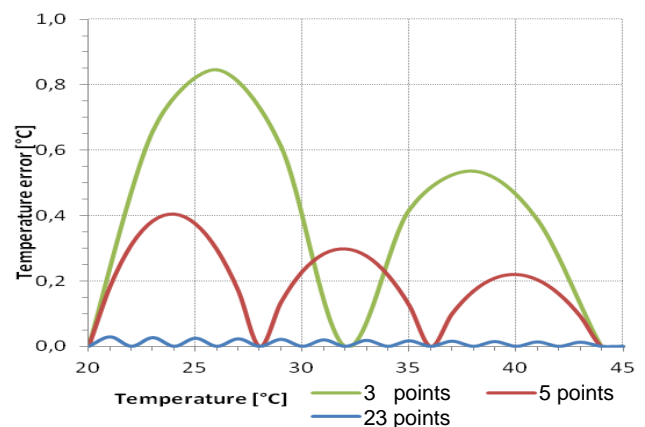Fig. 7. Conversion characteristic Sample/Temperature for 3-point and 23-points calibration

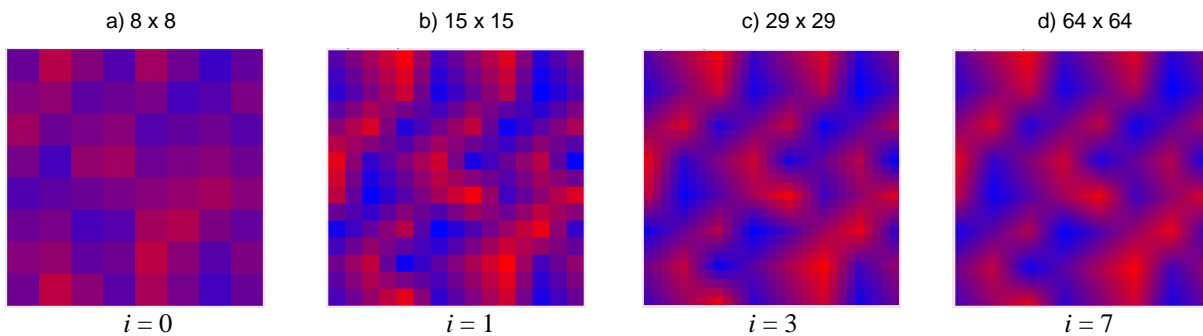Fig. 8. Temperature error for 3-point, 5-points and 23-points calibration

a) 8 x 8	b) 15 x 15	c) 29 x 29	d) 64 x 64
$i = 0$	$i = 1$	$i = 3$	$i = 7$

Fig. 9. Interpolation of measurement data – interpolation coefficient i

Visualization of measured values was done as temperature map in PC, where the lowest temperature (25°C) is of blue color, the highest temperature (45°C) is red color and the temperatures between the temperature range have the relevant colors from blue – red color range Fig. 9(a) Interpolation from 1 to 7 was used for better interpretation of measured field Fig. 9(b), Fig. 9(c), and Fig. 9(d), where value interpolation coefficient i defined amount of computed values was added between two measured values.

In Fig. 9, there is sample of measured data as a temperature footprint of three fingers as is described in Fig. 10.
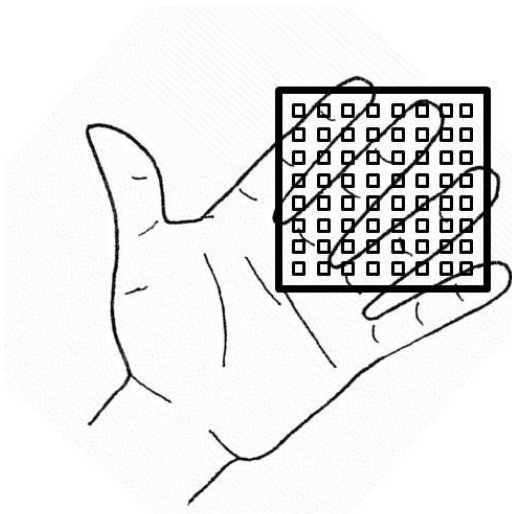

Fig. 10. Experimental measurement of three fingers with matrix of 8 x 8 of thermistors

V. CONCLUSION

The solution for low cost measurement device based on matrix of NTC thermistor was presented. This device should be used as a cheap substitution of common method of measurement of thermal two-dimensional field e.g. infrared thermo-camera. The proposed solution has price about $30comparing with price of infrared thermo-camera (starting at $2.000) is much cheaper. For some application could be advantage that this device could be placed behind solid barrier. This device can be used for measuring the temperature field with slow change of temperature (minutes) and where is not necessary detailed resolution. Relevant application of this solution could be in medical use as e.g.

mechanical industry, where the big distance between the sensors is not a problem.

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