Concept of a Wearable Temperature Sensor for Intelligent Textile

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Abstract. *This paper proposes the intelligent textile for human body temperature measurement. The main concept of the textile is based on two commercially available LM35DM temperature sensors, knitted electrically conductivity yarns and five areas for press-stud. Three different measurements methods were used in our experiment. Three measurements were performed in the first step, digital thermometer in person's armpit, contact-less thermometer in the places close to our LM35DM sensors and contact-less thermometer on the forehead. Next, two LM35DM in SOIC8 package were used for temperature measurement within intelligent textile. Finally, the first step was repeated. All measurements were done on ten subjects with their permission to collect body temperature data for scientific purposes. The results show that the average measurement error for first sensor is 0.844 $^{\circ}C$ and 0.278 $^{\circ}C$ for second sensor.*

Keywords

Body temperature, conductive yarn, wearable sensors.

1. Introduction

Wearable sensors are still more and more popular in every day activities. The data from sensors can be stored for personal evaluation, security reasons or for medical purposes. On the one hand we collect data for fun, on the other hand collected data can save lives. In general, we expect that wearable sensors measure the human body function like ECG, EMG, respiratory activity or body temperature. These sensors are included into various smart wearable devices and clothes.

Smart firefighter protective suit was presented in [1]. Their smart textile-based protective system should improve firefighter safety. The smart suit is able to monitor heart rate and movement, detect toxic gases and measure the outside and inside suit temperature and humidity. The suit is also equipped with GPS and other modules for communication purposes. Another smart clothes platform for long-term health monitoring was introduced in [2]. Their platform consists of five types of sensors for health monitoring and computing module, smart-phone and back-end cloud server. They are focusing on ECG, movement, EMG, respiratory acivity, and body temperature measurement. All sensors are embedded into the clothes. The system can run up to 281 hours with typical battery capacity of 1800 mAh.

The similar platform for health monitoring was proposed in [3]. They presented innovative smart textile system for continuous monitoring of cardiorespiratory signals where the measured data are transmitted to the mobile device via Bluetooth. The presented platform showed good performance, durability and versatility. The textronic system to monitor vital function of infants and small children called BabyTex was described in [4]. The system provides remote monitoring of respiratory rhythm, moisture, body temperature and motoric activity of infants and young children. Temperature, humidity and respiratory rhythm sensors are made in the form of knitwear and can be easily integrated into to cloths. The temperature sensor, namely MCP9700A in the SOT23-5 package was embedded into the knitted fabric. The humidity sensor is based on PW109. The measured data were transmitted to smart-phone via Bluetooth. Provided results showed that system is capable and reliable in the health monitoring of young children at home.

In [5], the authors proposed the humidity wearable sensor embroidered with electrically conductive yarn. The sensor was able to measure relative humidity in the range from 25 % to 80 %. They compared proposed sensor with the printed sensor and proved that both react well to relative humidity. They observed hysteresis in capacitance with increasing and decreasing humidity level.

A prototype temperature sensor for e-Health applications based on commercially available ferroelectric lead Zirconate Titanate (PZT) was introduced in [6]. The proposed sensor is using the large pyroelectric effect present in PZT and has several advantages over others temperature measurements. The sensor is very thick and cheap. They developed mathematical model to describe the sensor response to temperature change in the range from 20 °C to 40 °C. Proposed sensor capacitance showed a linear dependence as a function of temperature in investigated range.

Another method of body temperature measurement was presented in [7]. They developed remote health monitoring system for heart rate and body temperature. LM35 sensor was used for temperature measurement due to high accuracy and wide range. The sensor accuracy is ± 0.25 °C and output voltage has linear dependency to °C. They used Arduino with Ethernet shield to send measured data to remote server. MySQL database was used on server side and simple web graphical interface was developed to allow doctors to monitor patients remotely in real time. Even more precise body temperature measurement was proposed by [8] based on an analog frontend with new temperature calibration method. Proposed method consist of a current reference, a precision current source, a programmable gain amplifier and voltage source. The body temperature can be measured with precision ± 0.1 °C and power consumption is no more than 180 µW. A 1-V CMOS Low-Power Resistor-Based temperature sensor was developed in [9]. The sensing element is realized by an on-chip fully-differential RC filter. They used simple voltage comparator to compare two voltages and to measure the temperature-dependent crossing time. Their simulations showed that proposed sensor could achieve the maximum temperature error less than ± 0.05 °C.

Different approach to body temperature measurement was described in [10], where a novel non-invasive fibre-optic sensor monitoring basic vital sing was introduced. The sensor is capable of monitoring respiratory rate, heart rate and body temperature. The presented sensor is based on two Figer Bragg Gratings (FBGs) encapsulated inside an inert polymer. They used Bland-Altman statistic analysis for verification of temperature measurements and a total relative error of 0.31 % was determined.

The humidity and temperature sensor integrated in smart textile as sensing device that monitors the room climate was presented in [11]. They developed sensor system on flexible polyimide substrates and woven it into textile. Temperature had a linear response with resistance with sensitivity of 0.0028 °C per Ω. On the other hand, humidity sensor showed non-linear distribution in the range from 30 % to 80 % relative humidity.

In this paper we propose concept of a wearable temperature sensor for intelligent textile based on commercially available analog sensor LM35DM from Texas Instruments. The main task of our concept is to measure human body temperature within the smart shirt. Our paper is organized as follows: the first part is dedicated to the introduction and describing state-of-the-art. In the second part, methods and components used in our solution are presented. The third section describes practical textile proposal, performed tests, and results evaluation. In the Conclusion section, our concept and achieved results are summarized.

2. Methods

Our concept of smart wearable focuses on the continuous human body temperature measurement. The term *body temperature* represents the temperature inside the body. The measured temperature depends on the measured place and may varies during the day cycle up to 2 °C. The body temperature is very important indicator of human health and in the diseases diagnostics. The common human body temperature is around 37 °C.

2.1. Temperature Sensors

There are many commercially available temperature sensors. From the sensing point of view, the temperature from the sensor can be acquired in digital or analog form. Digital thermometer has output in predefined protocol, such as SPI, IIC or modbus while analog thermometer's output is an analog value, which needs to be converted into number.

In our work, we decided to use analog temperature sensor, namely LM35DM. Its accuracy is 0.5 °C with linear scale factor 10 $\text{mV}\cdot{}^{\circ}\text{C}^{-1}$. According to the thermometer's manufacturer, Texas Instruments, it is possible to achieve 0.1 °C accuracy by changing the reference temperature to 1.1 V. The downside of this solution is that the measurement's range is reduced. The reduced range is from 2 °C to 110 °C and is still suitable for body temperature measurement.

2.2. Pattern Design and Embroidery

Electrically conductive yarns created with embroidery machine were used to connect smart shirt components. Used yarns are made of common cotton yarns and a silver yarn SHIELDEX to ensure conductivity. Connections between yarn and electronics are ensured via sets of press-studs. The embroidery was done on machine Barudan BEXT-S1501CII.

First, the pattern design was created using embroidery DecoStudio from Wilcom elements. Our design, shown in Fig. 1, consists of electrically conductive paths, 5 areas for press-stud and two areas for temperature sensor. As it was presented in our previous work [12], the best path design in the terms of minimal electrical resistance and robustest was a design where two separate lines with zig-zag pattern overlay were used for one path. Electrically conducted glue and soldering were used to connect sensor with knitted paths. After the embroidery, the pres-studs were assembled and the electrical resistance with digital multimeter was measured between the connectors. Every measurement was repeated 1 times and, average values are shown in Fig. 1.

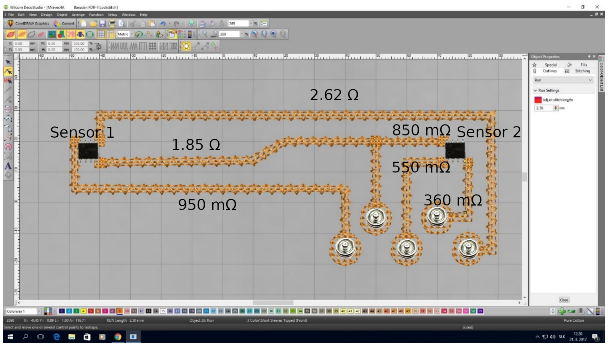

Fig. 1: Pattern design of electrically conductive paths and measured resistance.

3. Practical Proposal and Result

Smart shirt needs to be comfortable and the person who is wearing it should not notice the difference from the common cotton shirt. We had to avoid the direct contact between the electrical parts and human skin. On the other hand, we wanted to measure temperature and therefore the thermometer had to be as close to the human body as possible. The isolation material had to be flexible, had to persist washing and ironing and had to have sufficient resistivity. The silicone was used to ensure mentioned requirements.

3.1. Silicone Testing

We performed series of tests to find out which kind of silicone and its thickness is suitable for our smart shirt. The silicone was tested in the term of resistivity and ability of transferring the body surface temperature to the opposite silicone side because of its thickness. The two silicones were tested, namely biocompatible silicone RTV 615 and neutral silicone commonly used in construction and architecture. RTV 615 has wide usage in opto-electronics, electronics, LED diodes and food applications. We performed following tests:

- silicone applying on aluminum plate with different thickness (0.5, 1, 1.5 and 2 mm),
- heating up the aluminum plate,
- recording on thermal camera,
- analyzing the results.

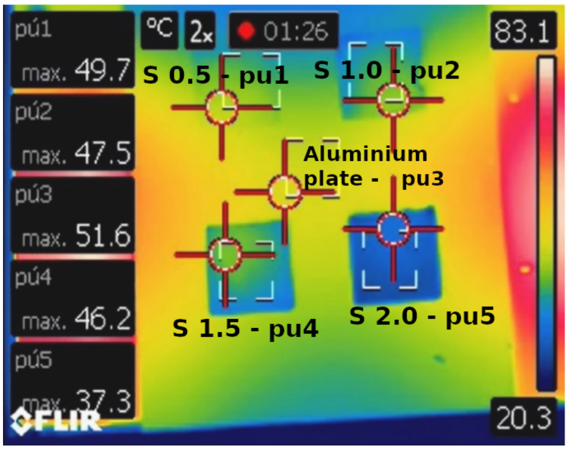

Fig. 2: Thermal camera aluminum plate measurement.

The temperature of particular silicones and the aluminum plate were investigated in range from 35 °C to 45 °C. Experimental setup for thermal camera and focused areas for measurement is shown in the Fig. 2. Camera was searching for the hottest position in areas of silicone and these temperatures were recorded. The results are shown in Fig. 3 and Fig. 4 for neutral silicone and for biocompatible RTV 615, respectively. The bottom x axis is the aluminum plate temperature (°C), top x axis is time (min:sec) and y axis represents the silicones temperature (°C). The neutral silicone has better ability of transferring the body surface temperature especially with the lower thickness of applied material over the RTV 615. The difference in temperature between aluminum plate and silicones were 1.7 °C for neutral silicone and 6.4 °C for bio-compatible silicone. Theses values were calculated when the temperature of the aluminum plate was 36.7 °C. Mentioned differences are for the thickness of material 0.5 mm. The results showed linear dependency between the aluminum plate temperature and the silicones temperature over the entire investigated range.

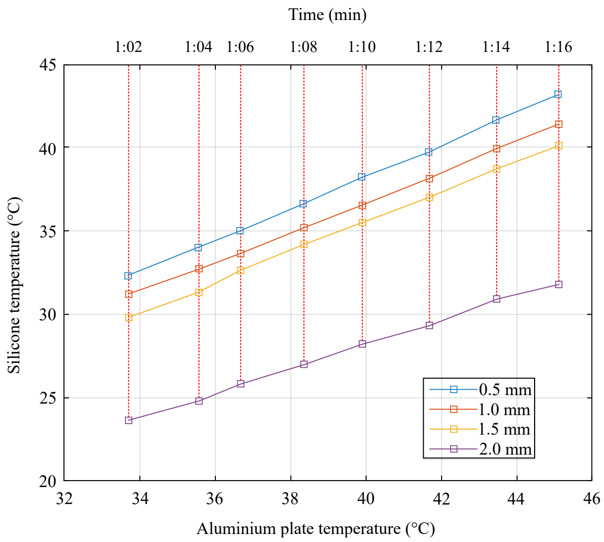

Fig. 3: Ability of transferring the body surface temperature for neutral silicone, dependency between aluminum plate temperature (°C) and silicone (°C).

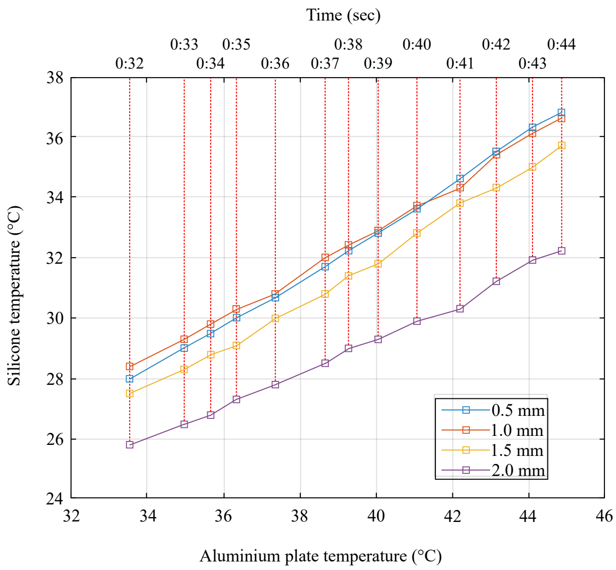

Fig. 4: Ability of transferring the body surface temperature for bio-compatible silicone, dependency between aluminum plate temperature (°C) and silicone (°C).

3.2. Intelligent Textile Preparation

We demonstrated proposed intelligent textile on the sport shirt. Instead of integrating the sensor directly into fabric as was showed in [13], we decided to put sensor on separated fabric with electrically conducted yarns. Afterwards, fabric with knitted paths was ironed in the inner side of shirt and the press-studs were assembled. Proposed intelligent textile with integrated sensors is shown in Fig. 5. In the next step, the electrically conductive paths were isolated with cotton fabric using ironing. The temperature sensors were encapsulated in bio-compatible silicone RTV 615. Totally, two separated temperature sensors LM35DM were used. The RTV 615 was chosen because it is bio-compatible and can be in contact with human skin. The biocompatible silicone does not have as good ability of transferring the body surface temperature as common silicone, but it can be still used, because the measured temperature of RTV 615 showed linear dependency with the aluminum plate temperature.

Fig. 5: Proposed intelligent textile with integrated sensors.

3.3. Data Collection and Evaluation

The Arduino platform was chosen to collect data from the intelligent textile. It was used because of it simplicity. In our work, Arduino Nano with ATMEGA 328p microcontroller was used. The data were measured using two independent analogs pins (A0 and A1). Each of them was connected to the output pin V_{OUT} of LM35DM. The reference voltage was 1.1 V. The analog values were read every 100 ms and after 10 measurements the average value was calculated and send to the computer for evaluation and storage.

Three different measurements methods were used to verify the functionality and accuracy of the proposed solution:

- our intelligent textile with two LM35DM,
- contact-less Microlife NC 100,
- common digital thermometer.

The all measurements were done with the subject's permission to collect temperature data for scientific purposes. The graphical representation of one temperature measurement with two LM35DM is shown in Fig. 6. In average, it took around 100 second for sensors to stabilize the output temperature. We performed

Tab. 1: Summary of temperature measurements.

	1. sensor (°C)	**SD**	**NC 100 (°C)**	**Error (°C)**	**2. sensor (°C)**	**SD**	**NC 100 (°C)**	**Error (°C)**	**Armpit (°C)**	**NC 100 - forehead (°C)**
subject1	32.015	0.097	32.9	0.885	32.6	0.095	33.2	0.561	36.1	36.7
subject2	32.185	0.114	32.7	0.515	32.7	0.137	33.1	0.428	36.2	36.8
subject3	32.228	0.054	33.1	0.872	32.8	0.130	32.9	0.133	36.7	36.8
subject4	31.250	0.058	32.1	0.850	31.9	0.061	32.3	0.426	36.7	36.5
subject5	32.795	0.071	33.8	1.005	33.7	0.060	34.0	0.315	36.3	37.4
subject6	33.295	0.072	34.0	0.705	33.6	0.051	33.9	0.324	36.3	36.7
subject7	32.292	0.049	33.2	0.908	32.9	0.061	33.3	0.390	36.5	36.4
subject8	32.475	0.104	33.8	1.325	34.1	0.058	34.2	0.120	36.3	36.5
subject9	32.342	0.076	32.9	0.558	34.0	0.101	33.5	−0.460	36.3	36.8
subject10	32.281	0.072	33.1	0.819	32.7	0.082	33.2	0.545	36.4	36.6
Average error				**0.8442**				**0.2782**		
Standard deviation				**0.2294**				**0.2986**		

our experiments as follows: measurement with NC 100 and digital thermometer was done in the first place. The NC 100 measurements were done in the place close to the our LM35DM sensors and forehead. Temperature with digital thermometer was measured in person's armpit. Then the intelligent textile with two LM35DM was put on and 10 values were collected after stabilizing the sensors output. Afterwards, the first step was repeated. The obtained results are shown in Tab. 1. Standard Deviation (SD) for LM35DM measurements for every person was calculated. Measurement error between referenced value obtained with NC 100 and sensors is also shown in Tab. 1. In the end, the measurement error standard deviation for both sensors is given.

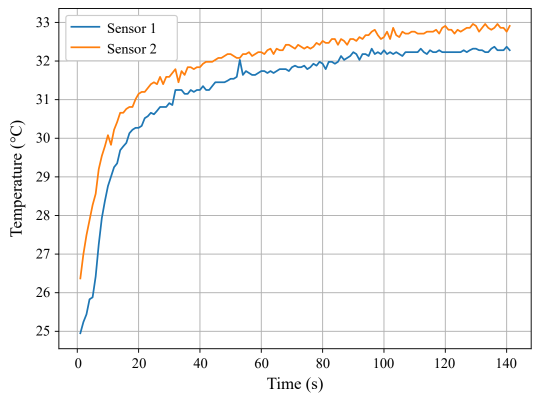

Fig. 6: Proposed intelligent textile with integrated sensors.

4. Conclusion

Concept of a wearable temperature sensor for intelligent textile based on commercially available LM35DM and knitted electrically conductive yarns was demonstrated. The sensor is encapsulated into the biocompatible silicone, which could interact with human skin. The results showed linear dependency for the temperature measured on silicone over whole investigated range from 35 °C to 45 °C. The temperatures from the intelligent textile were measured and transferred to PC using Arduino Nano platform. The measured temperatures were compared with professional contactless thermometer. Average measurement error 0.844 °C with standard deviation 0.2295 was achieved for first sensor and average measurement error 0.278 °C with standard deviation 0.2986 for second sensor. The difference in errors between sensors could be caused by difference in the silicone thickness, by the voltage drop on the longer knitted path or by the thermometers accuracy. The proposed intelligent textile's benefit is that it could be used for continuous monitoring while remaining the comfort of the person wearing it. On the other hand, the temperature measurement is not very precise and could be used only for informational measurement.

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