From human skin to Nano-Skin: an experimental study on human skin temperature measurement

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(Received 25 August 2010; final version received 2 March 2011)

The human state in human–machine systems should be monitored to improve system performance. In monitoring it is preferable to use physiological cues such as skin temperature. The sensing capabilities of human skin were analyzed. The sensing system of human skin was modeled, and inspired the design of a Nano-Skin for physiological measurement in dynamic human–machine contact for human state recognition. The Nano-Skin involves a flexible bottom layer, sensors, special integrated circuit, interconnection between sensors and special integrated circuit, and flexible top layer. The requirements for the sensors of a Nano-Skin are summarized, and compared with common sensors, MEMS sensors, and nano sensors. A Nano-Skin with deposited platinum was manufactured. The manufacturing process is shown to be feasible and repeatable. The Nano-Skin with deposited platinum was used to measure skin temperature. Its performance was investigated using experiments. The results verified that the accuracy of the Nano-Skin sensors will not be lower than Pt1000Ω. Smaller sensors in a Nano-Skin generally have better performance.

Keywords: human–machine system; human state; physiological parameter; sensor; skin temperature

1. Introduction

Recognizing the human state in human–machine systems is highly useful to improve the performance of human–machine systems [1,2]. Researchers usually use two categories of cues to recognize the human state, human physiological cues and machine dynamic cues [3,4]. Human physiological cues have a more direct relation with the human state, and are more suitable for human state recognition. They can be measured using contact technologies or non-contact technologies. The contact technologies require human–machine contact, which is the physical contact between humans and machines, whereas the non-contact technologies do not [5,6]. Compared to non-contact technologies, contact technologies can achieve larger signal-to-noise ratio and lower energy consumption. However, current contact technologies mainly use traditional sensors, which have limited sensitivity and large sizes. There are still challenges in using contact technologies to non-intrusively measure physiological cues for human state recognition. Addressing the challenges needs new paradigms in the area of sensing [7]. Biomimetics, the subject of copying, imitating, and learning from biology, shows new and exciting opportunities for researchers in the area of sensing [8]. Studying and mimicking the mechanism of natural sensing systems is
highly useful to improve current contact technologies for physiological cues based human state recognition. Researchers have revealed that natural sensing systems generally (1) are built from micro-scale to macro-scale, and (2) involve different sensors for different stimulus. Biomimics using ‘bottom-up’ approaches is now feasible with new development in technologies such as nanotechnologies. For example, sensing skins have been developed to expand the sensing capability of machines [9,10]. In order to monitor structural health, bio-inspired sensing skins were studied to detect strain, damage, and pH [11]. A capacitance-based sensitive skin was designed to measure the distributed pressure on lower limb prosthetic devices and healthcare robots [12,13]. An infrared-based sensitive skin was developed for motion planning in uncertain environment [14]. These sensing skins imitated the sensing function of human skin.

The motivation for this study was the development of a biologically-inspired sensing skin to address the challenges in contact technologies for physiological cues-based human state recognition. The sensing skin is flexible, and is able to be attached to any human–machine contact surfaces. It will non-intrusively measure physiological cues when humans touch it. The sensing skin produces high quality signals, and has low energy consumption and easy usability. It is named ‘Nano-Skin’ in this research as its fabrication uses nanotechnologies.

2. Human skin and the intelligent sensor array of Nano-Skin

Human skin covers human bodies, and is an essential human organ [15]. Its function includes sensation as well as protection and temperature regulation. Human skin is highly useful to enhance human adaptability to ambient environment. It involves a dense network of sensory receptors which is made from multiple kinds of receptors. Each kind of receptor is used to detect one kind of stimulus such as temperature. All kinds of receptors are scattered over human skin, and support the distributed sensing capability of human skin. Stimuli that are applied to any location of human skin will not be missed. Human skin shows a feasible method to continuously and consistently acquire multiple and dynamic stimuli. In human–machine contact, if the machine surface has sensing capabilities, it will be able to detect physiological cues from human skin. However, human–machine contact is dynamic. Humans may frequently change the location and area of human–machine contact. Ensuring the consistency and continuity of physiological measurement in dynamic human–machine contact needs the sensing mechanism of human skin.

In fact, the receptors in human skin are connected with the human central nervous system. There is no connection among the receptors. The receptors transform external stimuli, and then send the signals to the central nervous system. In Figure 1, a star network

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**Figure 1.** The receptor network of human skin and the intelligent sensor array.
models the receptor network of human skin, which has two kinds of receptors, A and B, connecting with the central nervous system. The star network can be mimicked using an intelligent sensor array, which involves one microcontroller and multiple sensors. The sensors A and B are employed to measure different measurands. All sensors connect with only the microcontroller. Their signals are continuously acquired and processed by the microcontroller. When an intelligent sensor array is embedded into a Nano-Skin, and is attached to a human–machine contact surface, it can detect the human physiological cues on human skin during dynamic human–machine contact.

The Nano-Skin operates in human working space of which the temperature usually undergoes slow changes in a slight range (e.g. 10–40°C). The temperature range may be larger if possible temperatures of human working space are considered. The intelligent sensor array of Nano-Skin has to work well at all these temperatures. Additionally, a Nano-Skin directly contacts with human skin and works under human force. The Nano-Skin must be safe to humans, and can resist the chemicals on human skin such as sweat. Their function and performance should not be impaired by human force. Moreover, the physiological cues on human–machine contact surfaces are weak. Measuring the cues needs sensors with high sensitivity. In order to recognize the human state in real time, the cues have to be acquired using sensors with quick response. Furthermore, the intelligent sensor array of Nano-Skin can be denser while employing smaller sensors. The sensors with higher sensitivity, quicker response, and smaller sizes are more suitable for Nano-Skins. Among common sensors, MEMS sensors, and nano sensors, common sensors are currently available on the market, and usually have sizes of millimeters and energy consumption of microwatts. MEMS sensors are produced using micro-electro-mechanical system (MEMS) technologies [16]. They have sizes in micrometers, and are much smaller than common sensors. The reduction in sizes leads to high sensitivity and low energy consumption. Nano sensors are fabricated using nanotechnologies. Their large surface-to-volume ratio may enhance the interaction between nano sensors and measurands. Their nano-sizes and large surface-to-volume ratio are highly useful to increase their sensitivity [17–20]. If nano sensors are built using flexible materials (e.g. polymers), bending them will not impair their function. Compared with common sensors, MEMS sensors and nano sensors are more useful to the development of Nano-Skin because (1) they are smaller, (2) their sensitivity is higher, and (3) integrating them with integrated circuits (IC) is not difficult. The integration shortens the distance between sensors and signal processing modules, decreases the signal distortion in signal transmission, and promotes the quality of sensor outputs. Developing a Nano-Skin needs the technologies of MEMS sensors and nano sensors.

3. Design of a Nano-Skin

So far, researchers used many physiological cues (e.g. heart rate, skin conductance, electromyography, skin temperature, sweat rate, operating force, etc.) to recognize the human state [21–31]. These physiological cues can be measured on human–machine contact surfaces using a Nano-Skin. A Nano-Skin has the structure of a sandwich, including a bottom layer, functional layer, and top layer. The bottom layer is the substrate of a Nano-Skin, and is employed to support and fix the components of the functional layer. The functional layer is used to acquire physiological cues and process signals. It involves sensors, a special IC, and interconnection between the two (Figure 2). The sensors are divided into many sensor groups that are evenly distributed on the bottom layer. Each sensor group involves multiple kinds of sensors such as a heart rate sensor, a skin temperature sensor, a pressure sensor, a sweat rate sensor, an alcohol sensor, and a skin conductance electrode. The special IC is
employed to (1) supply appropriate power to the Nano-Skin, (2) scan and acquire the signals of sensors, (3) perform signal conditioning, and (4) transmit the signals to upper-level computers. All sensors are wired to the special IC via the interconnection. The interconnection involves a signal network and a power network. The signal network connects the sensors with special IC for acquiring signals. The power network is used to supply power to the sensors. The top layer covers and protects the bottom layer and functional layer.

In applications, a Nano-Skin may be pressed, bent or stretched. When the Nano-Skin is pressed, the pressures on its three layers are same. When the Nano-Skin is bent, the maximum stresses happen on the bottom layer and top layer. If the functional layer is located on the neutral surface between the bottom layer and top layer, its stress will be minimized. When the Nano-Skin is stretched, the stress is distributed on the sections of its three layers. The bottom layer and top layer will sustain larger stress if their Young's modulus is larger than that of the functional layer. Moreover, the three layers of a Nano-Skin are bonded together. Large strains of the bottom layer and top layer result in a large strain in the functional layer, and may break the components of functional layer. The strains of bottom layer and top layer have to be as small as possible. Both layers prefer flexible material with large Young's modulus and high yield strength. Additionally, the bottom layer and top layer require good insulating capability because the components of functional layer are built directly between them. Polymers are appropriate materials for both layers.

In order to measure multiple physiological cues, the sensors of the Nano-Skin operate on diverse principles. The heart rate sensor employs the photoplethysmograph (PPG) method, and has a light source and a light detector. The light source projects infrared light to human skin. The reflected infrared light changes with the perfusion of blood in human skin, and then modifies the conductivity of light detector. The skin temperature sensor is a detector whose resistance changes with skin temperature. The pressure sensor is a piezoresistive sensor whose resistance varies with its stress. The sweat rate sensor is a humidity sensor whose resistance depends on human sweat rate. The alcohol sensor is a chemical–electrical sensor, the resistance of which is determined by the alcohol concentration of human sweat. The skin conductance electrode is a good conductor. Each sensor group has only one skin conductance electrode. Two electrodes in two sensor groups are required to measure human skin. All sensors produce resistive changes, and share the signal conditioning module.

As an example, a Nano-Skin is designed in Figure 2. It has 56 sensor groups in seven rows and eight columns. Each sensor group involves six sensors, a heart rate sensor (HR), a sweat rate sensor (SR), a skin temperature sensor (TE), a gripping force sensor (GF), an alcohol sensor (Al), and a skin conductance electrode (SC). The special IC of Nano-Skin
consists of two terminals for power supply and the other two terminals for signal transmission. Based on the ring size chart of US, the typical diameter of human fingers is in the range 11.95–22.33 mm. When a sensor group is smaller than a 5 mm × 5 mm square, a human finger will simultaneously touch at least two sensor groups. This is very useful to ensure the continuity and consistency of physiological measurement. In the Nano-Skin sensors, except the skin temperature sensors, the other sensors suffer from disturbances such as the temperature change. The signal of skin temperature sensors is required to calibrate the outputs of other sensors. The Nano-Skin involving skin temperature sensors should be firstly manufactured and then evaluated.

4. Manufacture of a Nano-Skin with deposited platinum

A Nano-Skin involves mainly two components, the special IC and the Nano-Skin without special IC. The special IC can be produced using typical IC technologies though it is now unavailable in market. Its manufacture will not be discussed in this paper. This section is focused on manufacturing the Nano-Skin without special IC.

Platinum is a normal metal to use for temperature sensors because of its stable performance. It is safe to humans according to the Food and Drug Administration (FDA) [32]. In order to measure skin temperature, platinum was deposited on the bottom layer of a Nano-Skin using an e-beam evaporator. Parylene was chosen for the bottom layer because it has a large Young’s modulus and yield strength, high dielectric constant, and FDA approved biocompatibility. Figure 3 shows the Nano-Skin with deposited platinum. The nine disks are nine platinum resistance thermometers with different diameters (i.e. 5.95 mm, 3.86 mm, 2.82 mm, 2.36 mm, 2.03 mm, 1.78 mm, 1.60 mm, 1.40 mm, and 1.32 mm). They are connected with the rectangular copper pads along the periphery using a copper interconnection with a width of 0.5 mm. The thickness of sensors, pads, and interconnection is 150 nm. Manufacturing the Nano-Skin with deposited platinum involves mainly preparing the bottom layer, building the interconnection between the sensors and special IC, depositing platinum to produce temperature sensors, and coating the top layer. The process is described in Table 1. In order to perform experiments, the Nano-Skin with deposited platinum was not covered with a top layer, and was not peeled off from the wafer.

The manufacturing process of the Nano-Skin was found to be feasible and repeatable. It has the potential to be expanded to deposit other materials on the bottom layer of a Nano-Skin for building other sensors because depositing other materials uses similar technologies. It is easy to modify the manufacturing process to customize the Nano-Skin for different applications.

Figure 3. The Nano-Skin with deposited platinum, involving nine platinum disks.
Table 1. Manufacturing process of the Nano-Skin with deposited platinum.

| No. | Description                                                                 | Illustration |
|-----|------------------------------------------------------------------------------|--------------|
| 1   | Use piranha solution to clean a silicon wafer.                               |              |
| 2   | Spin and coat a PMMA layer (150 nm in thickness).                            |              |
| 3   | Deposit a parylene layer (10 µm in thickness).                               |              |
| 4   | Spin and coat a Microposit® S1813® photore sist layer (150 nm in thickness). |              |
| 5   | Use a lithograph mask to pattern the photoresist layer.                       |              |
| 6   | Employ Microposit® MF-319 to develop the photoresist layer.                  |              |
| 7   | Use the MRC 8667 sputtering machine to deposit a copper layer.               |              |
| 8   | Employ acetone to lift off the copper layer.                                 |              |
| 9   | Use the MDC E-beam evaporator and a deposition mask to deposit Pt.           |              |
| 10  | Use acetone to peel off the Nano-Skin from the wafer.                        |              |

5. Experiments on a Nano-Skin with deposited platinum

The Nano-Skin with deposited platinum was manufactured. Experiments were required to verify the temperature measurement function of the Nano-Skin and investigate the relation between sensor sizes and sensor performance.

5.1. Experiment apparatus

The experimental apparatus included the Nano-Skin with deposited platinum, interface circuits, a USB6218, a computer, a stopwatch, a power supply, a fan heater, a type K thermocouple, a multimeter, a book, and a Pt1000Ω thermometer (Figure 4).

The Nano-Skin with deposited platinum has nine platinum temperature sensors. Three of them did not work because their resistances were not stable at room temperature (Table 2). The other six sensors worked well, and were tested in the experiments. At different temperatures, the resistances of the six sensors were measured using Wheatstone bridges, the signal of which was amplified using an AD623. The AD623 is a modified...
classic 3-op-amp approach based instrumentation amplifier, and has superior linearity, temperature stability, and reliability in a minimum space. Totally, seven interface circuits were prepared for the six Nano-Skin sensors and Pt1000Ω thermometer. Their signals were acquired and digitized using a data acquisition system, USB6218, which was connected with a computer. The sampling frequency of each signal was 500 Hz. The stopwatch was used to time the experiments. The power supply was employed to afford appropriate power sources for the interface circuits. The function of the fan heater was to blow hot air to apply experiment temperatures to the six Nano-Skin sensors and Pt1000Ω. The experiment temperature increased with a shorter distance between the fan heater and Nano-Skin (i.e. the D in Figure 4). The temperature was monitored using the K type thermocouple and multimeter. Preliminary experiments showed that the hot air from the fan heater achieves a stable temperature at 30 s after turning on the fan heater. The book was used to cut the pathway of hot air before the hot air temperature is stable. The Pt1000Ω thermometer is a commercial temperature sensor, and is used to verify the temperature measurement function of the Nano-Skin.

5.2. Design of experiments

The experiments were designed to verify that: (1) there is a significant difference between the relative resistive changes of the six Nano-Skin sensors and that of Pt1000Ω; (2) there is a significant difference among the relative resistive changes, response times, and recovery times of the six Nano-Skin sensors. The six Nano-Skin sensors and Pt1000Ω are the experiment factor, which has seven levels. Their responses to temperature were tested at temperatures of 19°C, 23°C, 26°C, 30°C, 33°C, 34°C, 37°C, 41°C, 45°C, and 48°C that involved the typical range of human skin temperature. The procedure of the experiments was as follows: (1) measuring the room temperature using the K type thermocouple and
Fan heater works
Place adiabatic board before Nano-Skin
Acquire the voltage of sensors
Remove adiabatic board
Place adiabatic board before Nano-Skin
Fan heater works

Figure 5. The schedule of each experiment.

multimeter, and then acquiring the voltages of the six Nano-Skin sensors and Pt1000Ω for one minute; (2) locating the fan heater at 400 mm away from the Nano-Skin to apply a temperature of 37°C; (3) placing the book between the Nano-Skin and fan heater, and then starting the fan heater when the stopwatch starts at 0 s; (4) beginning the acquisition of the voltages of the six Nano-Skin sensors and Pt1000Ω at 30 s, and then removing the book at 32 s; (5) turning off the fan heater at 150 s, and simultaneously placing the book between the fan heater and Nano-Skin; (6) acquiring the voltages of the six Nano-Skin sensors and Pt1000Ω till 270 s; (7) relocating the fan heater to apply other temperatures to the six Nano-Skin sensors and Pt1000Ω, and then repeating steps (3)–(6) (their schedule is shown in Figure 5); (8) repeating steps (2)–(7) another nine times. In each replication, the nine experiment temperatures were randomly applied.

5.3. Experiment results

Ninety data files were generated in the experiments. As an example, one data file is shown in Figure 6. A MATLAB program, program-A, was established to (1) read the data file and filter the noise, (2) calculate the resistances of the six Nano-Skin sensors and Pt1000Ω at nine temperatures, and (3) find their relative resistive change, response time, and recovery

Figure 6. The voltages of the six Nano-Skin sensors and Pt1000Ω at 30°C.
time at nine temperatures. Another MATLAB program, program-B, was coded to compare the relative resistive changes of the six Nano-Skin sensors with that of Pt1000Ω, and compare the relative resistive changes, response times, and recovery times of the six Nano-Skin sensors with each other using the analysis of variance (ANOVA).

In each experiment, the initial resistance of a sensor, \( R_{\text{ave}_0} \), was the average resistance of the sensor between 30 and 32 s. The resistance of the sensor at a temperature, \( R_{\text{ave}_1} \), was the average resistance of the sensor between 90 and 150 s. The relative resistive change of the sensor at a temperature

\[
\Delta R_{\text{relative}} = \frac{R_{\text{ave}_1} - R_{\text{ave}_0}}{R_{\text{ave}_0}}.
\]  

The response time of the sensor, \( T_{\text{response}} \), is the interval from the time that a temperature is applied to the time that the resistance of the sensor changes to \( R_{\text{ave}_1} \). The recovery time of the sensor, \( T_{\text{recovery}} \), is the interval from the time that the temperature is removed to the time that the resistance of the sensor recovers to \( R_{\text{ave}_0} \).

The relative resistive changes of the six Nano-Skin sensors and Pt1000Ω at nine temperatures are illustrated in Figure 7. The \( \Delta R_{\text{relative}} \) of the six Nano-Skin sensors was compared with that of Pt1000Ω using ANOVA (significance level \( \alpha = 0.05 \)). All \( p \)-values are less than 0.05. The result verified that the \( \Delta R_{\text{relative}} \) values of the six Nano-Skin sensors are significantly different from the \( \Delta R_{\text{relative}} \) of PT1000Ω at the nine experiment temperatures (Figure 8). The six Nano-Skin sensors are able to produce larger relative resistive changes than PT1000Ω for the same temperature change. The accuracy of the six Nano-Skin sensors will not be lower than the PT1000Ω.

Figure 9 shows the ANOVA (\( \alpha = 0.05 \)) result of comparing the \( \Delta R_{\text{relative}} \) values of the six Nano-Skin sensors with each other at nine temperatures. For example, the ANOVA result of the outputs of the Nano-Skin sensors #1 and #3 is 0.01 at 26°C, and 0.03 at 30°C. At eight temperatures, the \( \Delta R_{\text{relative}} \) of sensor #1 is significantly smaller than the \( \Delta R_{\text{relative}} \) values of the other sensors. The \( \Delta R_{\text{relative}} \) values of sensors #7 and #8 are statistically larger than the \( \Delta R_{\text{relative}} \) values of the other sensors. In the six Nano-Skin sensors, smaller sensors can produce larger relative resistive change for same temperature change.

The ANOVA (\( \alpha = 0.05 \)) result of comparing the response time of the six Nano-Skin sensors at nine temperatures is illustrated in Figure 10. All \( p \)-values are larger than 0.05. This result indicated that there is no significant difference among the response times of the six Nano-Skin sensors at the nine experiment temperatures. Changing the sizes of the six Nano-Skin sensors will not affect the response time of the Nano-Skin sensors.

![Figure 7](image-url)  
Figure 7. The \( \Delta R_{\text{relative}} \) values of the six Nano-Skin sensors and Pt1000Ω at nine temperatures.
Figure 8. ANOVA ($\alpha = 0.05$): comparing $\Delta R_{\text{relative}}$ values of the six Nano-Skin sensors with that of PT1000Ω at nine temperatures.

Figure 9. ANOVA ($\alpha = 0.05$): comparing $\Delta R_{\text{relative}}$ values of the six Nano-Skin sensors at nine temperatures. (The columns with a height of 0.055 illustrate the p-values over 0.05.)
Figure 10. ANOVA ($\alpha = 0.05$): comparing $T_{\text{response}}$ values of the six Nano-Skin sensors at nine temperatures. (The columns with a height of 0.055 illustrate the $p$-values over 0.05.)

The ANOVA ($\alpha = 0.05$) of comparing the recovery times of the six Nano-Skin sensors at nine temperatures produced the results shown in Figure 11. A few $p$-values are less than 0.05. It was proved that the recovery times of the Nano-Skin sensors #1, #3 and #5 are significantly different from those of the other Nano-Skin sensors only at some experiment temperatures. Generally, the sensor sizes have limited effect on the recovery time of the sensors.

6. Conclusions

The human state in human–machine systems is one of the main factors that affect their system performance. Human physiological cues have a more direct relation with the human state than machine dynamic cues, and thus are preferred in human state recognition. It is possible to measure the physiological cues on human–machine contact surfaces. The human–machine contact-based physiological measurement can be performed using a Nano-Skin that mimics the distributed sensing capability of human skin. The Nano-Skin is flexible, and can be attached to any machine surface. It is embedded with a dense network of sensors, and mainly involves a flexible bottom layer, sensors, a special integrated circuit, interconnection, and a flexible top layer. The sensors are connected with the special integrated circuit via the interconnection. Their signals are acquired, processed, and then transmitted using the special integrated circuit. This study investigated the manufacture of a Nano-Skin with deposited platinum. The manufacturing process of the Nano-Skin
Figure 11. ANOVA ($\alpha = 0.05$): comparing $T_{\text{recovery}}$ values of the six Nano-Skin sensors at nine temperatures. (The columns with a height of 0.055 illustrate the $p$-values over 0.05.)

was found to be feasible and repeatable. The experiments of the Nano-Skin with deposited platinum verified that, for same temperature change, the Nano-Skin sensors are able to produce larger relative resistive change than Pt1000Ω. Smaller Nano-Skin sensors possibly produce larger relative resistive change than the other Nano-Skin sensors. The sizes of the Nano-Skin sensors do not affect their response time, and have a little effect to their recovery time. A Nano-Skin offers an appropriate approach to non-intrusively measure human physiological cues on human–machine contact surfaces for human state recognition.

Acknowledgments
This work has been supported by NSF CMMI Sensors and Sensing Systems (SSS) program through a CAREER Award (# 0954579). The authors would like to thank Dr. S. C. Liu, the SSS Program Director, for his kind support to the research.

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