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Prediction of thermal sensation using low-cost infrared array sensors monitoring system

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Abstract. Using skin temperature to predict thermal comfort typically results in higher accuracy of thermal comfort prediction compared to other methods, however, such nonintrusive thermo-graphic cameras with high resolution/accuracy are more expensive compared to the thermistors with single point. Thus, a low-cost (and low resolution) thermal camera MLX90640 was studied in this study to predict individual thermal comfort, and compared with the prediction results from high accuracy thermocouple at single point of somewhere of localized body skin. Results show that the low-cost (low resolution) infrared camera (MLX90640) with accuracy of ± 2 °C and resolution of 32×24 pixels is able to be used to predict thermal sensation with a performance better than skin temperature measure system including thermocouples at different points of skin with an accuracy of ± 0.15 °C. And the performance of infrared camera (MLX90640) is as good as the performance of environmental air temperature sensor with accuracy of ± 0.10 °C. Thus, the usage of low-cost (and low resolution) thermal camera to predict individual thermal comfort worth to be further studied.

1. Introduction

The PMV and adaptive comfort models are based on averaged responses from a large population and are unable to accommodate the differences in estimating thermal comfort responses of individuals (1). In order to overcome the limitations of the PMV and adaptive comfort models, several researchers developed methods to model and predict thermal sensation, preference or satisfaction at an individual level (2-4). Such models typically rely on different sensors to monitor environmental parameters (5), such as air temperature, humidity, mean radiant temperature or physiological parameters(6), such as skin temperature to build individual comfort models using different Machine Learning (ML) techniques. The individual comfort predictions from the models could be also used to control HVAC systems or other Personal Comfort Systems (PCS) to improve occupant comfort and satisfaction with indoor thermal environments (7).

With the recent advancements in Internet of Things (IoT), collecting physiological data using different wearable and/or non-wearable devices is becoming prevalent. This has led to an increase in studies focused on predicting thermal sensations from physiological parameters, such as heart rate (8), blood pressure(9), skin temperature(10) from different locations, such as wrists, face, back, legs monitored using wearable devices (11). Recent studies have also considered monitoring skin temperature using nonintrusive methods such as infrared thermal imaging (12) (13). Using skin temperature to predict thermal comfort typically results in higher accuracy of thermal comfort prediction



compared to other methods, however, such nonintrusive thermo-graphic cameras with high resolution/accuracy are more expensive compared to the thermistors with single point. Moreover, privacy concerns surrounding the use of physiological data may limit user acceptability (14), which could be avoided by using a low resolution thermal camera in this study, as Table 1 shows.

Thus, in this study, we evaluate the accuracy using a low-cost (and low resolution) thermal camera to predict individual thermal comfort.

2. Method or Experimental

2.1 Selection of thermal sensors for skin temperature

Table 1. Comparison of skin temperature measurement devices in different studies.

Studies	Device	Type	Accuracy	Resolution	Cost
(15)	MP150-SKT100C System (BIOPAC)	thermistor	± 0.1 °C	Single point	~\$4,000 (system) ~\$300 (1 sensor)
(16)	Corre Dermalab System	thermistor	± 0.2 °C	Single point	~\$1,200
(17)	MLX90614 thermometer	Infrared	± 0.5 °C	Single point	~\$150
(18)	FLIR A655sc camera	Infrared	± 2 °C	640 × 480	~\$22,000
(19)	FLIR A35 camera	Infrared	± 5 °C	320 × 256	~\$5,000
(13)	FLIR lepton 2.5	Infrared	± 5 °C	80 × 60	~\$200
This study	MLX90640 HOBO U120-006M with TMC6-HD	Infrared thermistor	± 2 °C ± 0.15 °C	32 × 24 Single point	~\$100 ~\$500 (four sensors)

Thermocouples with an accuracy of ± 0.15 °C connected to a four-channel data logger (HOBE, UX120-006M) were used to measure the local skin temperature of the subjects. The skin temperature information was automatically recorded to the data logger every 2 s. This parameter was measured at 6 points, including the forehead, chest, upper arm, hand, calf, and thigh. Prior to the measurements, all the thermocouples were calibrated. On the basis of reliability and sensitivity, a four-point formula proposed in the literature (20) was used to calculate the mean skin temperature (T_{skin}), which can be expressed as:

$$T_{skin} = 0.3T_{chest} + 0.3T_{upperarm} + 0.2T_{thigh} + 0.2T_{calf} \quad (1)$$

A low-cost thermal camera MLX90640 with accuracy of ± 2 °C and resolution of 32 × 24 pixels was also used to monitor the maximum surface skin temperature at head and hand and the lowest surface background temperature.

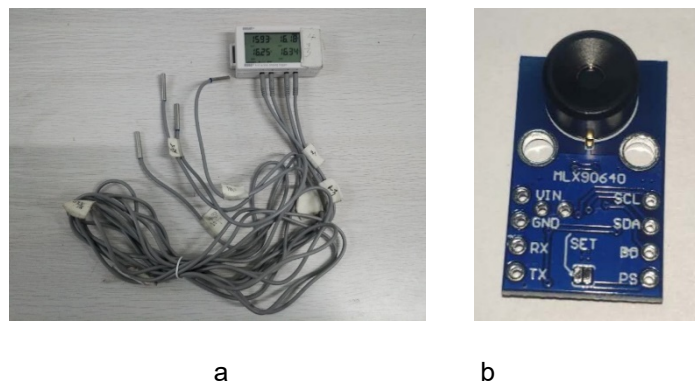


Figure 1. Thermal sensors: a) Thermocouples with HOBO; b) Infrared camera MLX90640

2.2 Experimental setup

Experiments were conducted in a climate chamber (Room 1.4 m × 3 m × 2.7 m (H)) where the room air temperature (T_a) was adjustable within the range of $-5\text{ }^{\circ}\text{C}$ to $40\text{ }^{\circ}\text{C}$ with an accuracy of $\pm 0.30\text{ }^{\circ}\text{C}$. The RH was controlled between 10%–90% with an accuracy of $\pm 5\%$. Thermal Comfort Monitoring Station equipment (LSI) was used to measure environmental parameters such as the indoor air temperature with accuracy of $\pm 0.1\text{ }^{\circ}\text{C}$, RH, air velocity and black-bulb temperature in the vicinity of the subjects. This station was capable of recording measurements and storing the data in a data logger.

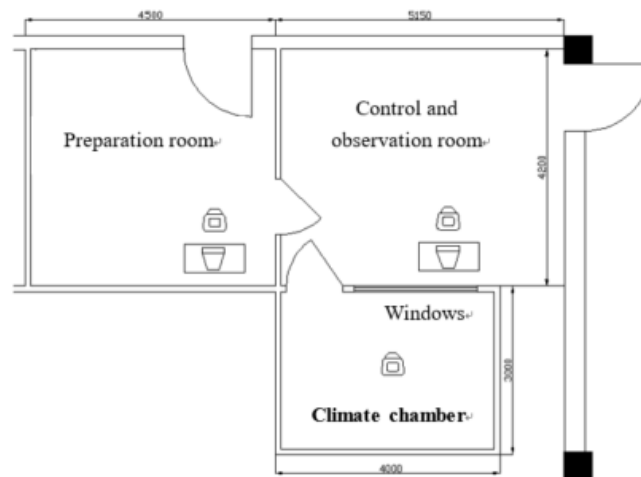


Figure 2. Climate chamber and the surrounding chamber layout. (The units of the dimensions: mm)

2.3 Subject characteristics

Power analysis, which was introduced by Lan and Lian (21), was helpful in determining the required sample size as well as the interpretation of the research results. Thus, the minimum sample size was obtained using the prior power analyses in G*Power 3.1 (22, 23), with the same setting parameters as previous studies(15) except the power ($1-\beta$ error) was set to be 0.95. For the statistical test (ANOVA: repeated measures, within factors), the minimum sample size was determined based on the effect size d ; the minimum sample sizes were 6, 8 and 10 when $d = 1, 0.8$ and 0.5 , respectively. In this study, the physiological responses were assumed to be relatively stable, thus, a minimum sample size of 8 subjects as a group ($d = 0.8$) was adopted and would be verified in Results Section 4.1.

A total of 16 gender-balance subjects participated in the experiments, with 8 college students and 8 middle-aged persons. All the subject lived in Chongqing for at least one year and could be considered to be thermally acclimated to the hot weather. The subject's basic information (e.g. age, height, weight) are summarized in Table 2. The middle-aged participants were recruited from the local residents, who lived in Chongqing for an average of 25.11 ± 15.84 years. None of the subjects were under prescription medication during the study and there was no history of cardiovascular disease among them. Subjects were asked to avoid caffeine, alcohol, and intense physical activity for at least 12 hours prior to the tests.

Table 2. Summary of information on human subjects in the climate chamber study.

Gender	Age (year)	Height (cm)	Weight (kg)
Male	23.6 \pm 1.0	171.8 \pm 4.0	60.7 \pm 4.8
Female	23.7 \pm 1.1	161.4 \pm 7.5	47.9 \pm 6.6
All	23.6 \pm 1.0	166.3 \pm 8.0	53.9 \pm 8.7

2.4 Experiment conditions

Firstly, they arrived in a preparation room and rested there for approximately 30 min at 26 °C to alleviate the thermal experience effect. At the meantime, their height, weight and body fat rate were measured using a height and weight scale (SUHONG) and body fat meter (TANITA BC-601), their personal information such as age, gender and length of residence were interviewed, as Table 3 shows. They were also instructed on the use of the physiological monitors and the process of completing the questionnaires. Subsequently, they entered the climate chamber where the room air temperature step changed beginning with 24 °C for 30 min, 20 °C for 60 min and 16 °C for 60 min. In this chamber, questionnaire describing their thermal perception and physiological measurements were performed every 15 min. During the experiments, the subject wore typical winter clothing including jackets, long sleeve underwear and leggings, shirt, trousers, thin sweaters, socks, shoes with an insulation level of about 1.2 clo (1 clo=0.155 m²·K/W) according to the ASHRAE Standard 55 (1). The thermal sensation vote (TSV) was quantified by using the ASHRAE 7-points scale (1), i.e., -3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot.

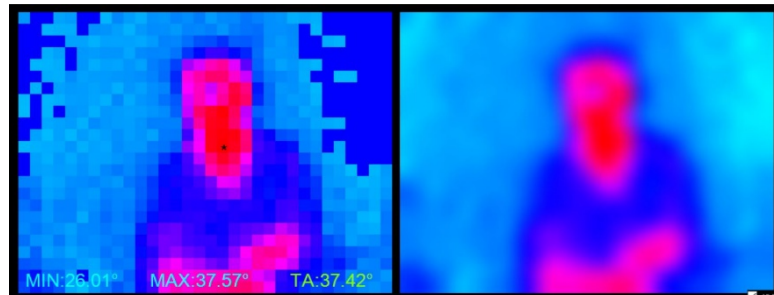


Figure 3. Subject in the experiment

Figure 4. Thermal image from infrared camera MLX90640

3. Results and discussion

3.1 Performance of the thermal camera

Thermal image from infrared camera MLX90640 was showed in Fig. 4, as we can see it is difficult to identify the person while the surface temperature of human was easy to extract from the thermal camera, the maximum surface temperature at face region and hand was used in this study, as well as the surface temperature of background.

3.2 Thermal environment and skin temperature

The air and skin temperatures with time using different thermal sensors were showed in Fig. 5. The air temperature was started from 24 °C for first 30 min, at 20°C from 60 – 90 min and ended at 16 °C from 120 -150 min. The background surface temperature was also monitored by the infrared camera MLX90640, which showed similar trend but different value with the air temperature, i.e. was started from about 24 °C for first 30 min, at 22 °C from 60 – 90 min and ended at about 19 °C from 120 -150 min. The overall skin temperature, and localized skin temperatures including head and hand measured by thermocouples (HOBO) and infrared camera (MLX90640) were both positively changed with the air temperature. While the values of localized skin temperatures were much higher by the infrared camera (MLX90640) than the thermocouples (HOBO), for the thermocouples (HOBO) constantly measured one point of skin to represent localized body part, while infrared camera (MLX90640) could record the highest temperature in the localized body part as a localized skin temperature value.

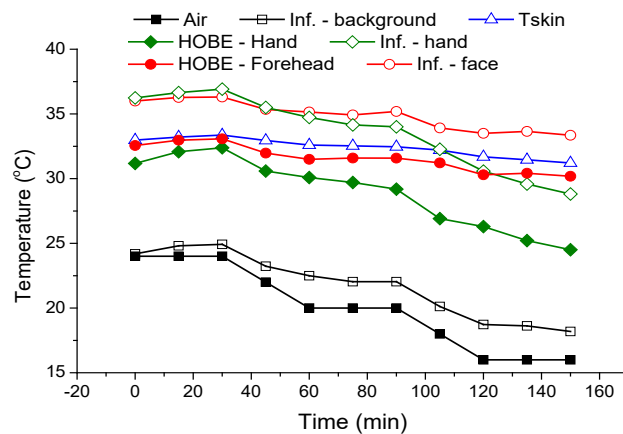


Figure 5. The air and skin temperature with time using different thermal sensors

3.3 Thermal sensation vote

The overall TSV with time are showed in Fig. 6. The overall TSV was started from about 1.4 for first 30min, decreased to about zero at 60 - 90min and ended at about -0.9 ± 0.1 from 120 -150min. The localized TSV of head and hand was similar with the overall TSV in fist 90min, while the head TSV was higher and the hand TSV was lower than that of overall TSV at 90 -150min in the cool environment.

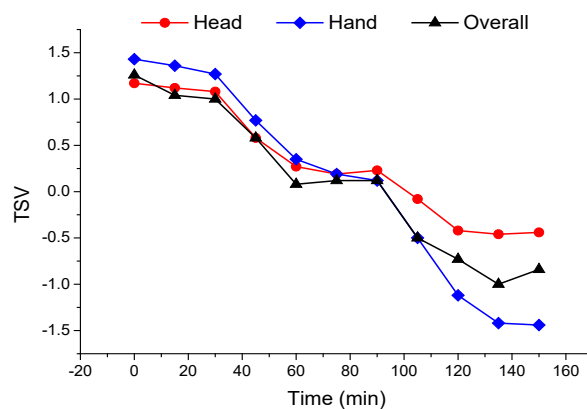


Figure 6. The overall TSV with time

3.4 Predictions of overall TSV

The relationship between TSV and temperature measured by different sensors are showed in Fig. 7. The highest R2 were 0.98, with the air temperature sensor (accuracy ± 0.1 °C) and face temperature by infrared camera (MLX90640, accuracy ± 2 °C). To predict overall TSV by face (0.98) and hand (0.91) skin temperature with the infrared camera (MLX90640) performed better than by forehead (0.92) and hand (0.90) skin temperature with thermocouple at single point of somewhere of localized body skin.

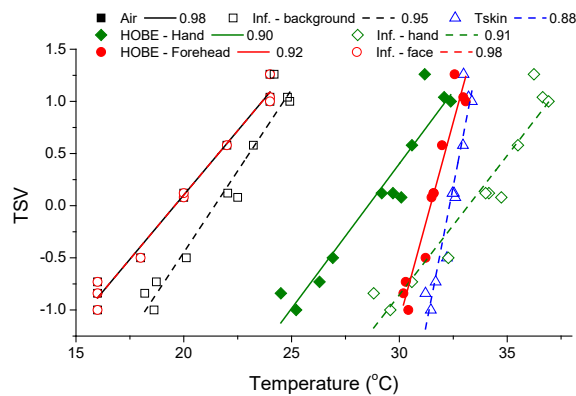


Figure 7. The relationship between TSV and temperature measured by different sensors

4. Conclusions

A conclusion should be drawn that the low-cost (low resolution) infrared camera (MLX90640) with accuracy of ± 2 °C and resolution of 32×24 pixels is able to be used to predict thermal sensation with a performance better than skin temperature measure system including thermocouples at different points of skin with an accuracy of ± 0.15 °C. And it is as good as environmental air temperature sensor.

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