INTEGRATED IR VISION SENSOR FOR ONLINE CLOTHING INSULATION MEASUREMENT

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Abstract. As one of the most important building systems, HVAC plays a key role in creating a comfortable thermal environment. Predicted Mean Vote (PMV), an index that predicts the mean value of the votes of a large group of persons on the thermal sensation scale, has been adopted to evaluate the built environment. Compared to environmental factors, clothing insulation can be much harder to measure in the field. The existing research on real-time clothing insulation measurement mainly focuses on expensive infrared thermography (IR) cameras. Therefore, to ensure cost-effectiveness, the paper has proposed a solution consisting of a normal camera, IR and air temperature sensors and Arduino Nanos to measure clothing insulation in real-time. Moreover, the algorithm includes the initialization from clothing classification with pre-trained neural network and optimization of the clothing insulation calculation. A total of 8 tests have been conducted with garments for spring/fall, summer and winter. The current results have shown the accuracy of T-shirt classification can reach over 90%. Moreover, compared with the results with IR cameras and reference values, the accuracies of the proposed sensing system vary with different clothing types. Research shall be further conducted and be applied into the dynamic PMV-based HVAC control system.

Keywords. Clothing insulation; skin temperature; clothing classification; IR temperature sensor; Optimization.

1. Introduction

As one of the most important building systems, HVAC plays a key role in creating a comfortable thermal environment. Because there are large variations of thermal comfort from person to person, it is difficult to satisfy everyone in a space. Therefore, Predicted Mean Vote (PMV), an index that predicts the mean value of the votes of a large group of persons on the thermal sensation scale, has been adopted widely to evaluate if the environment is comfortable or not for most of occupants. Moreover, the well-known Fanger's equation describes the relation between PMV and six primary factors, which are metabolic

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rate, clothing insulation, air temperature, mean radiant temperature, air speed and relative humidity. Compared to environmental factors, personal factors of clothing insulation and metabolic rate can be much harder to measure in the field. According to (ASHRAE 55, 2010), for near-sedentary activities where the metabolic rate is approximately 1.2 met such as in office areas, the effect of changing clothing insulation on the optimum operative temperature can reach approximately 6 C per clo. Therefore, the effect of clothing insulation on thermal comfort outweighs that of metabolic rate in typical office environment.

As to clothing insulation, most of the existing methods assume the values to be fixed by using thermal mannequins or developing some complex and time-consuming insulation models or predict them from the outdoor air temperature and the indoor operative temperature(Schiavon & Lee, 2013). Hence, none of them reflects the real conditions in the field and can be applied into dynamic HVAC operations. Moreover, the existing research on real-time clothing insulation measurement mainly focuses on using infrared thermography (IR) cameras so as to develop a non-invasive sensing system. However, IR cameras are still expensive in the market compared with other sensors such as IR temperature sensors. Therefore, this paper has proposed a real-time vision-based clothing insulation measurement method without IR camera for thermal comfort.

To ensure cost-effectiveness of the sensing system, unlike previous research, the proposed solution consists of a webcam, IR temperature sensors, air temperature sensors and Arduino Nanos. The total cost of the system is less than $150 while the price of a FLIR ONE Pro IR camera for smart phones could be as high as $399. Meanwhile, the algorithm of the proposed solution includes the initial clothing insulation measurement from clothing classification with the pre-trained neural network and non-linear optimization of the clothing insulation calculation based on ISO 7933 (ISO 7933, 2004).

The test bed is located in a typical private office room where occupants do not have large metabolic rates and relative humidity keeps steadily around 25%, thus the effects of moisture on clothing insulation being negligible. Moreover, the air velocity keeps lower than 0.1 m/s for the whole experiments. A total of 8 tests have been conducted with garments for spring/fall, summer and winter seasons, respectively.

2. Methodology

The real-time and in-situ clothing insulation estimation consists of two parts. The first part is the initialization with clothing classification and the second part is the estimation refinement. The following diagram shows the whole procedure of clothing insulation measurement.

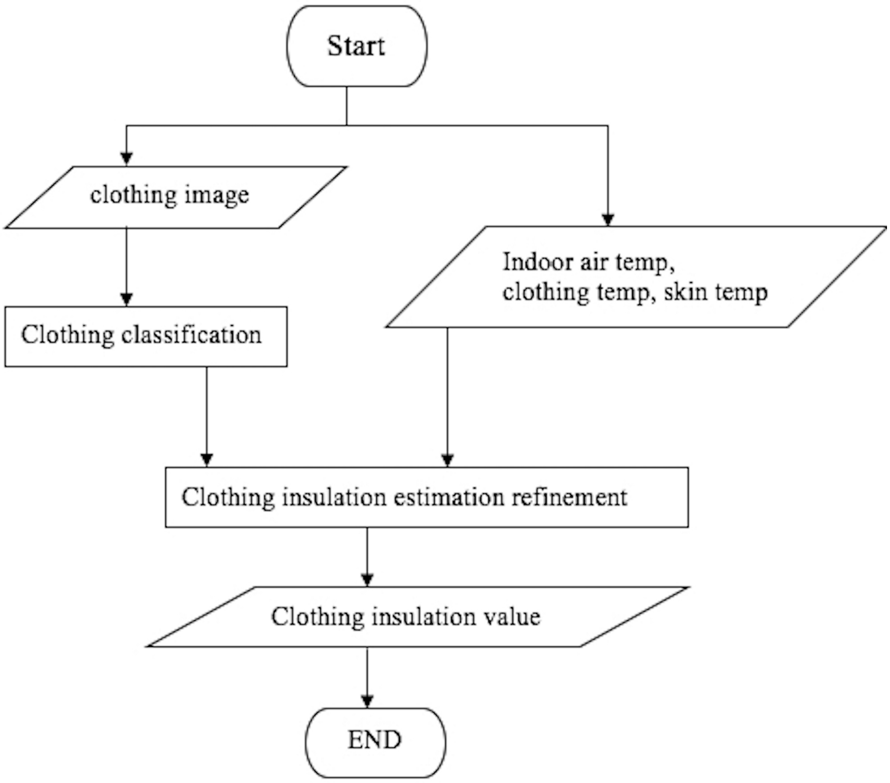

Figure 1. Diagram of real-time and in-situ clothing insulation estimation.

2.1. CLOTHING INSULATION ESTIMATION INITIALIZATION WITH CLOTHING DETECTION

The initialized value of clothing insulation was achieved by using pre-trained classifier of GoogLeNet (Szegedy et al., 2015) trained with all classes from ImageNet datasets. In addition, a general garment insulation table (ASHRAE 55, 2010) was used for clothing insulation initialization to map the classified clothing type with the clothing insulation.

2.2. CLOTHING INSULATION ESTIMATION REFINEMENT BASED ON ISO 7933 (ISO 7933, 2004)

Under static state conditions, there are no movements of the air or of the person. Therefore, the total static insulation expressed in Eq.1 is the sum of clothing insulation and the insulation of enclosed air layers under static conditions.

$$I_{tst} = I_{clst} + \frac{I_*}{f_{cl}} \qquad (1)$$

where I_{tst} is the total static thermal insulation, I_{clst} is the static clothing insulation,

$I_*$is the static air insulation (estimated as 0.111 m^2KW^{-1}). In addition, f_{cl} is the clothing area factor, which is the ratio of the clothed and naked-skin surface areas, which can be calculated with the static clothing insulation (I_{clst}) in Eq.2:

$$f_{cl} = 1 + 1.97 I_{clst} \quad (2)$$

Based on the unit conversion from m^2KW^{-1} into clo, the total static clothing insulation can be represented with I_{cl} with the unit of clo in Eq.3:

$$I_{tst} = 0.155 I_{cl} + \frac{I_*}{1 + 0.305 I_{cl}} \quad (3)$$

However, for in-situ measurement, the thermal state shall be dynamic. Therefore, when taking air movement into consideration, the dynamic air thermal insulation and the total dynamic clothing insulation shall be calculated with dynamic air correction factor of C_{ia} and dynamic total clothing correction factor of C_t, respectively. In the end, based on the proposed algorithm of (Lee et al., 2016), the clothing insulation of I_{cl} can be estimated in real-time based on the non-linear function of Eq. 4:

$$0.305 I_{cl}^2 + I_{cl} - \frac{1}{0.155 C_t}\{\alpha + I_*(C_{ia} - C_t)\} = 0 \quad (4)$$

$$\alpha = \frac{t_{sk} - t_{cl}}{h_c(t_{cl} - t_a) + 3.85 \cdot 10^{-8}(t_{cl}^4 - t_r^4)} \quad (5)$$

$$h_c = 12.1\sqrt{v_{ar}} \quad \text{if} \quad 2.38|t_{cl} - t_a|^{0.25} \leq 12.1\sqrt{v_{ar}} \quad (6)$$

$$C_t = C_{cl} \quad \text{if} \quad I_{cl} \geq 0.6 \quad (7)$$

$$C_t = I_{cl}\frac{C_{cl} - C_{ia}}{0.6} + C_{ia} \quad \text{if} \quad I_{cl} < 0.6 \quad (8)$$

where C_{cl} is the correction factor of dynamic clothing insulation, which can be calculated in Eq.9:

$$C_{cl} = e^{-0.263(v_{ar}-0.15)+0.0272(v_{ar}-0.15)^2+0.193v_w+0.101v_w^2} \quad (9)$$

$$C_{ia} = e^{-0.559(v_{ar}-0.15)+0.057(v_{ar}-0.15)^2+0.271v_w-0.027v_w^2} \quad (10)$$

Therefore, with the inputs of skin temperature (t_{sk}), clothing temperature (t_{cl}), indoor air temperature(t_a), mean radiant air temperature(t_r), air velocity($v_a r$) and walking velocity(v_w), the clothing insulation of I_{cl} shall be estimated by minimizing the result of left-hand side of Eq.(4) close to zero as much as possible and the outputs of clothing insulation estimation can be used for applications like PMV-based HVAC control.

3. Experimental setup

The proposed sensing system consists of a webcam, two IR temperature sensors (tmp006), one air temperature sensors (DHT11) and two Arduino Nanos. One of the IR temperature sensors was used to measure the neck or the ankle temperature while the other was used to measure the clothing temperature. Moreover, one of the Arduinos was used to transfer temperature data from the air temperature sensor to the monitor while the other was used to transfer temperature data from IR temperature sensors to the monitor. In addition, in order to compare the performances with IR camera, a FLIR B-series thermal camera was also used. The IR temperature sensors read a sample of clothing temperature or skin(neck) temperature every 4s and the air temperature sensors read a sample every 2.5s. The sensing system of air temperature sensors and IR temperature sensors is shown in the following figures. In addition, since all the participants are standing, the walking velocity is 0 m/s and the air velocity is assumed to be 0.1 m/s all the time.

3.1. SENSORS

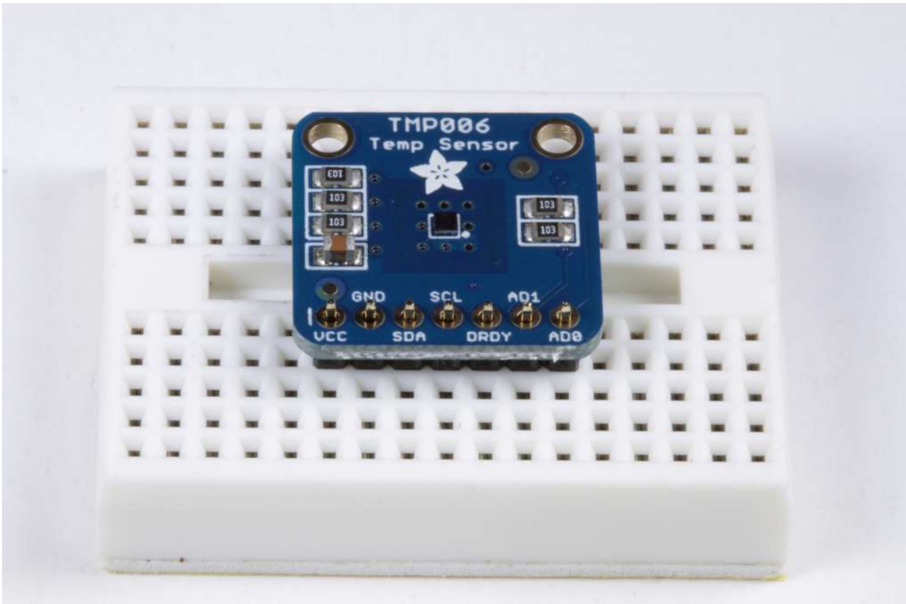

Figure 2. IR temperature sensors(tmp006).

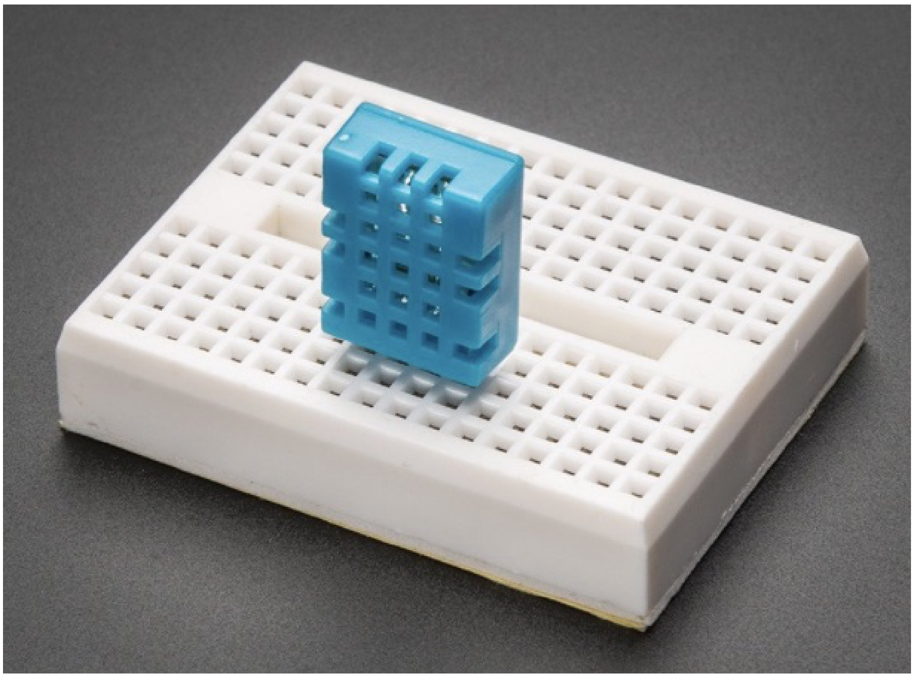

Figure 3. Indoor air temperature and humidity sensor (DHT11).

3.2. CLOTHING TESTING IMAGES

The following figure shows a total of 8 tested clothing images, including garments in all the different seasons, which are shirts, long-trousers, sweatshirt, T-shirt, walking shorts, jeans and an ensemble of a sweater and a shirt. Even if the general table in ASHRAE 55 was used for clothing insulation initialization, it was also used as reference value to roughly evaluate the accuracies of real-time clothing insulation estimation with the proposed solution and IR camera. However, more robust ground truths of clothing insulation shall be collected in the further research.

Figure 4. A total of 8 different garments.

4. Result analysis

4.1. CLOTHING DETECTION

The following table shows the performances of clothing classification of part of clothing garments with the pre-trained neural network. As shown in the table, the accuracies vary a lot for different garments. One of the reasons is that since the pre-trained classifier includes all 1000 classes, it classifies the image into the class with the highest probability, which is not limited within classes related to clothing types.

Table 1. Performances of clothing detection.

clothing detection	Accuracy
T-shirt	95%
jeans	67%
sweater	17%

4.2. CLOTHING INSULATION ESTIMATION

The following table shows the performances of real-time and in-situ clothing insulation measurements with the proposed sensing system and IR camera. The ID numbers correspond with the numbers in Figure 3. As shown in the table, due to different materials (i.e. the cotton shirt), some of the initialized values from ASHRAE 55 cannot be used as reference values. Moreover, compared with IR camera, 80% of the estimated values with the proposed system is closer to the reference values, which indicates the initialized clothing insulation could achieve fast convergence of the non-linear function of left-hand side of Eq.4. Moreover, the proposed sensing system is more cost-effective than IR camera. However, compared with IR camera, multiple IR temperature sensors were implemented to get the average clothing temperature or skin temperature (i.e. skin temperature of the neck for upper clothing while that of the ankle for lower clothing). It took longer time to get steady temperature values with the proposed solution than IR camera and the distance between IR temperature sensors and the participants has to be much smaller than that between IR camera and the participants.

Table 2. Performances of clothing insulation measurements.

		clothing insulation [clo]					
ID	clothing type	proposed measurement	IR thermography	reference	season	indoor air temperature [C]	mean radiant temperature [C]
1	shirt	0.25	0.91	0.25	spring	22	20
2	shirt(cotton)	0.66	0.77		spring	22	20
3	long trousers	0.18		0.15	spring	22	20
4	sweatshirt	0.27	0.39	0.34	spring	22	20
5	T-shirt	0.18	0.31	0.08	summer	22	20
6	walking shorts	0.13	0.24	0.08	summer	22	20
7	sweater+shirt	0.83	1	0.81	winter	22	20
8	jeans	0.2	0.21		winter	22	20

5. Discussions

Based on the results of clothing insulation estimation, the proposed sensing system can be used for estimation in real time. However, further research could be done to enhance the performances. Firstly, instead of using the general table from ASHRAE 55, more accurate ground-truths of clothing/garments shall be collected with either simulations or more detailed experiments. Secondly, instead of using pre-trained GoogLeNet with all classes, the clothing classification system shall be trained with only clothing classes to increase the accuracy of classification. Last but not least, due to the effects of dynamic air layers and wide angles of the IR temperature sensors, the measured skin temperatures and clothing temperatures with the current proposed system does not become steady within 2 minutes and the distance between the IR temperature sensors and the participants has to be limited. Therefore, further research could also be done to mitigate the effects of dynamic air layers and wide angles so as to increase the distances as well as decrease the measuring periods. Moreover, the current experimental space is a private office room with one single participants. It is also interesting to see how to measure clothing insulation with multiple people in an open plan office. Since the IR temperature sensors need to be close to the surface, it could be a potential to develop a portable sensing device or embedded into existing furnitures to measure online clothing insulation of each individual in an open plan office.

6. Conclusions

This paper has proposed a new sensing system for in-situ and real-time clothing insulation estimation for applications such as PMV-based HVAC control system to enhance the thermal environment indoors. A total of 8 tests have been conducted with garments for spring/fall, summer and winter. Compared with the results of IR thermography and reference values, the accuracies of the proposed sensing system vary with different clothing types. Research shall be further conducted to enhance the performances of real-time clothing insulation estimation with the proposed sensing system in terms of accuracy and cost-effectiveness.

Acknowledgement

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