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ABSTRACT

The purpose of this paper is to evaluate the performance of a novel office temperature control system. To make occupants more comfortable with less energy, we have been developing a new system that uses an inexpensive infrared camera to evaluate occupants' thermal sensation and optimize room temperature. The system (1) detects the positions of a person's face, nose, and hands in a thermal image taken by an infrared camera and measures temperatures in those areas; (2) predicts thermal sensation using measured skin temperatures; and (3) adjusts an HVAC set-point temperature based on the predicted sensation to optimize occupant thermal comfort. We compared the comfort and energy performance of the new system to conventional control using a fixed setpoint of 72.0 °F (22.2 °C) in a small conference room. The results indicate that the conventional control often overcooled the occupants, whereas our system reduced cooling energy consumption and made the occupants more thermally neutral and comfortable than the conventional control.

1 INTRODUCTION

Delivering a thermally comfortable indoor environment is a primary goal of building HVAC (heating, ventilation, and air conditioning) systems. However, traditional HVAC control systems regulate air temperature, rather than thermal comfort, and operators select temperature setpoints based on thermal comfort standards such as ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 55 (ASHRAE, 2017b), or the operators' judgments. Many studies have documented high levels of discomfort and inefficient HVAC system operation in commercial buildings (Schiavon et al., 2017). Overcooling is a representative example: occupants in commercial buildings may feel cool during summer while HVAC systems are wasting considerable energy to overcool the space (Derrible & Reeder, 2015; Mendell & Mirer, 2009; Parkinson et al., 2021). To address this issue, we have been developing a new sensor/control system that combines an inexpensive infrared camera, comfort model, and control algorithm. It aims to directly estimate occupants' thermal sensation and determine the optimum room temperature set-point. This paper describes a multi-month field trial of our system conducted in an office near Houston, Texas.

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2 METHOD

2.1 System

Figure 1 shows a photo of the server device and Figure 2 illustrates the diagram of proposed closed-loop control. The newly developed system is based on previous research findings showing that skin temperature is a good indicator of thermal sensation (Fanger, 1970; Wang et al., 2007; Zhang et al., 2010) . The system consists of an image server that captures color and thermal images and an image client that (1) detects the positions of a person's face, nose, and hands in the thermal image and measures temperatures of those areas; (2) predicts thermal sensation using temperature differences between the face and nose or face and hands; and (3) adjusts the HVAC set-point temperature to optimize comfort and energy use. The device used to capture the images is a small single-board computer that drives two color cameras and one thermal camera. The cameras have a pan/tilt function to adjust the camera direction based on occupant location (right side in the image in Figure 1); a wide-view fish-eye camera and small temperature reference board are attached for future development (left side in the image in Figure 1). Details of this system will be published separately.

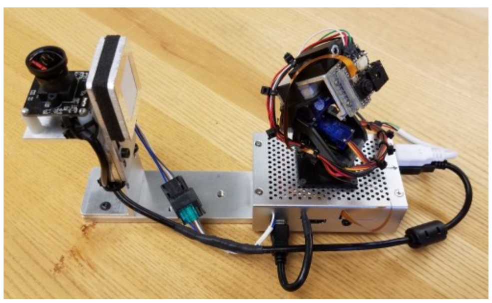


Figure 1 Photo of server device, including color and thermal cameras, a wide-view fish-eye camera and small temperature reference board.

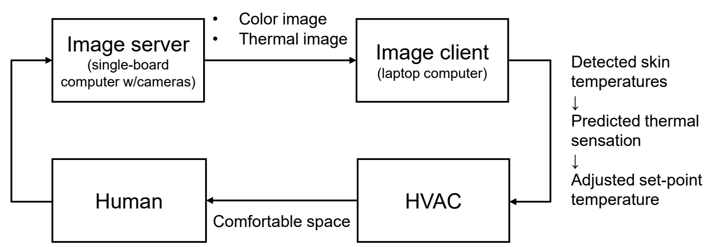


Figure 2 Diagram of proposed closed-loop control. This control estimates occupants' thermal sensation and determines an optimum room temperature set-point.

2.1.1 Detection algorithm (sensors). The feature detection is inspired by previously developed software that detects the location of the face and nose in color and thermal images (Ghahramani et al., 2022), but uses new algorithms to locate the subject's face, nose, and hands. Since the skin temperature of the extremities, such as hands and feet, tend to be more thermally sensitive to the ambient environment than other regions of the body, using the skin temperature of hands in addition to those of the face and nose can enhance the accuracy of thermal comfort predictions. The system takes color and thermal images in the server and streams those images to the client. It then processes the images in the client to detect the location of a person's face, nose, left hand, and right hand in the thermal infrared image; obtain the temperatures of pixels within the regions of the detected areas; and computes temperature statistics such as maximum, minimum, and median values within each region.

2.1.2 Thermal sensation prediction (comfort model). In this field trial, we used a previously developed machine learning-based method for predicting thermal sensation (He et al., 2022). He et al. proposed various models with local skin temperatures as input conditions in the paper, but in this study, we used one of two models depending on whether at least one hand was detected. When a hand is detected in the thermal image, the model predicts a simplified integer thermal sensation (+1: Warm, 0: Neutral, -1: Cool) from four inputs: the temperature differences between (1) face 90th percentile and face median; (2) face 90th percentile and nose median; (3) hand maximum and hand median; and (4) face 90th percentile and hand median. If no hands are detected, the simplified thermal sensation is predicted from two inputs: the temperature differences between (1) face 90th percentile and face median; (2) face 90th percentile and nose median. We call this the most-probable sensation (MPS). The model also predicts probability-weighted sensation (PWS) that is not an integer but a continuous value between 'Warm' (+1) and 'Cool' (-1). The PWS is used by the control algorithm. Table 1 shows the conversion to simplified 3-point sensation scale from the ASHRAE 7-point sensation scale. A score greater than +1 on the 7-point sensation scale corresponds to 'Warm' on the simplified 3-point sensation scale; a score between +1 and -1 maps to 'Neutral', and a score less than -1 is interpreted as 'Cool'.

2.1.3 Indoor set-point temperature adjustment (control module). To achieve closed-loop control between the thermal infrared sensing and the AC system, it is necessary to develop a control module that optimizes room set-point temperature based on predicted thermal sensation. To this end, a proportional-integral (PI) control approach was employed, which is a technique that reduces control deviation to bring the system closer to the control target. The control deviation was defined as the difference between the 10-second running mean of PWS and the target sensation. The target sensation value is an adjustable variable that balances energy consumption and thermal comfort. In this study, to minimize cooling energy consumption while preserving occupants' comfort, a target sensation value of 0.5 was set, which lies between 'Neutral' and 'Warm' on a simplified 3-point sensation scale and is deemed to be the upper limit of the occupants' comfort zone. However, the lower and upper limits of the room air temperature set point were restricted to 70 °F and 78 °F, respectively, when occupants were present. Moreover, if the system did not detect skin temperature for more than 10 minutes, it was assumed that the room was unoccupied, and the room temperature was set to either 76 °F (24.4 °C) or 80 °F (26.7 °C).

Table 1 Conversion to simplified 3-point sensation scale from 7-point sensation scale

ASHRAE 7-point scale	Simplified 3-point scale
+3: Hot, +2: Warm	+1: Warm
+1: Slightly Warm, 0: Neutral, -1: Slightly Cool	0: Neutral
-2: Cool, -3: Cold	-1: Cool

2.2 Field trial

The field trial was conducted in a conference room in an office building near Houston, Texas from August 2022 to January 2023, weekdays from 9:00 to 17:00. We implemented three control strategies in the room: (1) fixed setpoint of 72.0 °F (22.2 °C) (which was the setpoint throughout the office during occupied hours); (2) thermal infrared (TIR) control with an unoccupied setpoint of 80 °F (26.7 °C), denoted TIR control A; and (3) TIR control with an unoccupied setpoint of 76 °F (24.4 °C), denoted TIR control B. We collected occupants' thermal sensation votes and comfort votes and measured cooling energy use under each control strategy.

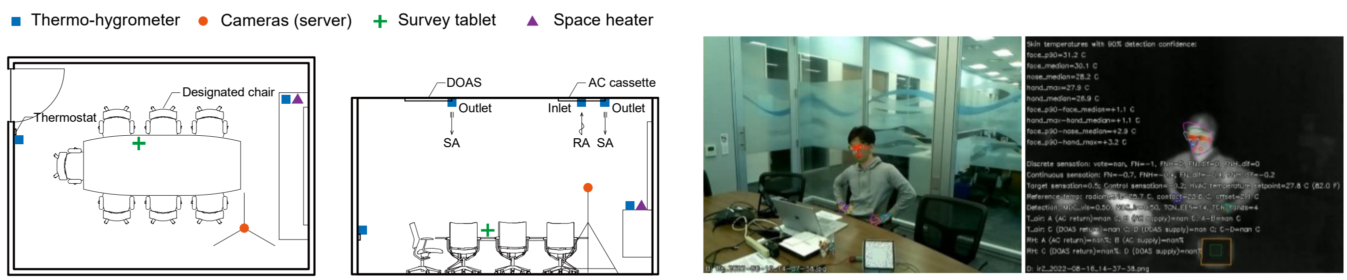
2.2.1 Participants. We did not choose the participants. The participants were the occupants in the office, and they used the room as a workspace or conference room as usual.

2.2.2 Conference room configuration. Figure 3 shows the conference room configuration. To ensure that the camera correctly detected the face and hands of the occupant, the subject was asked to sit in the designated chair and work as usual. The camera was positioned so that the horizontal distance between the camera and the designated chair was about 2.0 m and the height of the camera was about 1.5 m above floor level. The survey tablet was placed on a table near the designated seat so that the occupant could reach it while working to submit sensation votes. It should be noted that the conference room was in the building's interior zone (no exterior windows or walls) and the space outside the conference room was conditioned to 72 °F (22.2 °C). This made it difficult to simulate the heat load from outside the building during summer near Houston. Therefore, a 1,500 W heater was operated in the conference room during the trial (9:00 to 17:00) to simulate the heat load from outside the building in summer.

2.2.3 Thermal measurements. (a) Local skin temperatures: The system described above measured skin temperature statistics for the face, nose, left hand, and right hand of the occupants at 1-second intervals: maximum, 90th percentile, 75th percentile, median, 25th percentile, 10th percentile, and minimum values. **(b) Indoor thermal environment:** The temperature and humidity at the inlet and outlet of the air conditioning system were measured by a wireless thermo-hygrometer (Onset HOBO MX1101) at one-minute intervals to help estimate the HVAC energy consumption. Air temperature and humidity near the thermostat installed on the wall and near the space heater and at the outlet of the room's dedicated outdoor air system (DOAS) were measured by two other wireless thermo-hygrometers (Onset HOBO MX1101 and MX1104, respectively) to characterize the thermal environment in the conference room. Air cooling rate was estimated as the product of the air mass flow rate and the enthalpy reduction between the inlet and outlet of the air conditioning cassette using the calculation method in the ASHRAE Handbook (ASHRAE, 2017a). **(c) Thermal sensation and comfort votes:** Table 2 lists the survey questionnaire and response choices. We ran online survey software (Qualtrics XM) on a tablet device to conduct the survey. The occupants were asked to respond to the tablet-based survey approximately every 30 minutes while in the conference room and recorded their thermal sensation vote on the ASHRAE 7-point scale and thermal comfort (binary yes/no).

Table 2 Survey questionnaire and response choices

Questionnaire	Response choices
How long have you been in this room?	Less than 5 minutes, 5 minutes to an hour, More than an hour
Please rate your thermal sensation right now.	Cold, Cool, Slightly Cool, Neutral, Slightly Warm, Warm, Hot
Are you thermally comfortable right now?	Yes, No



(a) Plan view (b) Section view (c) Color image (d) Thermal image

Figure 3 Conference room configuration. Panels (a) and (b) illustrate the plan and section views of the conference room. Panels (c) and (d) show an example of face, nose, and hand detection. The face area is outlined in green, the nose in cyan, the right hand in yellow, and the left hand in blue. The eyeglasses are detected as bright yellow regions, distinguishing the surface temperatures of the face and eyeglasses.

3 RESULTS

3.1 Daily occupancy in room

Since the energy consumption under TIR controls depends on the total time the room is occupied, the room occupancy for each condition was calculated. The daily occupancy rate was calculated as ratio of the time that the occupants' skin temperature is detected (i.e., the time the room is used) to the total operating time of each system. The occupancy rate for each control condition was 16% for conventional control, 7% for TIR control ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)), and 40% for TIR control ($T_{set,\ unoccupied}$ = 76 °F (24.4 °C)).

3.2 Temperature, sensation votes and air-cooling rate under each control algorithm

Figure 4 shows examples of time series data under each control algorithm. Under the conventional control, the set-point temperature is constant regardless of the occupants' thermal sensation. The air-cooling rate is almost constant at 2.0 kW between 14:00 and 14:30 on October 4, even though the occupant voted 'Cool' on the 3-point simplified sensation scale, indicating that the room was cooled more than necessary. This represents an example of overcooling. On the other hand, the set-point temperature by the TIR controls are constant values of 80 °F (26.7 °C) or 76 °F (24.4 °C) when no one was in the room, but it dynamically changed based on an occupant's predicted thermal sensation when an occupant is detected by the cameras. Therefore, TIR control A ($T_{set,\ unoccupied}$ = 80 °F/26.7 °C) reduced air cooling rate when the room was empty and moderately adjusted when the room was occupied. Also, TIR control B ($T_{set,\ unoccupied}$ = 76 °F (24.4 °C)) used about 2.0 kW of cooling energy when no one was in the room from 10:30 to 11:30 on December 14, but reduced it when an occupant was detected by increasing the set-point temperature until the upper limit of 78 °F (25.6 °C). It should be noted that the characteristic of this air conditioner is that it stops when the thermostat temperature reaches the set-point, and that there was a difference between the actual room temperature and the set-point temperature among the three conditions.

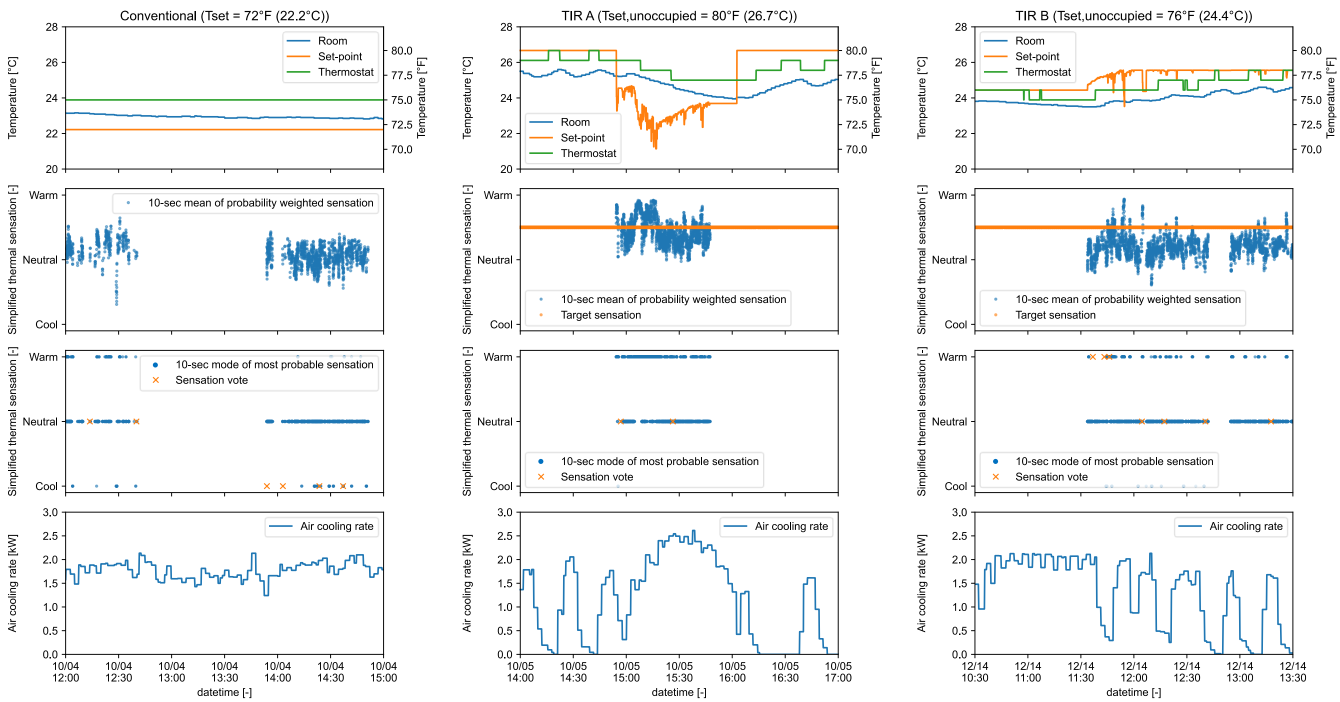
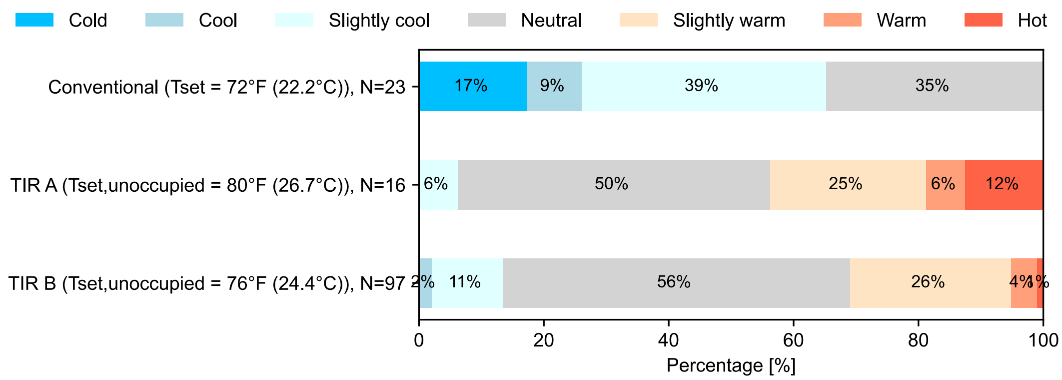


Figure 4 Examples of time series data under each control algorithm. The left column shows data under the conventional control; the center column shows data under TIR control A ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)); and the right column shows data under TIR control B ($T_{set,\ unoccupied}$ = 76 °F (24.4 °C)). The first row shows indoor room temperature measured by the thermo-hygrometer near the thermostat, set-point temperature, and temperature measured by the thermostat; the second row shows PWS and target sensation for air conditioning control; the third row shows predicted simplified MPS and sensation vote; and the fourth row shows air cooling rate.

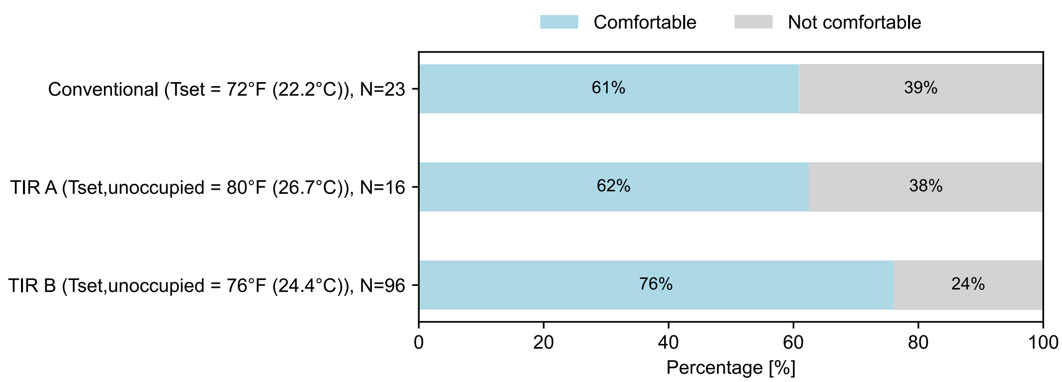
3.3 Occupants' thermal sensation and comfort votes under each control algorithm

Figure 5 shows the occupant's feedback for each control algorithm. Under the conventional control, there were total 23 thermal sensation votes and 35% of votes were 'Neutral' and the rest were 'Slightly cool', 'Cool' or 'Cold' (there were no warm votes). 50% of the responses under TIR control A ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)) were 'Neutral', which is higher than under the conventional control but there was no significant difference in thermal comfort votes between two groups. Although the percentage of 'Neutral' votes under TIR control A ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)) was higher than that of conventional control, 6% of the respondents answered 'Warm' and 12% answered 'Hot'. The main reason for this can be attributed to the temperature difference between the conference room and the adjacent space. Since the occupants entered the conference room with a temperature setting of 80°F (26.7°C) from the adjacent space with a temperature setting of 72°F (22.2°C), it is highly likely that they felt hot immediately after entering the room due to the temperature difference. In fact, the data showed that of the three votes within 5 minutes after entering the room by TIR control ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)), two were 'Slightly Warm' and one was 'Hot'. Under the TIR control ($T_{set,}$

unoccupied = 76 °F (24.4 °C)), there were total 97 thermal sensation votes and 56% of the responses were 'Neutral', the highest percentage of thermally neutral votes. Over 90% of the votes were either 'Slightly Cool', 'Neutral', or 'Slightly Warm', and 76% were 'Comfortable', indicating the most comfortable air conditioning control in the conditions.



(a) Distribution of thermal sensation votes under each control algorithm



(b) Distribution of thermal comfort votes under each control algorithm

Figure 5 Occupant's feedback for each control algorithm. The conventional control tended to overcool the occupants, whereas TIR controls made the occupants more thermally neutral and comfortable than the conventional control. *N* represents the number of votes.

3.4 Air-cooling rate under each control algorithm

3.4.1 All trial data. Between the hours of 9:00 and 17:00, the mean air-cooling rates for the conventional control (T_{set} = 72 °F (22.2 °C)), the TIR control A ($T_{set, unoccupied}$ = 80 °F (26.7 °C)), and the TIR control B ($T_{set, unoccupied}$ = 76 °F (24.4 °C)) are approximately 1.57 kW, 0.60 kW, and 1.28 kW, respectively. The TIR control A ($T_{set, unoccupied}$ = 80 °F (26.7 °C)) reduced the mean air-cooling rate by about 62% compared to the conventional control, while the TIR control B ($T_{set, unoccupied}$ = 76 °F (24.4 °C)) reduced it by 18%. Notably, the percentage of time the conference room was occupied under the TIR control A ($T_{set, unoccupied}$ = 80 °F (26.7 °C)) was the lowest of the three conditions (7%), resulting in the highest percentage of data when the air conditioning was not running (49%) and the lowest mean air-cooling rate. As such, the system functioned as an occupant sensor and conserved cooling energy by raising the set-point temperature when the occupants were absent.

3.4.2 Data when conference room is in use. Figure 6 shows the histogram of air-cooling rate under each control algorithm when the conference room was occupied. We focused solely on the data from when the conference room was in use to assess whether the system's skin temperature detection, temperature prediction, and set-point temperature adjustment truly saves energy, independent of the effects of increasing the set-point temperature when the occupants are absent. We determined whether the conference room was in use based on whether or not the occupants' skin temperatures were detected. When the occupants were in the conference room, the mean air-cooling rates for the conventional control (T_{set} = 72 °F (22.2 °C)), TIR control A ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)), and TIR control B ($T_{set,\ unoccupied}$ = 76 °F (24.4 °C)) were approximately 1.64 kW, 1.34 kW, and 0.95 kW, respectively. TIR control A ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)) reduced the mean air-cooling rate by about 18% compared to the conventional control, while the TIR control B ($T_{set,\ unoccupied}$ = 76 °F (24.4 °C)) reduced it by 42%. The data distribution in the figure revealed that the air-cooling rate data under the conventional control followed a normal distribution centered around the mean value, while data under both TIR controls exhibited a bimodal distribution with two peaks. This indicates that while conventional control often cooled at 1.5 to 2.0 kW due to a fixed set-point temperature, the TIR controls sometimes turned off the AC depending on the predicted thermal sensation, which can be seen in Figure 4. As a result, the AC under the TIR controls was turned off more than 20% of the time when the conference room was used, which reduced the mean air-cooling rate. The mean air-cooling rate under TIR control A ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)) was higher than that under the TIR control B ($T_{set,\ unoccupied}$ = 76 °F (24.4 °C)). This difference can be attributed to the set-point temperature during unoccupied period. During the unoccupied period, TIR control A ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)) yielded a higher set-point temperature compared to TIR control B ($T_{set,\ unoccupied}$ = 76 °F (24.4 °C)). Consequently, the occupants' predicted thermal sensation tended to be higher, resulting in a greater cooling demand to counteract their thermal discomfort during the occupied period. This pattern is discernible in Figure 4.

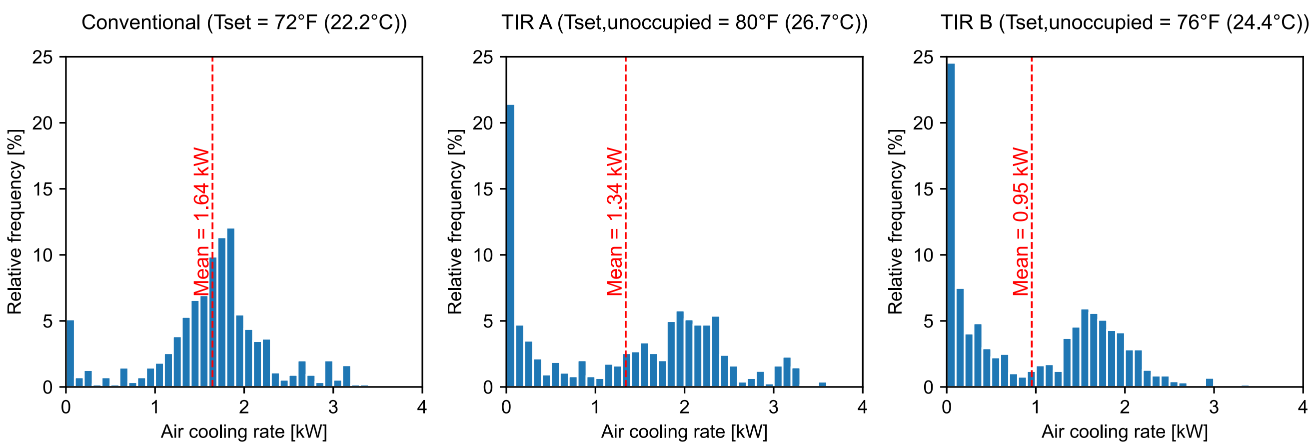


Figure 6 Histogram of air-cooling rate under each control algorithm when the conference room was occupied. TIR control A ($T_{set,\ unoccupied}$ = 80 °F (26.7 °C)) reduced the mean air-cooling rate by about 18% compared to the conventional control, while the TIR control B ($T_{set,\ unoccupied}$ = 76 °F (24.4 °C)) reduced it by 42%.

4 DISCUSSIONS

4.1 Prediction accuracy of thermal sensation model in office settings

The machine learning model we used in this field study to predict occupants' thermal sensation was developed based on data obtained in laboratory and carport settings (He et al., 2022), so we validated its accuracy in an office settings. We assumed that occupants' thermal sensations do not change very often while working in the office and that their sensations were the same for 150 seconds before and after the time they voted (for five minutes). Their votes were converted to the 3-point simplified sensation from 7-point sensation using Table 1 and were compared with the predicted simplified sensation. The overall prediction accuracy, a percentage of correct answers to test size, was 56%, which was worse than that reported by He et al (He et al., 2022). The predicted simplified sensation was mostly 'Neutral' as shown in Figure 4; thus the prediction accuracy was relatively high at 65% for 'Neutral' vote, but was low at 31% for 'Warm' and 17% 'Cool'. The reason for this can be attributed to the disparity between the actual office thermal environment and the environment used to develop the model. The current model was trained using skin temperatures and thermal sensation data obtained in cold environments (ambient air temperature T_a below 20 °C (68 °F)), neutral environments ($T_a \approx 24$ °C (75.2 °F)), and hot environments (T_a = above 30 °C (86 °F)). However, the actual room temperature in the office did not fall within these extreme temperature ranges. This led to the model overpredicting a 'Neutral' thermal sensation and resulted in a suboptimal prediction accuracy. Therefore, it is necessary to conduct subject experiments in warm and cool (rather than hot and cold) environments to retrain and improve the model, including the data obtained in this study.

5 CONCLUSIONS

This research aims to evaluate the performance of our newly developed system for office temperature control. A field trial was conducted in a conference room in an office building near Houston, Texas from August 2022 to January 2023. From 9:00 to 17:00 on weekdays, we operated a conventional control that set the room temperature to 72.0 °F (22.2 °C) operating throughout the office building, and thermal infrared (TIR) control that set the room temperature based on an occupant's predicted sensation and set 80 °F (26.7 °C) or 76 °F (24.4 °C) when the room was empty. We collected the occupants' thermal sensation votes and comfort votes and measured cooling energy use under each control.

The results show that on a 7-point scale, 35% of the sensation votes under the conventional control that set the room temperature to 72.0 °F (22.2 °C) were 'Neutral' and the rest were either 'Slightly Cool', 'Cool', and 'Cold', with no Warm or Hot votes; this indicates that the conventional control overcooled the occupants. The TIR control A that set the room temperature based on an occupant's predicted sensation and set 80 °F (26.7 °C) when the room is empty reduced the mean air-cooling rate by 62% during the trial period and made the occupants more thermally neutral than the conventional control. This indicates that our system worked as an occupant sensor and saved energy by raising the setpoint when the room appeared empty. However, some occupants complained that the room was hot and uncomfortable, especially immediately after entering the room because of the temperature difference inside and outside the conference room. The higher the set-point temperature when the conference room is unoccupied, the more energy use of AC can be reduced, but a longer time is needed to achieve the temperature required by the occupants—which could reduce thermal satisfaction. Hence, we tested another condition, which is TIR control B that set the room temperature based on an occupant's predicted sensation and set 76 °F (24.4 °C) when the room is empty. TIR control B reduced the mean air cooling rate by 18% during the trial period and made the occupants more thermally neutral than the conventional control: on a 7-point scale, 56% of the occupants, the highest percentage among the three conditions, responded 'Neutral', and over 90% of the sensation votes were either 'Slightly Cool', 'Neutral', or 'Slightly Warm', and 76% responded 'Comfortable', indicating the most comfortable air conditioning control among the conditions tested in this field trial. Apart from the effect of increasing the set temperature during an unoccupied period, the intrinsic energy-saving effect of our system's skin temperature detection, sensation prediction, and set-point temperature adjustment was verified by comparing the air-cooling rate data only when the conference room was in use. The results showed that both TIR controls reduced the mean air-cooling rate during the occupied period compared to the conventional control by avoiding overcooling.

To promote this system as a novel temperature control for homes and offices, we must retrain the thermal sensation model within a narrower temperature range and address detecting multiple subjects.

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