Doppler Radar Occupancy Sensor Assessment of Thermal Adaptation

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***Abstract*— This study examines the use of a Doppler radar occupancy sensor to assess thermal adaptation. Current heating, ventilation, and air-conditioning (HVAC) systems are important for the productivity of employees and the healing of patients; however, their control systems are typically limited to a narrow temperature range, which is usually not comfortable for most occupants. Occupant vital signs can be used to assess thermal comfort, due to the role cardiovascular regulation plays in heat dissipation. This research aims to correlate physiological and thermal adaptation with the goal of optimizing HVAC system operation. A Doppler radar occupancy sensor was used to measure the physiological parameters of ten human subjects under two temperature conditions, and thermal comfort surveys were used to record thermal sensation. The results demonstrate that the Doppler radar occupancy sensor could not only detect heart rate changes due to a significant environmental temperature difference but also detect subtle changes in heart rate during thermal adaptation that were not captured by the surveys.**

Keywords—Doppler radar, occupancy sensor, thermal comfort, and heart rate

I. INTRODUCTION

Heating, ventilation, and air conditioning (HVAC) systems consume about half of overall building energy consumption, significantly contributing to greenhouse gas emissions and climate change [1]. The primary function of HVAC systems is to maintain a level of comfort for occupants in the building; however, current HVAC systems often fail to achieve occupant satisfaction. Control systems for conventional HVAC systems rely upon one heat index, for example, temperature or humidity, resulting in occupants being often too cold or too hot in their environments [2]. To address this issue, an HVAC system model, called the predicted mean vote (PMV) model, that involves thermal comfort information in the control system, has been proposed [3]. However, this model has limitations in detecting the actual occupant thermal sensation [4], due to considering only human metabolic rate and thermal insulation provided by clothing [5].

Physiological and thermal adaptation models have been studied previously using contact sensors [6,7]. The relationship between ambient temperature and heart rate [8,9,10] has been assessed previously using contact sensors while the effect of temperature change on respiration rate has been explored using Doppler radar [11].

However, these studies were focused on physiological differences at different temperatures and did not include thermal comfort surveys nor examine how physiology changes during adaptation time. This study aims to determine if a Doppler radar occupancy sensor can be used for a more comprehensive thermal comfort assessment. A 2.4 GHz occupancy sensor was used to collect physiological data of ten human subjects in cold (70 °F) and warm (85 °F) conditions. To the best of the authors' knowledge, this work is unique in examining the relationship between the heart rates obtained with Doppler radar and thermal comfort during thermal adaptation.

II. EXPERIMENTAL SET-UP AND APPROACH

The True Presence Occupancy Detection Sensor (TruePODS™) used in this work is a Doppler radar-based occupancy sensor [12] operating at 2.4 GHz, that has been used to extract heart rate with high accuracy [13]. Fig. 1 shows a block diagram of the TruePODS module. A microcontroller with a programmable radio was used to generate a 2.4 GHz signal, that is split and amplified before being transmitted through a single patch antenna. The reflected signal is received by the same antenna and mixed with the portion of the original signal for down conversion to baseband. The baseband signal is filtered and amplified before it is digitized with a 100 Hz sampling rate and recorded through the UART serial port. The output baseband signal can be expressed in the Eq. (1) where the parameters are amplitude of output signal (A), wavelength (λ), the distance between the radar and a target (d_o), and time-varying displacement x(t) corresponding to periodic chest movement. Heart rate can be obtained from the time-varying chest displacement x(t).

$$B(t) = Acos[\frac{4\pi}{\lambda}(d_o + x(t))] \quad (1)$$

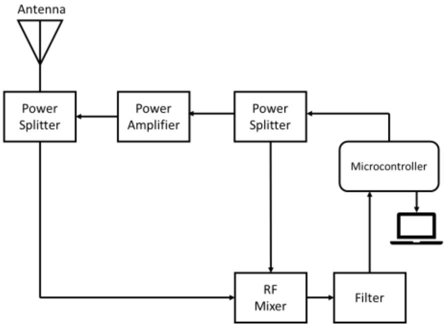

Fig. 1. Block diagram of the Doppler radar sensor.

A health sensor band, MAXREFDES103, was used to verify accuracy by analyzing the photoplethysmography (PPG) data with a 100 Hz sampling rate. MX1102 Hobo Logger measured temperature, humidity, and CO_2 level with a 1 Hz sampling rate, globe thermometer, and air velocity sensor to monitor environmental conditions. The experimental setup is displayed in Fig. 2

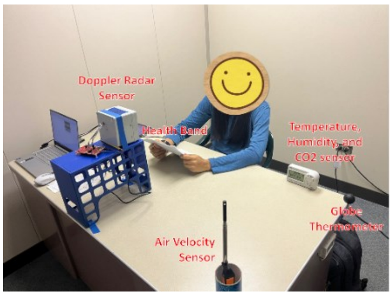

Fig. 2. The experimental setup. A Doppler radar sensor was used along with various environmental sensors to unobtrusively assess thermal adaptation.

The experiments for this study were conducted according to the Committee on Human Studies (CHS) protocol number 2021-00191 which was approved by the CHS of the University of Hawaii system. Ten healthy participants, five women and five men, were tested at two different temperatures, 70 °F, and 85 °F, respectively, on the same day, for 30 minutes per temperature point. Participants were provided two short stories to read during the testing, one at each temperature. The testing was carried out in an office with central air-conditioning that normally maintains the temperature at 70 °F. Temperature was raised to 85 °F by using three space heaters and two fans to distribute the heat evenly. Participants were asked to fill out the general survey before the start of the experiment, and the thermal comfort survey after 15 minutes and 30 minutes of exposure at each temperature point. The general survey included questions about physical activities, caffeine intake, and choice of clothes [14]. None of the participants exercised before testing, and only one participant took caffeine 30 minutes before the experiment. The thermal comfort survey followed the ASHRAE PMV scale [15]: 1 is hot, 2 is warm, 3 is slightly warm, 4 is neutral, 5 is slightly cool, 6 is cool and 7 is cold.

III. Data Processing

The data from the Doppler radar was filtered by setting thresholds calculated from the statistic median of the data plus–minus thousands. The reason for this filter is the high-value signal from participants turning reading materials pages as in Fig. 3. Clear 30 seconds signals in the aforesaid period, as displayed in Fig 4, were selected to filter again by bandpass filter with 0.7 - 3 Hz frequency range (Fig. 5) to extract heart rate using FFT (Fig. 6).

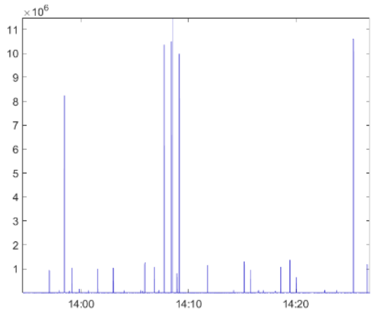

Fig. 3. Raw data showing high-peaks when participants turn pages.

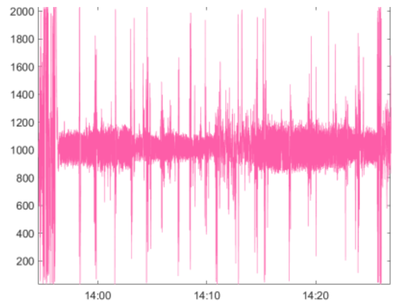

Fig. 4. Filtered radar with calculated threshold.

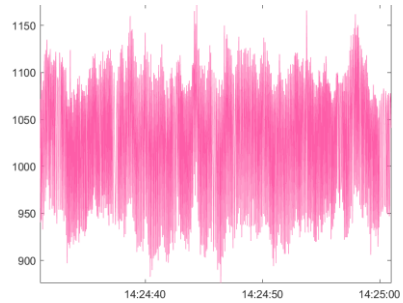

Fig. 5. Thirty-seconds of threshold filtered radar data.

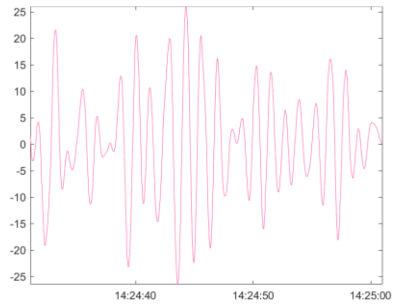

Fig. 6. Bandpass filtered selected radar data.

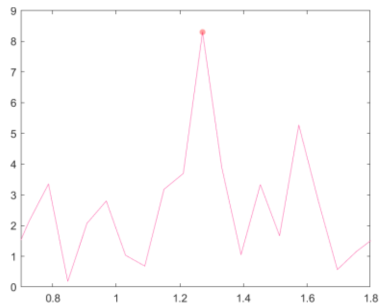

Fig. 7. FFT of filtered radar data.

IV. Results and Discussion

Table I. displays the heart rate of participants which was extracted from a radar sensor at two temperature points (70 °F and 85 °F). In all cases, the difference between TruePODS and PPG heart rate was within 4%. At each temperature point, heart rate was extracted at 10-15 minutes and 25-30 minutes. At 70 °F, eight out of ten people had lower heart rates when they had higher adaptation time (Participants numbers 2-7 and 9-10). On the other hand, the heart rate of seven people at 85 °F increased following the expansion of acclimation time (Participant number 2-8). Therefore, more than 15 minutes of acclimation time tended to provide more accuracy in representing participant heart rates in one environment. To compare between 70 °F and 85 °F, a 25–30 minute period was considered, and showed that seven people had higher heart rates when the ambient temperature was higher.

The thermal comfort level from survey responses is also shown in Table I. Nine out of ten of the participants provided the same survey response after 15 and 30 minutes at each temperature, while their heart rates were still adjusting. This result demonstrates the potential for Doppler radar to detect subtle physiological changes that participants were not aware of.

V. Conclusion

This work demonstrated that a Doppler radar occupancy sensor can be used for non-contact thermal adaptation assessment. Heart rate under the cold conditions was found to decrease following higher acclimation time while heart rate in the hot conditions had an opposite trend, which was not captured by the surveys. After 25-30 minutes of acclimation time, for a majority of participants, heart rate was higher at higher temperatures. Future work may involve survey response analysis and additional physiological parameters such as respiration rate, heart rate variability, and respiration rate variability for non-contact assessment of thermal comfort.

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TABLE I. Heart rate at 70 °F and 85 °F Measured for two periods, along with Thermal comfort level.

Participant number	**70 °F**				**85 °F**			
	10-15 minutes		***25-30 minutes***		***10-15 minutes***		***25-30 minutes***	
	Heart rate(bpm) Radar	***Thermal comfort***	***Heart rate(bpm) Radar***	***Thermal comfort***	***Heart rate(bpm) Radar***	***Thermal comfort***	***Heart rate(bpm) Radar***	***Thermal comfort***
1	76.08	4. Neutral	76.26	4. Neutral	70.32	2. Warm	67.86	2. Warm
2	86.52	4. Neutral	84.30	4. Neutral	79.50	3. Slightly Warm	83.28	3. Slightly Warm
3	48.71	5. Sligthly cool	48.20	5. Sligthly cool	50.60	3. Slightly Warm	51.40	3. Slightly Warm
4	78.54	4. Neutral	76.38	4. Neutral	78.96	2. Warm	84.18	2. Warm
5	98.76	4. Neutral	95.94	5. Sligthly cool	89.46	1. Hot	97.80	2. Warm
6	82.56	4. Neutral	81.36	4. Neutral	82.08	3. Slightly Warm	90.06	3. Slightly Warm
7	75.96	4. Neutral	70.26	4. Neutral	64.74	2. Warm	71.04	2. Warm
8	77.46	4. Neutral	80.58	4. Neutral	80.28	3. Slightly Warm	81.96	3. Slightly Warm
9	64.92	3. Slightly Warm	60.78	3. Slightly Warm	69.12	2. Warm	64.38	2. Warm
10	75.90	5. Sligthly cool	72.00	5. Sligthly cool	70.38	2. Warm	70.68	2. Warm