Towards Non-Intrusive Metabolic Rate Evaluation for HVAC Control

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Abstract:

To provide comfortable environments by heating, ventilation, and air conditioning (HVAC) systems, occupants' perspective should be taken into account. The predicted mean vote (PMV) model, which is commonly used in design of HVAC systems, accounts for human factors such as metabolic rate. However, pre-determined values (i.e., met unit) for metabolic rates are used due to difficulty in their contextual and real-time evaluation. As a solution, we propose a novel and non-intrusive respiration ratio evaluation method using a cost-effective Doppler radar sensor (DRS) system. This method has been inspired by the statement from ASHRAE: respiratory ratio (i.e., the ratio of exhalation to inhalation) is correlated with heat production of the body (i.e., metabolic rate). DRS systems could be used to identify subtle movements, including periodic movements such as pulmonary activities, by processing the modulated returned signal from an environment. Therefore, using the information, contained in the return signal, exhalation (Q_{CO_2} exhaled) and inhalation (Q_{O_2} inhaled) can be distinguished by processing transitions from local minima to maxima to minima, which indicate inhalation and exhalation, respectively. We leveraged the representation of pulmonary activities (intensity and duration) in the DRS signal to calculate respiration ratio. Our proposed framework uses the Savitzky-Golay method and band-pass filtering to reduce noise in the time-domain representation of the signal and utilize the peak detection algorithm to distinguish each pulmonary activity. By multiplying intensity and duration of each pulmonary activity the volumetric flow of inhalation/exhalation was estimated. The overall exhalations and inhalations within a given time were used to calculate the instantons respiration ratio for an individual. In the experimental study performed to evaluate the feasibility of the proposed approach, an increase in respiration ratio was observed for all human subjects (six healthy males participated) when they experienced a higher temperature. This study contributes to our vision, in which cost-effective DRS-based sensing nodes could be adopted in an environment either as personal sensing nodes or as room sensing capabilities to provide human-awareness for building systems. The reparation ratio obtained through this method could be used to quantify real-time metabolic rates by accounting for additional parameters such as body surface and volumetric rate of oxygen consumption. Integrating real-time and actual occupants' thermophysiological response under varying ambient conditions could be used to improve energy efficiency of HVAC systems.

Keywords: HVAC, Thermal comfort, Thermoregulation, Respiration, Metabolic rate, Doppler radar sensor.

1. INTRODUCTION

Occupants' thermal demands are the principle driver in operation of heating, ventilation, and air conditioning (HVAC) systems. Accordingly, the predicted mean vote (PMV) model is commonly employed in design of HVAC systems as the approach to account for occupants' thermal demands (ASHRAE, 2017). In other words, the PMV model plays a critical role in representing occupants' perspectives in control logic of HVAC systems for providing comfort. To do so, the PMV model takes two human-related parameters (metabolic rate and clothing insulation) into account (Fanger, 1970). This model reflects occupants' physical, physiological, and insulation states. However, those human-related values were often deemed as constant because of the difficulty in their actual and real-time evaluation (Torresani et al., 2013; Tse & Chan, 2008). Therefore, pre-determined values (the met unit for metabolic rate (18.4 Btu/h·ft^2) and clo unit for clothing insulation (0.88 ft^2·°F·h/Btu)) are widely used for simplification (Luo et al., 2016). Due to the lack of realistic information on human parameters, studies have reported discrepancy between the PMV-derived and actual thermal sensations (Becker & Paciuk, 2009; Maiti, 2013; Wong & Khoo, 2003; Yao et al., 2008). Additionally, it has been shown that a majority of occupants tolerate thermal dissatisfaction in buildings (Huizenga et al., 2006) and buildings are commonly overcooled during the summer (Mendell & Mirer, 2009). Several studies have demonstrated the importance of having precise human-related inputs to derive accurate PMV-based thermal sensations (Hoof, 2008; Luo et al., 2016) for HVAC control in buildings.

Accounting for occupants' perspective for thermal conditioning could be achieved through different techniques. One potential approach is to survey occupants' thermal sensations. This approach directly asks for occupants' perception about an environment (Nicol & Roaf, 2005) and was shown to be effective. Studies have proposed to use web-based (Huizenga et al., 2002) and smartphone-based (Jazizadeh et al., 2011) methods to facilitate the process of information integration in survey-based methods. However, these methods require dedication from users as they demand user input on a continuous basis. The consistent use of the PMV model, as a source of assessing thermal demands, is attributed to its non-intrusiveness regardless of the criticism of the PMV model and underwhelming performance of HVAC systems. In other words, it is desirable to have a system that requires less dedication from a user. Accordingly, another promising category of methods have emerged that leverage human physiological responses (as the reflection of thermoregulation states) with respect to ambient conditions. It has been demonstrated that skin temperature, heart rate, skin blood perfusion, and respiration patterns are correlated with thermal sensations (Dabiri & Jazizadeh, 2016; Jazizadeh & Jung, 2018; Jazizadeh & Pradeep, 2016; Jung & Jazizadeh, 2017a; Maiti, 2013; Wang et al., 2015; Xiong et al., 2016). The human body regulates these physiological processes to adjust heat production of the body (i.e., metabolic rate) to maintain the internal body temperature (Havenith et al., 2002).

In this study, we introduce a novel method of calculating respiration ratio (i.e., the ratio of exhalation to inhalation) as a first step for calculating metabolic rate. This study is inspired by the Equation (1) from ASHRAE (2013). This equation, developed empirically by Nishi (1981), represents the correlation between respiratory ratio and metabolic rate (i.e., a linear relationship).

$$M = {567(0.23RQ + 0.77)Q_{O_2}} \Big/ {A_D} \tag{1}$$

where M: metabolic rate (Btu/h·ft^2),
A_D: body surface area (ft^2)
RQ: respiratory quotient (hereinafter respiration ratio); molar ratio of Q_{CO_2} exhaled to Q_{O_2} inhaled, dimensionless
Q_{O_2}: volumetric rate of oxygen consumption at conditions of 32ºF, 14.7psi (ft^3/h)

Hence, we have proposed to evaluate the feasibility of using Doppler radar sensor (DRS) systems, as a non-intrusive method of measurement of pulmonary activities (i.e., inhalation and exhalation) and calculating respiration ratio. DRS could quantify the dynamics of a target by identifying the modulation in the received signal compared to the transmitted signal due to the movements of the target. Accordingly, it has been used for movement and cardiopulmonary activity monitoring in medical applications. Inspired by such capability, in our previous research efforts (Jung & Jazizadeh, 2017a; Jung & Jazizadeh, 2017b), we investigated a novel use of DRS to evaluate the variations of respiration patterns under different thermal conditions. That study shed light on the potential of leveraging respiration in thermal sensation assessment and HVAC control. We are further motivated in exploring the potential of using respiration as a tool of calculating actual metabolic rate non-intrusively. As for the first step, respiration ratio acquisition is proposed in this study. Quantification of this parameter will contribute in enabling human-in-the-loop control of HVAC system as it could be adopted either in calculation of a realistic PMV value or as a new data-driven indicator of thermal sensation. This method will contribute to our vision, in which cost-effective DRS-based sensing nodes could be adopted in an environment either as personal sensing nodes or as room sensing capabilities to provide human-awareness for building systems.

The rest of this paper is structured as follows. The second section further reviews the use of the PMV model and states the necessity and contributions of our proposed approach. The third and fourth sections describe the mechanism of DRS and details of the proposed DRS-based respiration ratio evaluation method, respectively. We performed an experimental study to evaluate the feasibility of the proposed method that is described in the fifth section. The paper is continued with presentation of results in the sixth section and is concluded in the last section.

2. RESEARCH BACKGORUND

The PMV model is intended for predicting the largest possible percentage of people in thermal comfort (Fanger, 1970). Given the PMV model development objectives, ASHRAE (2017) requires the provision and maintenance of the PMV-defined comfort zones as the design compliance criteria. The use of the PMV model in the design phase can play a pivotal role given the actual occupants' data is not yet available. This model presents occupants' perspective in advance, thereby HVAC engineers can outline the required performance of HVAC systems. For example, the met unit, one of the human related parameters in PMV model, is provided according to intended indoor activities (ASHRAE, 2013), hence the needed thermal demands can be calculated based on the functionality of a space (e.g., office or gym).

However, this PMV model-based setup requires an update to better comply with actual occupants' thermal desires. This is due to the fact that it has been shown that individuals manifest different and diverse response to ambient condition variation. In other words, the generalized assumption by the PMV model might not accommodate the characteristics of actual occupants. As noted, this fact has been reflected in several field studies. As an instance, Humphreys & Hancock (2007) revealed diverse thermal preferences throughout all thermal sensations (from cold to hot), but the PMV model assumes that the neutral state is the preferred thermal sensation across all occupants. The process of adapting to specific thermal desires from end-users has been called user-adaptable, user-centered, and personalized control across different studies (Federspiel & Asada, 1994; Fukuta et al., 2015; Jazizadeh et al., 2013).

In realization of user-centered HVAC control, one of the key attributes is the characteristic of the measurement method for collecting occupants' information. The use of non-intrusive methods for assessing occupants' thermal sensations is generally preferred (Jung & Jazizadeh, 2017b). The rationale of using metabolic rate as a human-related input in the PMV model is to minimize interference with occupants' activities. However, when it comes to operations, there has been no practical way to measure metabolic rate in real-time. As an indicator of challenges in its quantification, ASHRAE (2013) describes 27 parameters to calculate actual metabolic rate, which has been a barrier for its contextual assessment. Accordingly, when the actual occupancy information could be available in operation phase, studies have chosen to employ pre-determined values (i.e., the met unit) for metabolic rate.

In our prior research efforts, we have shown that DRS can non-intrusively capture variations in respiration induced by the thermoregulation mechanism to regulate heat dissipation (Jung & Jazizadeh, 2017a; Jung & Jazizadeh, 2017b). The advancements in sensor technologies have brought about cost-effective DRS technologies (with small footprints) that supports our vision for ubiquitous quantification of human-related parameters. Therefore, in order to move towards the objective of creating and maintaining better indoor conditions with less dedication from end-users, we have expanded our approach to develop a non-intrusive method of quantification for metabolic rate or parameters that are highly correlated with metabolic rate. This approach in turn could either be used as an update in PMV values or as a personalized measure of human dynamics. As a first step of this envisioned metabolic rate evaluation, we developed a novel method of calculating respiration ratio.

3. DOPPLER RADAR SENSOR

Before explaining the proposed approach, in this section, we elaborate on the mechanism of Doppler radar sensing. As noted above, DRS captures the motion of a target by comparing the received signal (modulated by the motion) to transmitted one. In so doing, the sensor processes signal as follows:

The signal transmitted from DRS transceiver is represented by Equation (2)

$$T(t) = \cos\left(2\pi f t + \phi(t)\right) \tag{2}$$

where f: frequency, t: time,
ϕ: the arbitrary phase shift or the phase noise of the signal source.

If the transmitted signal is reflected by a target (human in this study) at a nominal distance d_0 with a time-varying displacement $x(t)$, the distance between the DRS and the target becomes $d(t) = d_0 + x(t)$. After the reflection, the transceiver receives the signal delayed by $d(t)/c$ (as it travels back to the antenna; c is signal's propagation velocity). Accordingly, the received (i.e., modulated) signal will be

$$R(t) = \cos\left(2\pi f t - \frac{4\pi d_0}{\lambda} - \frac{4\pi x(t-\frac{d(t)}{c})}{\lambda} + \phi\left(t - \frac{2d_0}{c} - \frac{2x\left(t-\frac{d(t)}{c}\right)}{c}\right)\right) \tag{3}$$

where λ: wavelength.

Considering that $x(t - d(t)/c)$ can be represented as $x(t)$ and $x(t - d(t)/c)/c$ in the ϕ term is negligible due to their subtleness, the received signal can be presented as Equation (4)

$$R(t) \approx \cos\left(2\pi f t - \frac{4\pi d_0}{\lambda} - \frac{4\pi x(t)}{\lambda} + \phi\left(t - \frac{2d_0}{c}\right)\right) \tag{4}$$

Accordingly, the modulation presented in the received signal indicates the movement of the target, which can be further processed by a local oscillator to obtain the baseband output given as Equation (5)

$$B(t) \approx \cos\left(\theta + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)\right) \tag{5}$$

where θ: the constant phase shift due to the nominal distance to the target $4\pi d_0/\lambda$,
$\Delta\phi(t)$: the residual phase noise.

Furthermore, as stated by Li et al. (2015), the amount of the displacement is represented by the amplitude of the signal, which is one of the key factors in this study in quantification of pulmonary activities. Using this mechanism of DRS, we proposed the DRS-based respiration ratio evaluation method in detail in the following section.

4. DRS-BASED RESPIRATION RATIO EVALUATION

The objective of the proposed method is to calculate respiration ratio by using the ratio of exhalation and inhalation represented in the received signal from DRS. It has been indicated that a transition from local minima to maxima on the signal in the time domain illustrates an inhalation and vice versa for an exhalation (Lee et al., 2015). To distinguish each pulmonary activity and calculate respiration ratio, reflected on the return signal, our proposed framework has been depicted in Figure 1.

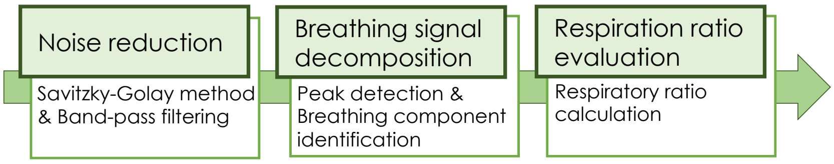

Figure 1. Proposed framework for the DRS-based respiration ratio acquisition method.

4.1. Noise Reduction

Given that DRS signals can be modulated by non-pulmonary activities, improving the signal to noise ratio (SNR) is an important step. Accordingly, we have adopted the Savitzky-Golay and band-pass filtering methods for that purpose. The former approach helps smooth the signal using local least-squares polynomial approximations, hence, it preserves the shape and height of waveform peaks while reducing noise and redundancy (Schafer, 2011). The latter filters the signal according to the desired breathing frequency range (Lee et al., 2015). In order to clarify the importance of these steps, Figure 2 illustrates the outcome of signal processing through using these methods on an example signal.

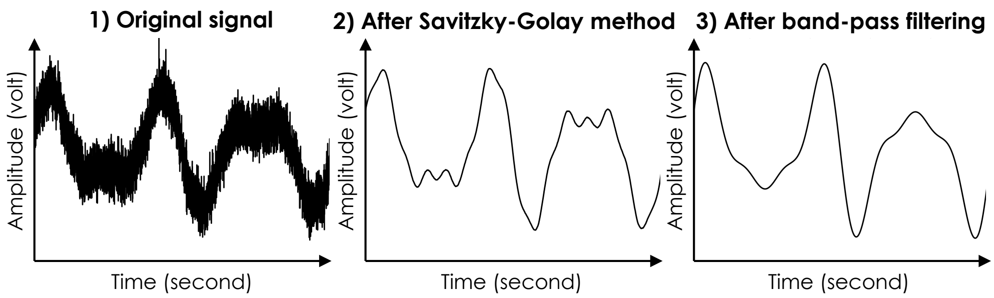

Figure 2. Signal processed by the Savitzky-Golay and band-pass filtering methods: 1) original signal, 2) signal after the Savitzky-Golay method, and 3) signal after band-pass filtering

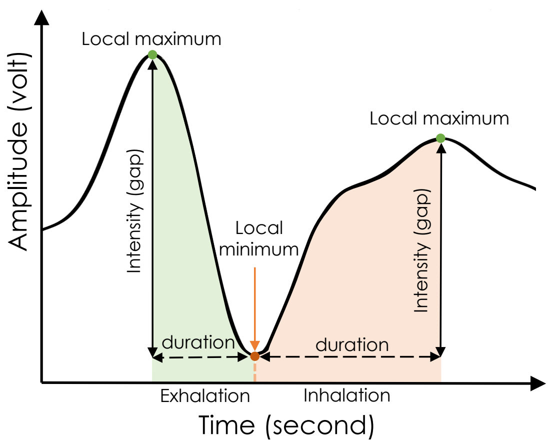

Figure 3. Exhalation and inhalation components in the signal and their characteristics.

4.2. Breathing Signal Decomposition:

The enhanced signal from the first step is used to infer exhalation and inhalation activities. We employed a peak detection algorithm to identify local maxima and minima. The algorithm assigns local maxima when derivative of a point changes from negative to positive and local minima when vice versa. After that, each transition is classified. The interval from local maxima to local minima is assigned as exhalation and vice versa as inhalation (Figure 3). Given the typical respiration rate (0.1 – 0.5Hz (Jung & Jazizadeh, 2017a)), at least one minute of measurement is necessary for valid evaluation.

4.3. Respiration Ratio Quantification

As for the last step, we considered two characteristics of the pulmonary activities to calculate respiration ratio: intensity and duration. The former is acquired by the gap between the amplitudes, which illustrates the intensity of displacement caused by pulmonary activities (Jung & Jazizadeh, 2017a; Li et al., 2015). The latter quantifies the time spent on each activity. Figure 3 shows two characteristics of pulmonary activity, presented in a DRS signal. In order to convert these characteristics into a single metric, two features are multiplied, and then exhalation (Q_{CO_2}exhaled) and inhalation (Q_{O_2}inhaled) are summed separately (because several exhalations and inhalations are present during measurement) to compute respiration ratio (RR_{DRS}) as indicated in Equation (6).

$$RR_{DRS} = {\sum I_e \times D_e}\Big/{\sum I_i \times D_i} \tag{6}$$

where I: intensity, D: duration, *e*: exhalation (Q_{CO_2}exhaled), *i*: inhalation (Q_{O_2}inhaled)

Under different indoor conditions, this newly proposed respiration ratio evaluation method should reflect variation of metabolic rate with respect to ambient conditions (owing to their linear relationship presented in Equation (1)). We hypothesized that an increase in respiration ratio in higher temperatures will be observed (Havenith et al., 2002). If so, this indicates the potential of reflecting actual metabolic rate, thereby further exploration for the actual metabolic rate evaluation can be proceeded. In the end, the envisioned non-intrusive metabolic rate evaluation can be used in the PMV model as well as in the envisioned thermoregulation-based control of HVAC as feedback.

5. EXPERIMENTAL STUDY

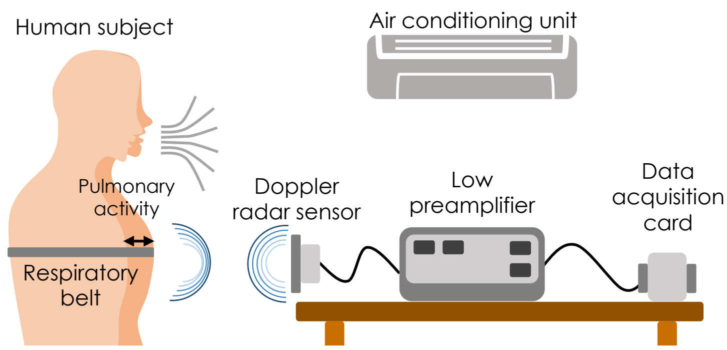

Figure 4. Experimental setup.

An experimental study was designed and conducted to assess the feasibility of the proposed DRS-based respiration ratio evaluation method. We utilized a test-bed with a dedicated air conditioning unit, capable of adjusting air temperature from 20 to 30ºC to measure DRS-based respiration ratio in different indoor conditions (20 and 30ºC). Six human subjects participated in this study. They were males, whose ages were between 25 and 32 and declared no pulmonary-related illnesses at the time of experiment. We requested them to wear short-sleeved T-shirts and trousers (around 0.5 clo) to minimize the effect of clothing insulation. They were also asked to avoid activities that could influence pulmonary activity prior to the experiment (e.g., drinking alcohol). After subjects entered the test-bed, they were asked to wear a respiratory belt (the MLT1132 piezo respiratory belt transducer as the ground truth sensor), seat on a chair, and stay for at least 20 minutes to fully acclimate to the thermal condition in the room (Liu et al., 2008). After satisfying all requirements, we measured subjects' respiration for two minutes employing the developed DRS platform. We used a K-LC2 dual channel Doppler radar transceiver (frequency: 24GHz). It is an economical sensor (USD 20) and the size is small (25mm×25mm×7mm). A low-noise preamplifier (SR560) is connected to the K-LC2 to perform a bandpass filtering (0.1 to 3.0Hz) and amplify the received signal in order to acquire a robust representation of pulmonary activities. The signal was collected through the National Instrument data acquisition card, NI DAQ 6008 with a 1.0kHz sampling rate. The DRS was placed at the height of subjects' chest and abdomen area and it was facing the subject to fully capture the movements. The distance between the DRS and subject was almost 50cm. Figure 4 shows the experimental setup in this study.

6. RESULTS

Before computing DRS-based respiration ratios, the validity of the DRS signals was checked with the respiratory belt signals. Both signals were converted into the frequency domain using fast Fourier transform (FFT) and we were able to check the respiration signals (the peak) in the typical respiration frequency range and both were matched (i.e., DRS accurately captured pulmonary activities). Then, the respiration ratios of six subjects in both conditions were calculated.

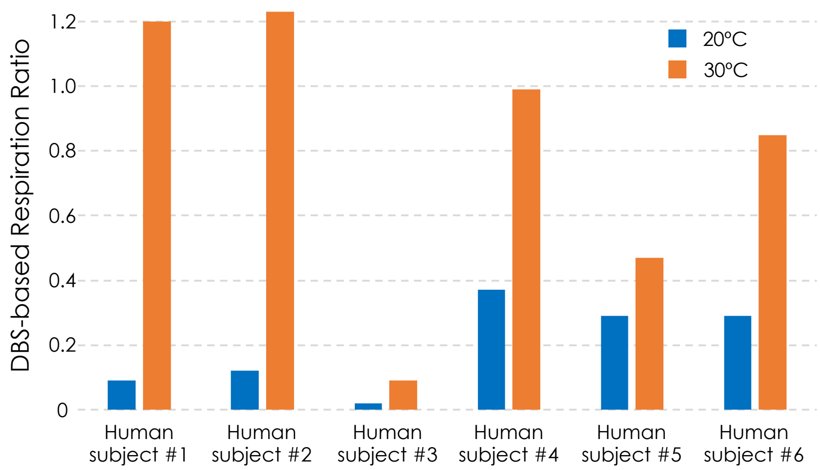

Figure 5. Six subjects' DRS-based respiration ratios in two temperatures.

As shown in Figure 5, every subject responded with an increased respiration ratio in the condition with higher temperature. However, it was noticed that individuals had different variations in their respiration ratios. Specifically, in the case of subject #3, a slight increase was observed compared to other subjects. This observation could reflect the possibility of using other heat dissipating mechanisms such as skin blood perfusion or sweating. On the other hand, for subject #1 and #2, a considerable increase in respiration ratio was observed. These observations further emphasize the variability of individuals' response when it comes to thermoregulation processes. Apart from such conclusion, it has been demonstrated that the proposed DRS-based respiration ratio evaluation method could be leveraged in reflecting occupants' sensation to the control logic of HVAC systems. It is worth noting that all human subjects felt cool/cold and warm/hot in ow and high temperatures, respectively.

7. CONCLUSIONS

Actual evaluation of metabolic rate has been deemed as a challenging task, resulting in the use of pre-determined values in the control logic of HVAC systems. As a solution, we introduced a novel and non-intrusive method of evaluating respiration ratio as a correlated indicator of metabolic rate by a cost-effective Doppler radar sensing system. Inhalation (Q_{O_2}inhaled) and exhalation (Q_{CO_2}exhaled) were quantified using the transitions from local minima to maxima and vice versa on the modulated returned signal to the sensor, affected by chest movements due to respiration. Then, respiration ratio was computed using the ratio of exhalation to inhalation. The experimental study was conducted with six male human subjects in two indoor conditions (20 and 30ºC) and we observed that all subjects had an increasing trend in their respiration ratio in the high temperature. Therefore, it was demonstrated that the proposed method enlightens the potential of obtaining actual metabolic rate non-intrusively as, according to Equation (1), the body surface area and volumetric rate of oxygen consumption are the only remaining parameters that are required to calculate metabolic rate using respiration. In the end, it is expected to provide actual metabolic data to current HVAC systems and our envisioned thermoregulation-based HVAC system as one of the features that this system can leverage.

In our future efforts, we have planned to expand this study. We only considered two distinct indoor conditions in our experiment and subjects went through an acclimation time to ensure a fully triggered thermoregulation state. However, it is desired to provide prompt feedback to HVAC systems and minimize discomfort. Therefore, sensitivity of the measurement technologies is an important factor that should be taken into account. Accordingly, analyses under transient temperatures will be considered in our future study. Furthermore, evaluating the feasibility of DRS systems with different spatial distribution in an environment as a factor of technology applicability in concomitant with addressing the challenges in multi-occupancy environments are among our future research directions.

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