Potentials of radar sensor detecting the presence of an imitated user for optimising short-range presence-sensing lighting in homes

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Abstract. Current presence-sensing technologies for energy-efficient lighting control and building optimisation are (i) catered to commercial and institutional environments, and (ii) focused on lamp technology and occupancy detection. They often ignore user behaviour characteristics, which significantly influence energy consumption. Therefore, this study aims to identify alternative sensing techniques as part of a lighting control system that can energy-efficiently support user's behavioural needs in mixed-function residential spaces. An exploratory study investigated the optimal placement of a non-wearable radar sensor to detect an imitated user's breathing frequency at varying pre-set horizontal distance positions, and the sensor's performance was validated with a spirometer. The procedure measured a balloon's radar-detected distance, radar-detected breathing frequency, and spirometer-registered breathing frequency at each pre-set position. The radar sensor detected all simulated breathing frequencies with almost 100% data accuracy but was not comparable in detecting all distances. The radar offers a less intrusive short-range presence-sensing for homes, accurately detecting breathing frequencies in a contactless way between 0.2m to 0.8m. Further investigations are recommended to develop radar sensing that could predict lighting options based on user's objective feedback.

1. Introduction

Energy-efficient and saving strategies for the residential sector are prioritised in Sweden as energy price rises. The Swedish residential sector (small, multi-family, and holiday houses) consumed almost one-third (28%) of the total electricity power in 2019 [1]. It is expected that household electricity consumption will increase even more with a hybrid workstyle and longer occupancy hours at home becoming prevalent post-pandemic [2,3]. Moreover, Swedish homes are known for most luminaires per home, sparsely switching them off and purposely leaving them on in unoccupied rooms for psychological well-being and sociocultural reasons [4,5]. In terms of household electricity usage, lighting consumes 15% to 30% of energy in Sweden [4,6,7].

Interestingly, sensing technologies have evolved rapidly over the last few years, connected to the Internet of Things for assisting user's day-to-day lives in built environments. However, most sensing technologies were developed based on large, uniform typologies applicable to commercial and institutional settings rather than small, integrated home layouts [4,8,9]. Available energy-saving sensing approaches focused on lamp technology [7,9] and occupancy detection [10], ignoring user behaviour characteristics, which significantly influence energy consumption [9,11–13]. Energy efficient effectiveness is lost when homes that incorporate the sensing technologies experience inconvenience with unwanted lighting triggering unnecessarily, likely due to the sensor's wide detection coverage and placement conflicts [14]. Therefore, there is a need to study how the sensors as part of a lighting control system can energy-efficiently support user's behavioural needs in a home. Alternative presence-sensing techniques may be required for homes with mixed-function spaces and dynamic occupancy behaviours. The research question lies in the prospective type of sensors and the localised placement for optimising presence-sensing lighting in a mixed-function home.

Radio Detection And Ranging (Radar) sensors were explored as they enable presence sensing in smaller zones by detecting user's vital signs like breathing frequency (BF) and heart rates. It could be a strategy to (i) anticipate localised lighting for a user according to his/her BF, activity, and time of day; (ii) switch on/off the lighting efficiently in unoccupied spaces, overcoming the problems of false alarms caused by non-human objects, dead spots in conventional sensors; and (iii) avoid privacy concerns related to visual sensing [15,16]. A radar sensor offers short-range vital signs detection from 0.2m to 1.2m and presence detection up to 4m [17,18]. Focusing real-time sensing on specific parts of the human body (torso) and limiting the type of objective vital sign measurements could also help reduce user's indirect psychological stress as fewer personal data (non-invasive to privacy) are permitted to be tracked in a private home environment. For example, sensing a user's BF in smaller zones could assist the daily living of at least two users in a small home with personalised lighting for each person if they are beyond a pre-set distance. It is theoretically hypothesised that an activating lighting could be applied for a user who is exercising (detection of higher breathing rate) in the living zone, while dim/no lighting for another who is sleeping (detection of slower breathing rate) in the bedroom zone in a small, integrated mixed-function home.

2. Methodology

In line with the hypothesis, this study first initiated an exploratory experiment investigating the non-wearable radar sensor's sensitivity in detecting an imitated user's BF at varying pre-set horizontal distance positions (HDX). A 60 GHz pulsed coherent radar sensor module (XM112 and XB112, Acconeer) was used to capture the movement of a reflective foil balloon, mimicking the inhaling and exhaling chest movements of an artificial human lung in a sitting position. The pre-set HDX were marked on the surface of a rectangular tabletop starting at 0.2m, 0.3m, and consistently increasing to 1.0m from the fixed balloon's position. The radar sensor could slide along the tabletop to relate to the varying HDX, maintaining a fixed height and angle (90º perpendicular) measurement with the balloon, which was also fixed on the tabletop (0.8m height from finished floor level) and its expandable plane positioned to face the radar sensor (Figure 1).

A spirometer (Oxycon Pro, Jaeger) was used to physiologically register the BF measurements (standard medical technique) and verify the accuracy of the radar-detected BF for ground truth comparison. A 3-litre calibration syringe (Welch Allyn) simulated three BF 6, 12, and 20 breaths per minute (bpm), representing the normal relaxed and resting physiological range of respiratory rate among adults over 18 years old during sedentary activities [19–21]. A mobile app (Paced Breathing 2.0) guided the rhythmic BF simulation. The exploratory experiment procedure involved 5-minute measurements of the radar-measured distance of the balloon (RX), radar-detected BF (RBF), and spirometer-measured BF (SBF) at each HDX. The measurement for 6bpm was done in ascending HDX order, while randomised for 12bpm and 20bpm. A Python-coded algorithm recorded the continuous real-time data and plotted the relative movement graph for computing the 2nd, 3rd, and 4th minute RBF. The 1st and 5th minute RBF were used for stabilising the rhythmic BF simulation, and data transfer for signal processing (data not included in the analysis). The study was conducted in January 2023 in a controlled laboratory environment. The laboratory's environmental conditions were measured every 5 minutes using a Hobo Pendant MX sensor for horizontal illuminance, and a YoYo YL-M62 sensor for temperature and relative humidity.

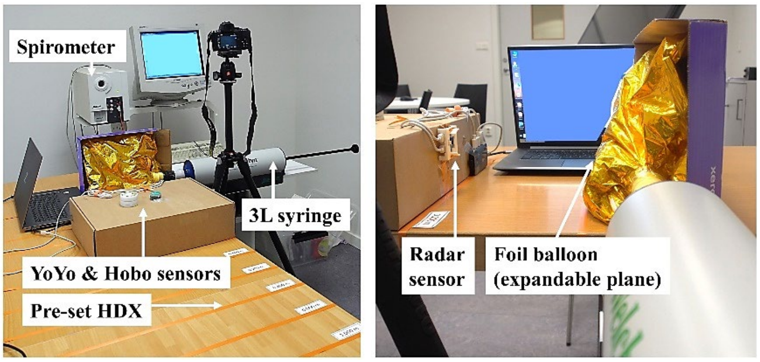

Figure 1. Exploratory experiment setup.

3. Results

A total of 81 stimuli (3 minutes per BF x 3 BF x 9 HDX) were analysed for each outcome measure - RBF, SBF and RX. The RBF for 6, 12, and 20 bpm were manually computed from the relative movement graph (Figure 2). Results are presented as descriptive statistics and Bland-Altman plot analysis (IBM, SPSS, v.28). Bland-Altman analysis was used to assess any likely agreement between the RBF and SBF for vital sign measurements and RX and HDX for distance [22,23].

3.1. Breathing Frequency

The radar sensor detected all three BFs. The descriptive statistics indicated almost 100% data accuracy between the mean RBF and mean SBF for each HDX (Figure 3a). The Bland-Altman plot (Figure 3b) indicated no proportional bias in the data points (unstandardised β coefficient = -0.001, p = n.s.), which were mostly distributed close to the mean bias line of 0.004 m, and within the limit of agreement (upper and lower 95% confidence interval).

3.2 Distance

The radar sensor detected distances with a reasonably good agreement between the RX and the HDX, except for distances 0.9m and 1.0m, which lacked accuracy. A consistent trend of closely overlapping RX was observed (data points with similar distribution) for the three BF from 0.2m to 0.8m (Figure 3c). The RX ranged between HDX ± 0.1m, likely due to the balloon's dynamic wavy surface movement. The Bland-Altman plot (Figure 3d) indicated no proportional bias in the data points (unstandardised β coefficient = -0.083, p = n.s.), which were mostly distributed close to the mean bias line of 0.011 m, and within the limit of agreement (upper and lower 95% confidence interval).

4. Discussion, Limitations and Conclusion

This study validated the performance of the radar sensor (relative sensitivity and accuracy) in presence-sensing an imitated user (foil balloon) with a spirometer and pre-set HDX as ground truth comparison. The fairly accurate measurements of RBF and RX indicate that the proposed short-range presence-sensing method offers a promising and effective solution to continuously detect a user in a sitting posture within a smaller horizontal zone between 0.2m to 0.8m. Interestingly, this study noticed increasing the presence-sensing zone beyond 0.9m to 1.0m could be slightly tricky. The radar sensor efficiently captured a user's breathing activity up to 1.0m concurring with findings from [24,25], but came with larger errors in the distance measurements.

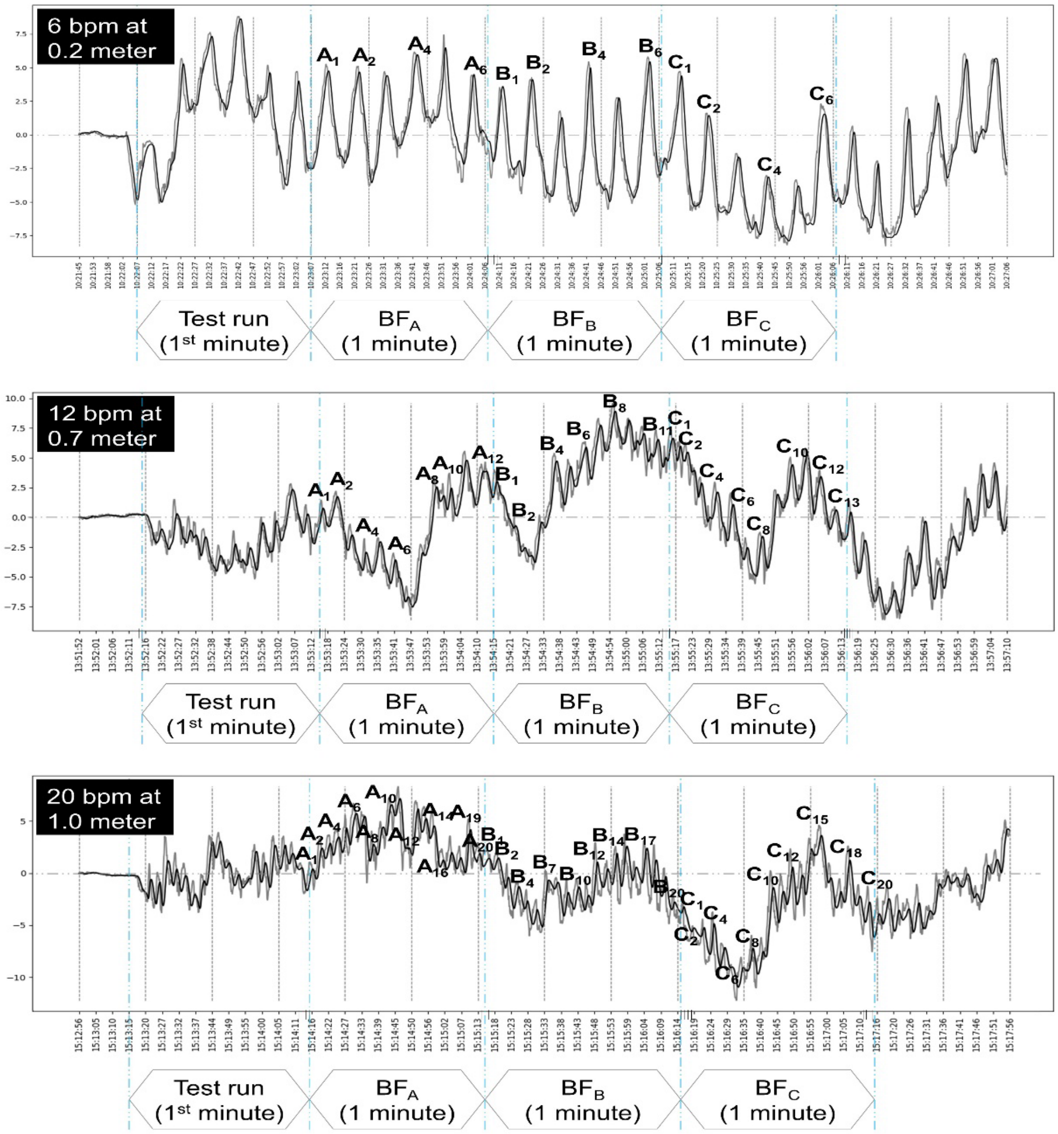

Figure 2. Sample of RBF at 6, 12, and 20 bpm manually computed from the relative movement graph.

These results were interpreted based on the detection of three controlled BF, representing a slow (6 bpm) and typical range (12 to 20 bpm) of human respiratory rates during sedentary activities. Studying short-range presence-sensing (0.2m to 1.0m) presented a radar sensor's effective horizontal zoning limit for practical positioning within a small, mixed-function home. Understanding presence-sensing by 0.1m interval accuracy is a starting point to help minimize zone overlaps, thus reducing the conflict of unnecessarily switching on almost all lights as users move between integrated spaces like living, kitchen, and bedroom. In real-life conditions, the user's BF is dynamic and posture orientations may not always face the sensor perpendicularly. Hence, further investigations are recommended to evaluate the radar sensor's performance in terms of vertical and angular detection, considering the different height levels of a user's torso and varying postures. They will provide valuable insights into understanding the directionality in sensing a user's presence in a 3D space.

Additionally, this study presents the prospectives of a user-responsive presence-sensing for private home environments that provides objective feedback which does not require complex interpretation from medically trained professionals. Optimising the radar presence-sensing lighting with vital sign detection in smaller zones could also energy-efficiently minimise any wasted light practice (unnecessary lights left on in unoccupied spaces) and be plausible in triggering an emergency alarm if abnormal BR is detected for security and safety or saving people from dying alone. In conclusion, the radar sensor offers a less invasive approach for sensing a user's presence at home and detecting objective BF measures in a contactless way. It provides an alternative for predicting lighting options that could support user's behavioural needs according to activity and time of day.

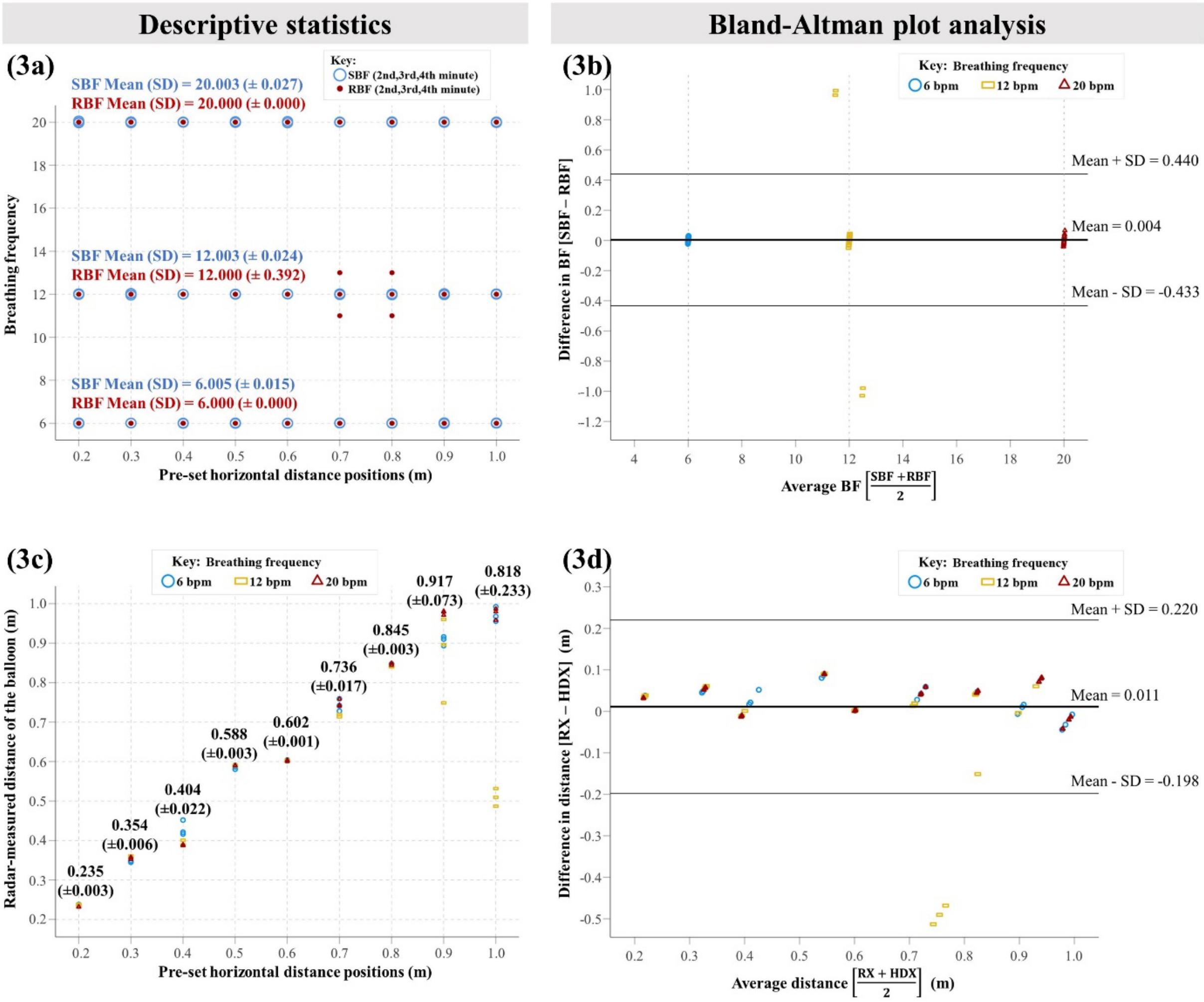

Figure 3. Descriptive statistics and Bland-Altman plot analysis for BF and distance.

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