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Doppler Radar Occupancy Sensing and Monitoring for Smart Buildings

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Abstract— **Smart buildings promise to adapt environmental conditions to the needs of occupants based on statistical analytics applied to various monitored data. While sensors for accurate monitoring of building parameters such as temperature, lighting, and air-quality abound, currently available occupancy sensors are limited to sensing of presence only, with limited accuracy. Doppler radar sensors have shown great promise for unobtrusive recognition and monitoring of occupant presence, count, activity, and cardiopulmonary vital signs. With such measures, a smart building can optimize operations not only for the most efficient use of energy and space, but also to create healthy and sustainable environments that support occupant wellness, comfort, and productivity. This paper presents an overview of Doppler radar occupancy sensors for smart building applications.**

***Keywords*—Doppler radar, occupancy sensing, smart buildings.**

I. INTRODUCTION

In urban environments, people spend about 90% of their time indoors [1]. Besides residential dwellings, these indoor environments include commercial buildings, such as, for example, office buildings, educational institutions, healthcare facilities, and commerce and hospitality buildings. Since people spend most of their time indoors, understanding how indoor environmental quality (IEQ) impacts human health and productivity is of great importance. Studies have shown that improvements in IEQ are correlated with human health [2]. However, while sensors for accurate monitoring of building parameters such as temperature, lighting, and air-quality are readily available, measuring impact of IEQ on human physiology is still a challenge. Another important aspect of human interactions with built environment is energy use and its contribution to climate change. Residential and commercial buildings account for 40% of global energy consumption, and 28% of CO_2 emissions [3]. About half of the energy used in residential and commercial buildings is consumed by heating, ventilation and air-conditioning (HVAC) [4].

HVAC systems are usually controlled with simple thermostat settings and typically operate at full capacity regardless of actual occupancy in the conditioned space. This results in significant energy waste, while not necessarily providing optimal thermal comfort [5]. The key to eliminating waste in HVAC systems is to provide heating and cooling only when, where, and as much as they are needed. Such occupant based HVAC control would require high resolution occupancy information, including not only binary information on human presence, but also occupant count. Furthermore, occupant vital signs may be used to assess wellness and comfort of occupants. Occupancy and comfort information may enable proactive adjustment of lighting, temperature, and ventilation to maintain occupant wellness, comfort, and productivity while reducing energy consumption [6].

Fig. 1. Doppler radar occupancy sensors concept. Radio waves reflected from the occupants are modulated by human vital signs. Room occupancy data may be used to optimize energy and space utilization, and vital signs data may be used to optimize IEQ for occupant wellness.

Occupancy sensors are most commonly implemented using passive infrared (PIR) and ultra-sound (US) technology, and used to control lighting. PIR sensors are based on detecting a thermal change in the field of view and typically require a large motion, such as walking, to trigger detection. These sensors often fail to detect occupants (false negatives) if there is no significant motion, for example if occupants are doing office work, or watching TV [7]. Thus long time delay settings are typically implemented with lighting controls to reduce user dissatisfaction, however this reduces potential electricity savings. On the other hand, ultra-sonic sensors commonly exhibit high rates of false positives, due to for example air movement, which also limits energy savings.

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Doppler radar (DR) technology has recently been demonstrated to provide a more robust alternative for occupancy sensing [8-10]. Figure 1 illustrates DR occupancy sensor concept. DR sensor emits radio waves that are reflected from the occupants and objects in the monitored space. Reflections from occupants are modulated with human chest motion due to respiration and heartbeat, and by mixing the reflected signal with the fraction of the transmitted signal, this modulation can be detected. Room occupancy is determined based on presence of human vital signs. Room occupancy data may be used to optimize energy and space utilization, and vital signs data may be used to optimize IEQ for occupant wellness. While detection of a single stationary occupant is the most challenging scenario for PIR sensors, this is the most ideal case for obtaining vital signs using DR sensors. Additionally, occupant count may be estimated based on the number of physiological signal sources, and individual physiological data may be recovered. Thus the advantages of DR technology include the ability to not only detect stationary occupants, but also provide occupant count [11] and occupant vital signs that may be used for thermal comfort assessment [12]. These features are particularly promising for both HVAC energy reduction and IEQ improvement in indoor environments.

This paper present an overview of recent developments in DR technology for smart buildings, including occupancy/vacancy sensing, occupant count, and measurements of human thermal response.

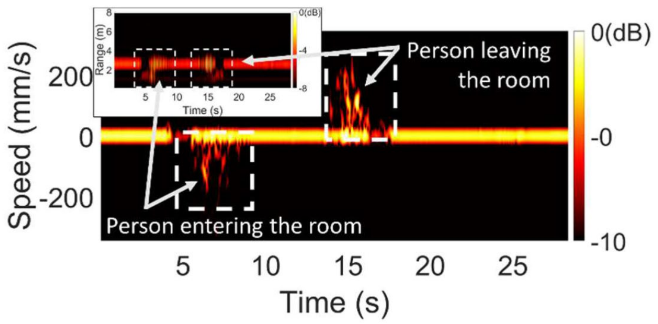


Fig. 2. Micro-Doppler signatures of door crossing obtained using 24 GHz Infineon BGT24MTR11 transceiver operating in FMCW mode [8].

II. DOPPLER RADAR OCCUPANCY SENSING

Doppler radar fundamentally operates as a motion detector, with the ability to detect a wide range of motion, including walking and very small physiological displacements due to respiration and heartbeat. This principle has been explored for occupancy sensing both through detection of entry/exit events [8, 13-14], and detection of stationary occupants, at frequencies ranging from 2.4 GHz to 60 GHz [9-10, 12]. In [8], 24 GHz DR ranging sensor uses Infineon BGT24MTR11 SiGe transceiver operating in FMCW mode. This sensor was used on the upper side of a door frame to detect door crossings, as well as for indoor occupancy monitoring, and HVAC control gesture recognition. Fig. 2 shows micro-Doppler signatures of door crossing obtained using this sensor. The same sensor was also used to reliably detect a stationary occupant at a distance of 5 meters, and to interpret occupant start, stop, and reset commands to control HVAC. In

Fig. 3. 2.4 GHz and 5.8 GHz DR sensor mounted on top of a doorway [13].

[13], sensors mounted on top of a doorway (Fig.3) were used to detect occupancy at zone transition points. 2.4 GHz radar was used for door crossing detection, whereas 5.8 GHz radar was used for direction estimation. Data was collected for 200 hours, with over 1600 doorway crossings, with precision, recall and direction accuracy of over 99% in the scripted studies, and over 95% in the in-situ studies, with average power consumption of 6.1 mW.

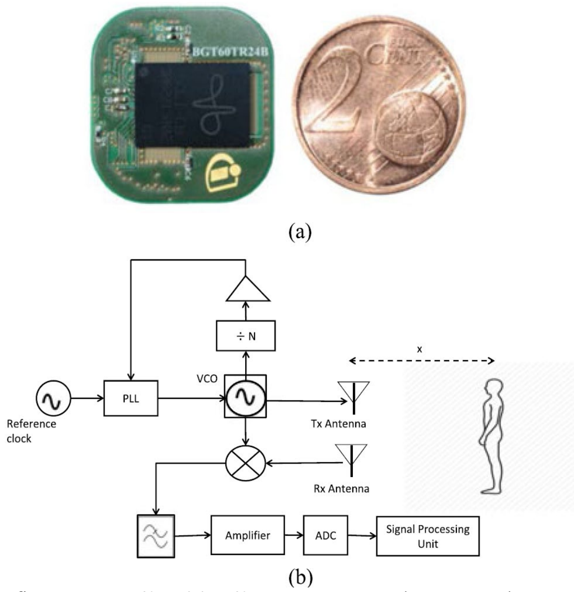
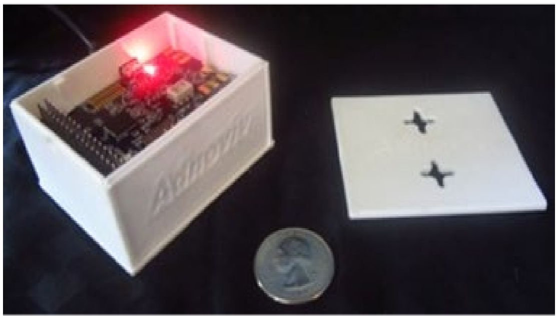
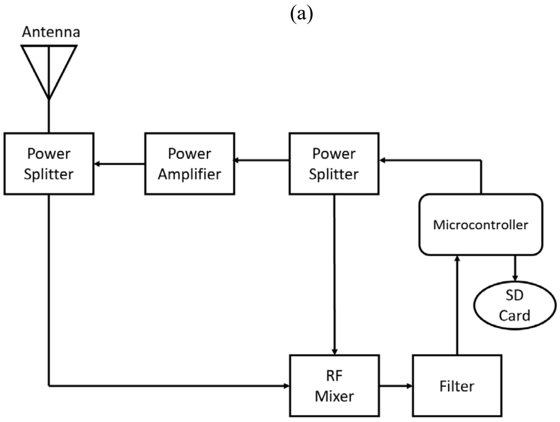


Fig. 4. Infineon's BGT60TR24B 60 GHz FMCW radar sensor photograph (a) and block diagram (b) [10].

24 GHz DR occupancy sensor was also demonstrated effective with a low power consumption of only 0.2 mW by using intermittent measurements. This system reliably detected periodic motion of a small metallic target simulating human breathing at a distance of 2 meters [9]. 60 GHz FMCW ranging sensor, shown in Fig. 4, was demonstrated effective for reliable occupancy detection and occupant count of up to three people in a typical office environment [10].



(a)



(b)

Fig. 5. TruePODS photograph (a), and a block diagram (b). A single channel CW radar operating at 2.4 GHz is used to minimize cost and optimize room coverage.

The True Presence Occupancy Detection Sensor (TruePODS™) shown in Fig. 5 is the first fully-integrated DR occupancy sensor using simple, low-cost single channel 2.4 GHz radar that has been validated for occupancy/vacancy detection under realistic conditions [12]. Operation frequency of 2.4 GHz was chosen to minimize hardware cost, while providing wide area coverage of about 1000 square feet with a single ceiling-mount sensor. TruePODS modules have been tested in the Smart Conference Room testbed in the LESA (Light Enabled Systems & Applications) Center at Rensselaer Polytechnic Institute with over 27 hours of data. The Smart Conference Room (SCR), has dimensions of 3.4m x 8.5m, and seats up to 23 people. Occupancy was differentiated from an empty room over 93% of the time with a single sensor in both wall and ceiling-mounted configurations. Heart and respiratory rates were detected in all seats in the conference room with a single ceiling-mounted sensor. Heart and respiratory rate sensing could provide information to future human-building interactive systems to optimize occupant comfort.

III. Thermal Response Assessment

Human thermal comfort plays an essential role in human productivity in office areas [15] and healing in hospitals [16]; however HVAC systems often fail to provide a comfortable environment. The main reason for this issue is that most HVAC control systems operate within a narrow temperature range, often resulting in uncomfortable temperatures: too hot or too cold [17]. Although there are emerging HVAC system

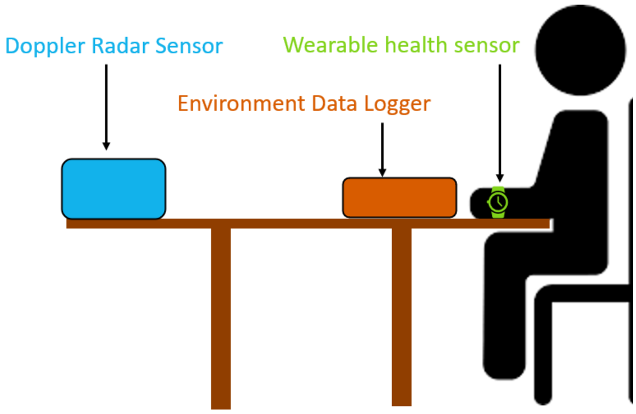


Fig. 6. Experimental set-up for thermal comfort assessment. DR occupancy sensor was used to detect changes in physiology due to changing environmental conditions.

models that involve thermal comfort information in the control system, these models have limitations due to the requirements for contact measurements, such as skin temperature and electroencephalogram (EEG) [18-19]. Occupant heart rate and respiration rate can be used to assess thermal comfort, due to the role cardiovascular regulation plays in heat dissipation. The relationship between ambient temperature and heart rate has been assessed previously using contact sensors [20]. DR occupancy sensors have a potential to provide a non-contact alternative for thermal comfort assessment.

A preliminary study was carried out using TruePODS to assess thermal adaptation. A wrist-worn wearable health sensor from Maxim Integrated, MAXREFDES103, was used as a reference to extract human vital signs by analyzing the data from the photoplethysmography (PPG) sensor with a 100 Hz sampling rate. MX1102 Hobo Logger was used to measure temperature and humidity with a 1 Hz sampling rate. Experimental set-up is illustrated in Fig. 6. Heart rate and respiration rate for three human subjects were measured under varying environmental conditions, and PPG was used to verify Doppler radar accuracy. Three locations were used with a range of temperature between 70 °F to 80°F. Each participant' information was taken in the three locations on the same day. The experiment started in the hottest environment and ended in the lowest temperature area. In each location, participants were seated for 10 minutes so that their bodies can be adjusted to the environment. After that their physiological signs were recorded for 3 minutes with a Doppler radar sensor and a wearable health sensor, while an environmental data logger was used to simultaneously record temperature and humidity. Both heart rate and respiration rate increased at higher temperature, while correlation with comfort levels was less clear. This may be due to varying humidity levels and choice of clothing

TruePODS was further used to measure physiological parameters of ten human subjects under two temperature conditions, of 70°F an 85°F with 30 minutes of adaptation time at each temperature. Thermal comfort surveys were used to record thermal sensation on the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) scale [21]. The results demonstrate that the

Doppler radar occupancy sensor can be used to 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 are not captured by the surveys [22].

IV. Conclusion

Doppler radar occupancy sensing is a promising technology for minimizing energy consumption and optimizing human comfort in smart buildings. The particular strength of Doppler radar is its ability to reliably detect stationary occupants, which is a limitation for most commonly used passive infrared sensors. Radar modules operating at frequencies from 2.4 GHz to 60 GHz have been demonstrated effective for occupancy detection. Radar sensors can be used both for detection of door crossings and indoor occupancy. In addition, heart and respiration signals obtained with Doppler radar can be used for non-contact assessment of occupant thermal comfort and future HVAC control to provide healthy and sustainable environments that support occupant wellness, comfort, and productivity.

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