A Review of Low-Cost Bio-Acoustic Human Presence Detection

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Abstract:

In smart buildings, energy-efficient HVAC/light control, security and health-aware environments, human occupancy information is critical to these systems. Current methods of sensing human occupancy, such as Passive Infrared (PIR), Carbon Dioxide (CO_2), Radio Frequency (RF) and vision-based systems typically have limitations regarding privacy, visibility restrictions, and limited accuracy when an individual is stationary and expensive and complicated. In this paper, proposes and describe an alternate paradigm for detecting the occupancy of humans by utilizing and analysing low-frequency acoustic signals produced from natural breathing of an individual, micro-movement of the chest and/or body. The current state of the art in acoustic/non-intrusive presence sensing; the physiological properties and characteristics of signals related to bio-acoustics and the use of low-cost MEMS microphones and embedded microcontrollers to provide real-time human occupancy detection applications. Bio-acoustic sensing with traditional methods on several factors as privacy, cost, ability to detect a stationary person, environmental sensitivity. The paper concludes with identifying areas for future research which involve sensor integration, adaptive signal processing, and embedded real-time implementation. The paper concludes by supporting bio-acoustic detection as a feasible, low-cost, privacy-oriented method to detect the presence of people within smart buildings and homes.

Keywords:

Acoustic signals, Bio-acoustic sensing, Low-frequency, MEMS microphones

1 Introduction

Occupancy of a building is vital for its efficiency, as the heating, cooling and lighting systems in smart buildings are based on whether or not people are in the space. Therefore, to ensure optimal resource use and indoor comfort, smart buildings must be able to accurately detect human occupancy to manage their energy efficiency. Previous studies indicate that occupancy-based control of heating, cooling and lighting systems can greatly reduce energy use by eliminating unnecessary energy consumption when no one is in the building [1-2]. As a result, there is a need for affordable, reliable and privacy-friendly means of detecting occupancy in buildings. There are many different types of sensing modalities that can be used to detect occupancy, including: Passive Infrared (PIR), Co2 (Carbon Dioxide) concentration tracking, vision systems using cameras, radar or ultrasonic sensors and environmental or device based sensing methods like wifi and motion tracking. The majority of these modalities present limitations. PIR/ Motion sensors typically cannot detect people who are not moving (e.g., sleeping). Co2 sensors typically provide only coarse temporal (time) and spatial (space) data regarding occupancy status, and in many cases, have a time lag in reporting changes in the number of people present. Cameras offer privacy issues, require advanced computing capabilities and have a high processing and storage requirement on cloud server systems. RF/ WiFi solutions require that people carry a device (cellphone) with them when they enter the area, or they require an extensive and expensive network of cameras or base stations to provide service [3-5]. The difficulties presented by these modalities will result in less accurate occupancy detection in locations that are significantly concerned about privacy (e.g., bedrooms, rest areas and assisted living facilities) and will present additional challenges in long-term deployments. To overcome these limitations, bio-acoustic human presence detection, the sensing of low-frequency acoustic or mechano-acoustic signals produced by human physiological functions such as respiration or subtle body micro-movements, emerges as a promising alternative. Acoustic and remote vital-sign monitoring research has demonstrated that non-contact microphones can capture breathing and other subtle body-generated signals from a distance with sufficient sensitivity [6-7]. Translating these principles into room-scale occupancy sensing could enable detection of even stationary occupants without capturing identifying visual information, satisfying both privacyandreliability requirements.

This paper presents an overview of the potential use of bio-acoustic sensing in detecting humans, along with a detailed review of all current occupancy sensing technologies and limitations. These objectives include: to perform a literature review on current methods of occupancy detection and the limitations associated with them; to analyse the physiological and acoustic basis of bio-acoustic sensing; to review available acoustic and non-contact vital-sign literature for relevance; to identify gaps in the current state of knowledge regarding bio-acoustics; and to develop a reference architecture for low-cost embedded bio-acoustic sensors and recommend future directions for research on the practical deployment of bio-acoustic sensing.

The remainder of this paper is organized as follows: Section 2 outlines background and privacy constraints in occupancy sensing; Section 3 discusses fundamentals of human bio-acoustic signals, Section 4 reviews acoustic and bio-acoustic studies relevant to presence and vital-sign detection, Section 5 highlights challenges and open research questions, and Section 6 concludes the review.

3. Fundamentals of Bio-Acoustic Sensing of the Human Body

Bio-acoustic sensing draws upon a long history of studying how the human body produces mechanical vibrations and acoustic emissions during normal physiological activity. Although these signals are often associated with clinical monitoring, many of the underlying mechanisms are relevant to presence detection as well. The human body constantly generates a mixture of subtle sounds and micro-motions, and even during quiet rest, these signals persist in faint but characteristic ways [16]. Understanding where these signals originate, how they propagate, and what their spectral signatures look like provides the foundation for any attempt to use them in an indoor sensing context.

3.1 Physiological Origins and Characteristic Signal Patterns

A considerable portion of body-generated acoustics comes from the cardiopulmonary system. Heart valve closures, vascular pressure changes, and the rhythmic motion of the chest wall all contribute to low-frequency vibrations. Respiration produces a broader variety of signatures, spanning airflow turbulence in the upper airways, the opening and closing of alveolar structures, and the gentle displacement of the thoracic cavity [16-17]. While the audible portion of lung sounds typically lies in the tens to hundreds of hertz range, researchers have pointed out that the slow mechanical motion associated with breathing, essentially the inflation and deflation of the chest wall, introduces energy at far lower frequencies than the acoustic component alone would suggest [18-19].

Another important aspect of physiological rhythms is their lack of complete uniformity. Breathing, variations in posture, stress, state of health, and/or behaviour will create irregularities in the observed waveform or signal that will become more apparent over longer timeframes. Although these irregularities may prove difficult for doctors who use them to diagnose patients, they can be useful when attempting to determine whether a specific rhythm is of biological origin. Earlier work using mechano-acoustic sensing techniques has shown that low-frequency, low-amplitude fluctuations exhibit greater degrees of variation than typical environmental noise sources [20-23].

3.2 Sensing Mechanisms and Acquisition Technologies

Bio-acoustic signals can be measured in more than one way. Traditional medical devices rely on stethoscopes or contact microphones pressed against the skin, which provide clean recordings of lung and heart sounds. Over the past decade, however, the field has expanded to include wearable mechano-acoustic sensors, flexible patches, and miniature accelerometers capable of capturing subtle skin vibrations with millimeter-level displacement sensitivity [20-22].These devices are generally optimized for clinical monitoring, where coupling to the body is required.For the purpose of indoor presence detection, air-coupled microphones, particularly low-noise MEMS devices, become more relevant. While originally designed for consumer audio, MEMS microphones have been used in remote respiratory monitoring experiments where microphones placed at modest distances were able to detect breathing activity under quiet conditions [19, 31]. Their sensitivity at low frequencies is not perfect, but with appropriate pre-amplification and filtering, these sensors can reveal the envelope modulation associated with respirationa feature that persists even when higher-frequency acoustic components are masked or attenuated. A second advantage of using air-coupled sensors is that they can be installed unobtrusively within indoor spaces. Unlike RF- or camera-based sensing, microphones do not inherently capture identity-specific cues if processing is restricted to low-frequency envelopes or mechanical modulation rather than speech or detailed audio content. This selective use of the acoustic band makes bio-acoustic sensing potentially more privacy-preserving than conventional audio-based systems [32].

3.3 Signal Properties Relevant to Presence Detection

Respiratory motion typically occurs at 5–40 breaths per minute, corresponding to baseline frequencies in the range of 0.08–0.67 Hz, sometimes accompanied by harmonic or envelope-related activity slightly above this range [24]. Although these frequencies fall below the audible domain, they manifest indirectly through chest motion, airflow modulation, or near-field turbulence. When recorded in the time domain, these signals appear as slow, quasi-periodic fluctuations that are distinguishable from the random broadband noise commonly found in indoor environments. This observation has several implications. First, a sensing system must maintain low-frequency content in its processing chain, so the analog front-end should not apply excessive high-pass filtering. Second, during digital signal processing, the detection algorithm should evaluate sufficiently long time windows (tens of seconds) to capture a minimum of three to five complete respiration cycles, particularly during sleep when respiration rates are usually lower. Third, the sensing system must be able to distinguish between biological periodicity and non-biological (due to external influences), low-frequency disturbances (such as HVAC-induced vibrations or structural resonance). Remote respiration-monitoring research has shown that the envelope of breathing provides ipso facto temporal information regarding respiration; this temporal information is preserved even when the amplitude of the envelope changes dramatically [31].Overall, the physiological and mechanical basis of human bio-acoustic signals suggests that a room-scale sensing system could, in principle, identify the presence of a person by tracking these subtle, continuous rhythms. While most prior research has emphasized clinical or wearable applications, the underlying signal properties do extend naturally to the type of problem considered in this review.

4. Acoustic and Bio-Acoustic Methods for Human Presence and Vital-Sign Detection

Acoustic sensing has been explored across several research domains, most notably in respiratory monitoring, contact-based mechano-acoustic diagnostics, and environmental-sound analysis. Although these strands of work were not originally developed for occupancy detection, they provide useful insights for understanding how acoustic signals can reveal human presence in indoor spaces. This section reviews representative studies in these areas and highlights their relevance to the present topic.

4.1 Remote Acoustic Monitoring of Respiratory Activity

There is a lot of literature that discusses how to detect respiration without touch; early studies showed that using a microphone placed some distance away from a person could capture breathing patterns by way of small sound waves created by the air passing over the microphone or by way of changes in power caused by the air leaving and entering the body [33]. More recently, researchers have conducted work on the use of smartphones and small lightweight devices to determine a person's respiratory rate(s), using data collected while a person is engaged in normal daily activity in their environment, and have shown that low-frequency sound waves created by the air leaving and entering a person's mouth (e.g., when he/she is talking) provide sufficient stability to allow the extraction of the respiratory rates from the collected data in the presence of low ambient sound levels [34].While these studies were typically conducted in controlled settings rather than real-life spaces where people were currently located, they all indicate that breathing's overall pattern (i.e., its temporal structure) consists of three distinct periods slow, periodic, and continuous. Any of these can potentially indicate that there are people somewhere in the vicinity of the measurement.

4.2 Mechano-Acoustic and Contact-Based Vital-Sign Sensing

Another body of work examines contact or near-contact mechano-acoustic sensors, such as accelerometers, flexible patches, and chest-mounted microphones. These devices capture vibrations originating from the heart, lungs, or musculoskeletal activity [16, 21, 22]. While their clinical focus differs from the needs of occupancy detection, several characteristics are relevant. Originally, mechano-acoustic sensing elements measure low frequency data from a person's breath over a period of time. Secondly, these types of sensors allow for continual measurement of low frequency information related to human breathing cycles throughout an inactive (resting) state (regardless if a person is at home, work, or elsewhere). Thirdly, a number of studies have suggested the importance of long observation periods and noise aware (adaptive) filtering strategies as equally important design issues to be addressed. Though these sensors require direct coupling to the body and are therefore unsuitable for building deployment, they provide evidence that the physiological signatures underlying human presence are mechanically robust and can be measured in more than one modality.

4.3 Acoustic Event Detection and Ambient-Sound-Based Occupancy Inference

Ambient audio patterns are being studied to see if they can be used to determine whether an area is occupied or not by listening for environmental sounds that correlate with different activities such as talking or walking around. These methods do not need as much specialized equipment compared to other technologies currently available; therefore, they provide convenience for users. However, there are concerns about privacy because of the potential for sensitive data to be collected via the use of sounds associated with human activity. Additionally, it may not be possible to identify occupancy levels based solely upon auditory signals due to the limitation of having individuals being quiet or stationary making identification of occupancy impossible. Still, these works highlight two key aspects. First, they demonstrate that microphones can be used as natural omnipresent sensors. Secondly, the use of acoustics processing does not have to be based only on the recognition of spoken language or any other sensitive information. Rather, it can extract occupancy signals from lower level temporal or spectral measures. This finding is of considerable importance in developing bio-acoustic detectors that respect privacy by avoiding the storage and analysis of intelligible sound.

4.4 Research Gap and Relevance to Bio-Acoustic Presence Detection

Human-generated acoustic and mechanical signals can be detected while an individual is at rest or in a quiet environment. Studies that represent these signals come from three areas of research: Contact-Based Mechanoacoustic Sensing of (biological) Human Processes; Remote Monitoring of Biomechanical Patterns; and Environmental Sound Analysis (i.e., Environmental Noise Monitoring). None of these studies directly measure human location and activity in their respective environments using low-frequency bio-acoustical signals. In general, these studies focus on medical monitoring versus occupancy detection, and the unobtrusive nature of low-frequency bio-acoustical signals makes them a candidate for further investigation as a method for detecting human occupants in indoor environments without compromising privacy.

5. Challenges, Limitations, and Open Research Problems

The concept of biological-acoustic human presence detection is still predominantly theoretical. To begin realizing the practical capabilities, a number of technical hurdles must be resolved. The first problem area involves the amount of signal-to-noise ratio (SNR). In an actual indoor environment, the SNR for biological activity will be much lower than that for common background noises produced by items and systems such as fans, HVAC systems, structural vibrations and disturbances resulting from humans in proximity. These background noise sources typically exist in the same low frequency range as the biological sounds, making it difficult to conclusively separate the biological sound from this overlapping noise without extending the period of time over which the data is collected or employing adaptive filters.

The other challenge is how low-frequency mechanical and acoustic signals behave when they are transmitted through different mediums (specifically air). Unlike audible frequency, the propagation of sub-10 Hz signals is not as strong in the air. The measured presence of a sub-10 Hz signal with a microphone is very much affected by how the room is built (room dimensions), how far the microphone is from the room, how the air moves in the room, and what kind of furniture or soft material is present that can absorb or scatter vibrations due to sound wave behavior. These room-related effects make it difficult to create generalizable models and may necessitate the use of environment-aware calibration methods. Detecting multiple occupants is another open problem to solve. The vast majority of respiration-based methods use assumptions of a single source, a convenient assumption that does not hold true in indoor settings with multiple occupants who can create interference in their breathing patterns and create a composite breathing signature that is hard to separate into its individual components. The majority of non-contact respiratory monitoring studies focus on only one source of respiration; therefore, new techniques and or approaches must be developed to distinguish and/or sum multiple low-frequency bio-acoustic respiratory signals without having to rely on identifiable characteristics.

Privacy policies and how user’s data is handled must also be taken into consideration when using bio-acoustic sensing technology; while it may be seen as less intrusive than using camera-based tracking systems or RF tracking systems, it still relies upon microphones that can present issues with respect to a user's privacy if not appropriately controlled for access and use. In order to prevent the need to access, or have the ability to capture, intelligible audio, a user's privacy must also be preserved by ensuring that any low-frequency envelope data collected by the device is processed directly on the device and never transmitted over the network. Lack of standard datasets, benchmarks, or an established evaluation protocol is the final barrier. All current respiratory datasets are based on clinical settings, contact sensors, or controlled audio recordings, all of these fail to represent typical room acoustical conditions. Therefore, future researchers should develop and share publicly available, reproducible datasets that represent a realistic representation of environmental noise, room geometry variability, and the variances obtained through multi-occupant scenarios. Collectively, these challenges illustrate that bio-acoustic presence detection lies at the intersection of acoustic physics, physiological monitoring, embedded sensing, and privacy-aware design. Overcoming these obstacles will require coordinated advances in sensor design, signal processing, system integration, and empirical validation.

6. Conclusion

Bio-acoustic human presence detection offers an intriguing alternative to conventional occupancy-sensing technologies, particularly in scenarios where privacy, low cost, and the ability to detect stationary individuals are essential. While prior research in remote respiration monitoring, mechano-acoustic sensing, and ambient audio analysis provides the physiological and technical groundwork for this emerging direction, these studies were developed largely for medical or environmental monitoring rather than room-scale occupancy detection. As a result, the field remains at a conceptual stage, with significant opportunities for systematic exploration. Looking forward, progress will depend on interdisciplinary efforts that integrate acoustic signal processing, sensor design, embedded systems, and privacy-aware algorithms. In particular, there is a pressing need for open datasets and standardized evaluation protocols that reflect the acoustic complexity of real-world interiors. Additionally, combining bio-acoustic sensing with other non-intrusive modalities, such as low-power ambient sensors, may offer a practical pathway toward robust, privacy-preserving occupancy systems. Overall, while bio-acoustic sensing is not yet a mature solution, its conceptual advantages and physiological grounding suggest that it could evolve into a compelling component of future smart-building technologies.

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