Radar Sensing of Vital Signs in Assisted Living Applications

Giovanni Diraco, Alessandro Leone and Pietro Siciliano

Abstract In order to be accepted by users, one of the most important requirement for any assisted living technology is unobtrusiveness. This is particularly true when this technology is intended for continuous monitoring of vital signs, since traditional approaches require the subject to be tethered to measurement devices. The radar sensing is a very promising technology, enabling the measurement of vital signs at a distance, and thus meeting both requirements of unobtrusiveness and accuracy. In particular, impulse-radio ultra-wideband radar has attracted considerable attention in recent years thanks to many properties that make it useful for assisted living purposes. The aim of this paper is to investigate such radar technology for vital signs monitoring in assisted living scenarios. An algorithmic framework for the detection of respiration and heart rates during various activities of daily living is presented, including a method for compensation of movements of both the monitored subject and a second person present in the same environment (e.g., family member, caregiver, etc.). Experiments are carried out in various conditions that can be frequently encountered in assisted living scenarios. The reported results show that vital signs can be detected also while carrying out ADLs, with accuracy varying according to the level of movements and kind of involved body's parts and postures.

Keywords Patient monitoring · Vital signs · Radar · Ultra-wideband
Non-contact sensing · Assisted living

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N. Casiddu et al. (eds.), *Ambient Assisted Living*, Lecture Notes in Electrical Engineering 540, https://doi.org/10.1007/978-3-030-04672-9_1

1 Introduction

In the context of assisted living, there is an increasing demand for unobtrusive sensing of human activities and behaviors as well as physiological parameters, suitable for detection of dangerous situations (e.g., falls [1]) and even for early prediction of health disorders (e.g., illness or functional decline [2]), in order to actually provide timely medical assistance and alerts to caregivers. Nevertheless, in this context, the emphasis on unobtrusiveness is especially important. In fact, as it has been assessed in [3], older adults are more likely to accept in-home sensing technologies when these are unobtrusive, i.e., they do not demand to wear any device, not interfere with daily life, not require to learn new technical skills and, above all, not capture video images. By the way, it is only by means of a good acceptability that it is possible to provide a continuous monitoring, essential to produce long-term health data from which informative patterns can be extracted.

Among vital signs, respiration rate (RR) and heart rate (HR) are fundamental physiological parameters whose alterations may be correlated, especially during ageing, with the progress of physical illnesses (e.g., sleep-disordered breathing [4], congestive heart failure [5], subclinical inflammation [6]) as well as mental and neurodegenerative diseases (e.g., major depressive disorder [7], Parkinson disease [8, 9]).

The golden standard for measurement of the heart activity is the electrocardiograph (ECG) [10], which involves various kind of electrodes (i.e., conventional Ag–AgCl suction, adhesive gel, etc.) attached to the skin on the chest and limbs. Whereas in regards to the respiration activity, the standard measurement technique is the transthoracic impedance plethysmography (IP), requiring skin electrodes placed on the chest of which at least two must be ECG electrodes [11].

Focusing on the measurement of basic parameters, such as RR and HR, slightly more comfortable approaches may involve the use of textile dry or capacitive ECG electrodes, elastic bands around abdomen and/or chest (e.g., respiratory inductance plethysmography), optoelectronic sensors (e.g., Photoplethysmography—PPG), and even pressure or accelerometer sensors. However, all these approaches still require the subject to be tethered to a body-worn or closely located measurement device, resulting uncomfortable and unpractical for continuous monitoring in assisted living scenarios.

Remote sensing techniques offer a more suitable alternative by which RR and HR can be unobtrusively detected and measured at a distance (ranging from tens of centimeters to meters). Such techniques may exploit either optical or radio waves, leading to camera-based photoplethysmography (cbPPG) and radar sensing respectively. The working principle of cbPPG is to detect small changes in the skin color due to cyclic variations of blood volume in arteries and capillaries under skin, and thus to estimate the PPG signal which is proportional to such skin color changes [12]. Instead, the remote sensing of vital signs using radar is based on detection of small movements induced by the heartbeat and respiratory chest-wall motions [13].

The cbPPG technique, unlike the radar-based one, allows to estimate also the blood oxygen level (SpO2), but radar sensing is more accurate in estimation of RR and HR (particularly in presence of multiple heartbeats and cluttered scenarios with obstacles) [14] and, additionally, it has some characteristics that make it a promising technology for assisted living applications. First of all, it is a fully privacy-preserving sensing technology, since captured information is outside the human sensory capabilities (unlike cbPPG that captures images), and thus not directly usable for obtaining privacy-sensitive information. Secondly, it is a multi-purpose technology whose application range spans from detection and measurement of vital signs to localization, movement detection, critical event detection, and even secure high-throughput wireless communication, and all these features are available in non-line-of-sight (NLOS) and through-wall (TW) modalities [15].

The remainder of the paper is organized as follows: Sect. 2 analyses the state-of-the-art of vital signs detection, highlighting related works based on radar systems; Sect. 3 starts by giving an overview on IR-UWB radar technology adopted in this study and, afterwards, describes the processing framework, then continues detailing the experimental setup. The achieved experimental results are shown and discussed in Sect. 4. Some conclusive remarks are, finally, provided in Sect. 5.

2 Related Work

Radar-based vital sign sensing caught the interest of researchers from the 70s, when the first experiments were carried out aiming to detect remotely RR [16–18] and HR [19] parameters. The measuring principle of vital signs with radar exploits tiny chest movements caused by the respiratory and circulatory motions (contraction and expansion) which induce changes in electromagnetic (EM) wave returning back to the radar system once reflected by the subject's chest.

Such changes contain information about RR and HR of the subject, and they essentially may occur in terms of frequency, phase, and arrival time of reflected EM wave [20]. The frequency-changing effect is used in the Doppler radar which is one of the earlier radar-based approach for vital sign detection [16], and also successfully adopted for long-range (up to 69 m, in line-of-sight) detection of RR and HR [10, 21–23]. The phase-changing effect is normally exploited in the interferometric radar, recently demonstrated also for vital sign detection achieving highly accurate measurements although at the price of a greater complexity and expense [24]. Regarding the third changing effect, i.e., arrival time, it governs the working principle of impulse radar systems which, thanks to generated train of ultrashort EM pulses, can operate over a larger bandwidth and wider range of frequencies than continuous wave (CW) systems.

Impulse radars are generally referred to as impulse radio (IR) ultra-wideband (UWB) radars and, together with Doppler radars [25], are the most investigated for physiological function monitoring [26]. Since Doppler radars typically are CW narrowband systems, they can accurately measure the velocity of targets (i.e., high

Doppler resolution) but not their position (i.e., low spatial resolution), making it difficult the cancelation of motion artefacts caused by the subject or by other nearby people as well as the detection of vital signs from more than one person. Instead, IR-UWB radar sensing provides additional features over CW systems [27], particularly useful in assisted living contexts. The sub-millimeter range resolution (i.e., high spatial resolution) and high penetration power enable accurate target localization even through obstacles (e.g., TW/NLOS sensing). The shorter pulse duration, lower than the total travel time of the wave even in case of multiple reflections, is helpful to deal with multipath effects particularly insidious in indoor environments. The very low power spectral density (−41.3 dBm/MHz) prevents interferences with other radio systems operating in the same frequency range (typically, from 3.1 to 10.6 GHz), and guarantees a low probability of interception; enabling secure high-data-rate communication in short range (e.g., up to 500 Mbps at 3 m).

Although by now radar-based monitoring of physiological functions such as HR and RR is well understood and established in experimental and clinical settings as well as rescue searching and military operations [14, 25, 28–30], there are still questions about its effectiveness in assisted living contexts that should be properly addressed. Indeed, assisted living technology aims primarily to support senior citizens and frail people performing their activities of daily living (ADLs) within their living environments, in families or community homes. In such contexts, monitored subjects do not spend all day in a bed, motionless and alone, but on the contrary they are often in motion performing ADLs, sometimes receive visits, enjoy the company of a pet, and so on.

Thus, the assisted living setting poses new challenges to radar sensing of vital signs, which can be mainly ascribed to the possibly presence of “multiple people,” “slight movements of the monitored subject’s body,” and “presence of occluding obstacles.” In presence of multiple people, the radar sensor should be able to distinguish between monitored subject’s vital signs and those of other nearby people, and should be able to work properly also if nearby people move. The radar sensor should be able to still operate even in presence of slight (random) movements of the subject’s body not correlated with cardiopulmonary ones, and also under different body’s postures. In home environments, the presence of obstacles is very common, such as walls, doors, closets or other piece of furniture; nonetheless, measurement of vital signs should not be compromised by occlusions or NLOS conditions.

Some of these issues have been partially addressed in [31], suggesting an interesting radar technology (essentially, CW Doppler) for vital signs monitoring in smart homes. The authors reported good results in both HR and RR detection with accuracy ranging from 90 to 99% in various scenarios such as different distances (up to 8 m), TW, multiple people (up to 3), and during quasi-static activities (e.g., typing on laptop, watching TV, sleeping). However, this study shows several limitations, for example, the multiple-people scenario required a minimum person-to-person distance of 2 m, and common ADLs (e.g., dressing, feeding, locomotion, etc.) as well as critical circumstances (e.g., post-fall phase and recovery during which the subject may be on the ground) were not taken into account.

On the other hand, using UWB radar systems, some other studies reported better results in multi-target vital signs detection [32, 33]. Actually, the fine spatial resolution obtainable through UWB technology allowed to accurately discriminate HR ad RR of multiple people within a radius smaller than 1 m. Moreover, UWB radar was successfully used for monitoring of vital signs in environments containing other motion (i.e., nonstationary clutter suppression) [34], and even to detect the RR of a moving subject (i.e., movement compensation/suppression) [18, 35, 36]. Another common issue arising in radar-based vital signs detection concerns the breathing signal harmonics which may be several times stronger than the heartbeat frequency. Also in this case, a viable solution (i.e., harmonic canceller) has been demonstrated by using UWB radar [37].

Despite the many properties that make UWB radar useful for assisted living purposes (i.e., compact size, high penetration capability, high spatial resolution, low EM interference, low multipath interference, low power consumption, low specific absorption rates), to the best of the author's knowledge, IR-UWB radar technology has not been fully investigated for vital signs detection in assisted living contexts.

3 Materials and Methods

3.1 System Overview

The detection system, of which a schematic representation is given in Fig. 1, is composed of two IR-UWB radar units, namely the Time Domain Pulson® P410 [38], connected via USB to a laptop computer which run the computational framework described in the following section.

The P410 is a state-of-the-art UWB radar sensor, working from 3.1 to 5.3 GHz centered at 4.3 GHz, covering a distance range of about 30 m, with good object penetrating capabilities and compact (7.6 × 8.0 × 1.6 cm) board dimensions. It is equipped with an omnidirectional antenna, which in this study has been modified by adding a planar back reflector in order to reduce the azimuth pattern to around 100° (also referred as FOV—field of view—in the following). Range data coming from the P410s are stored and later analyzed in MATLAB® software R2014a (The MathWorks, Inc.).

3.2 Algorithmic Framework for Vital Signs Detection

The algorithmic framework, enclosed within the dashed area in Fig. 1, includes the following six main parts: (1) IR-UWB radar P410, (2) bandpass filtering, (3) clutter removal, (4) micro(μ-)motion spectral analysis, (5) empirical mode decomposition (EMD), (6) vital sings extraction.

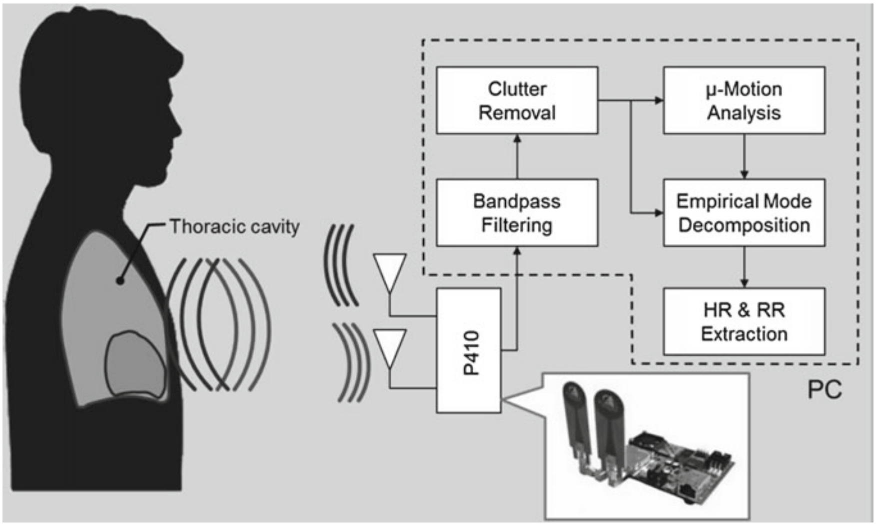

Fig. 1 System overview

In order to suppress the unwanted signal/noise frequencies out of the operative band (i.e., 3.1–5.3 GHz), a bandpass filter has been included in the first stage of the pipeline. At this end, a 16th order IIR (infinite impulse response) Butterworth bandpass filter has been applied to the radar signal in the fast-time. Similarly, unwanted signals or noise generated by periodic sources (e.g., fans, motors, curtains/doors motion, etc.) can be removed in order to ease the post processing of signals reflected from the monitored subject's chest useful for vital signs estimation. Thus, a second bandpass filter has been implemented, namely a 6th order IIR Butterworth in slow-time with a passband from 0.2 Hz (corresponding to a minimum of 12 breaths/min) to 3 Hz (corresponding to a maximum HR of 180 beats/min).

The clutter removal stage is devoted to the attenuation of signals reflected from static structures included in the environment (i.e., walls, furniture) whose energy can be several orders magnitude larger than signals reflected from the moving chest cavity. For this task a Singular Value Decomposition (SVD) [39] based approach has been adopted. Following this approach, the signal matrix was SVD decomposed obtaining a diagonal matrix whose first 'few' descending-ordered singular values conveyed the largest amount of clutter energy. By setting these singular values to zero and reconstructing the signal matrix, the clutter energy was removed and the signal-to-noise ratio (SNR) improved.

Since the UWB radar sensing of RR and HR is demoted due to non-cardiorespiratory body movements (i.e., random movements) done by the monitored subject, i.e., during the execution of ADLs, a preliminary stage for the compensation of such movements is required. For that purpose, the micro-Doppler effect has been exploited [15]. The micro-Doppler effect accounts of the relative micro-motion between radar sensor and target in terms of frequency shifts related to the radial velocity (i.e., there is a positive shift when target moves away from the radar and negative otherwise) and small motion of non-rigid parts (i.e., body parts). Exploiting the high distance resolution of IR-UWB radar, the Doppler spectrogram has been segmented in regions characterized by different kinds of motion (i.e., using the cross-correlation metric) on the basis of their spatial position with respect to the radar sensor. For each segmented region, the associated radar signal has been decomposed via EMD into a series of intrinsic mode functions (IMFs) each of which represents the oscillatory character of the original signal in a different frequency scale [40]. After that, IMFs were k-Means clustered and the IMFs associated with the subject's vital signs were selected as those falling into the frequency range from to 0.2 to 3 Hz. For the sake of example, the vital signs, RR and HR, extracted by using the EMD approach are reported in Figs. 2 and 3, respectively. It is important to note that the described micro-motion/EMD approach allowed to compensate slow random movements of both limbs (up to 5 cm/s) and torso (in the order of 5–10 cm max.), as well as motion artefacts caused by the presence of other people moving near the monitored subject (at a minimum distance of 1 m).

In the remaining of this section, the micro-motion analysis and EMD-based vital sign measurement are further discussed in detail, with a special focus on Doppler spectrogram processing given its importance in motion detection and compensation.

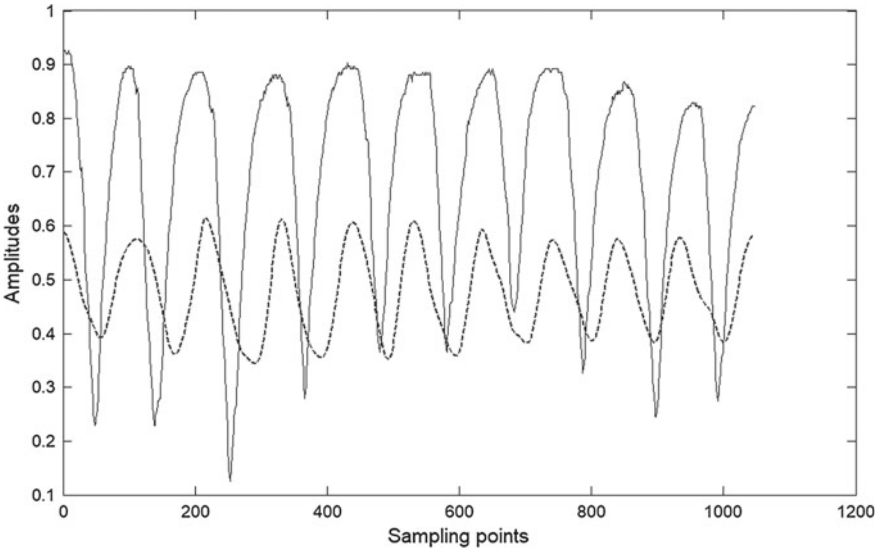

Fig. 2 RR measured with WWS (solid line) and extracted via EMD (dashed line)

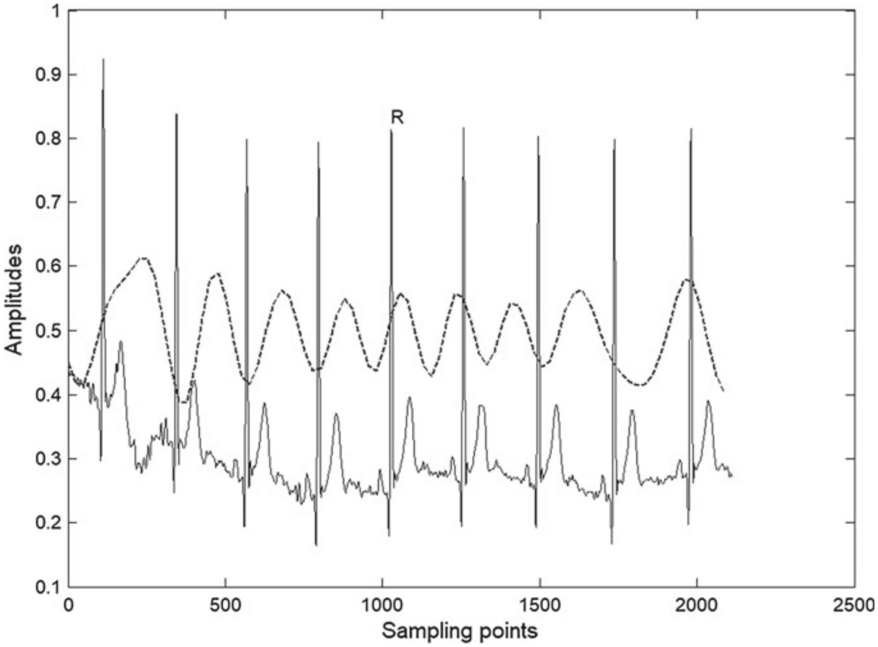

Fig. 3 HR measured with WWS (solid line) and extracted via EMD (dashed line). The ‘R’ wave is marked for reference

3.2.1 Micro-motion Analysis

As it is well known, the radar principle is based on the transmission of electromagnetic waves toward a target and the receiving of the returned waves reflected by the target. By comparing the transmitted and received signals, the radar station is able to determine position (range) and velocity of the target. In particular, the velocity of the moving target is obtained by exploiting the Doppler effect, on the basis of which the frequency of the received signal is shifted from the frequency of the transmitted one.

The Doppler frequency shift is proportional to the radial (i.e., in the direction of the line of sight) velocity of the target: it is positive if the target approaches the radar, and negative if the target moves away. Moreover, when the target is not a rigid body but has parts characterized by an oscillatory motion in addition to the main motion of the target (e.g., a walking human), such oscillation produces an additional Doppler frequency modulation called micro-Doppler effect [15]. Such micro-Doppler modulation can be regarded as a distinctive signature able to account for unique properties of a target. More specifically in this study, the micro-Doppler signature is exploited to detect and track human targets for monitoring of vital signs.

Normally, in the frequency domain, a signal is analyzed by using the Fourier transform technique which provides the frequency spectrum, i.e. magnitude and phase at different frequencies, of the signal during a certain time interval. Due to the micro-Doppler effect, the frequency spectrum deviates from the center frequency in a characteristic way, allowing to a certain extent to detect the presence of micro-motions. However, due to the lack of range information, the Fourier transform is not able to provide adequate information in presence of more complicated time-varying frequency modulations, but a high-resolution time-frequency transformation (i.e., able to characterize both the temporal as well as the spectral behavior of the signal) is needed instead. To this end, in this study, the short-time Fourier transform (STFT) was applied to the analytic form (i.e., computed via Hilbert transform) of the returned signal. In such a way, the micro-motion of one or more subjects can be effectively detection, as shown in Fig. 4 (left side).

At the purpose to reliably measure vital signs, also in presence of (moderated) subject's movements or a moving person nearby, the subject's micro-Doppler signatures need to be detected and eventually isolated from that of other subjects. Thus, the spectrogram (Fig. 4) was treated as a grayscale image and segmented in order to separate the foreground (i.e., one or more micro-Doppler signatures) from the background (i.e., noisy frequency components due to clutter reflections). Since the Doppler spectrogram is characterized by broad peaks corresponding to moving subjects, a simply adaptive thresholding technique was used.

After slightly smoothing the spectrogram (via averaging filter) to suppress noisy frequency components which can affect the segmentation process, the threshold was selected as equal to the standard deviation of the spectrogram. Once foreground

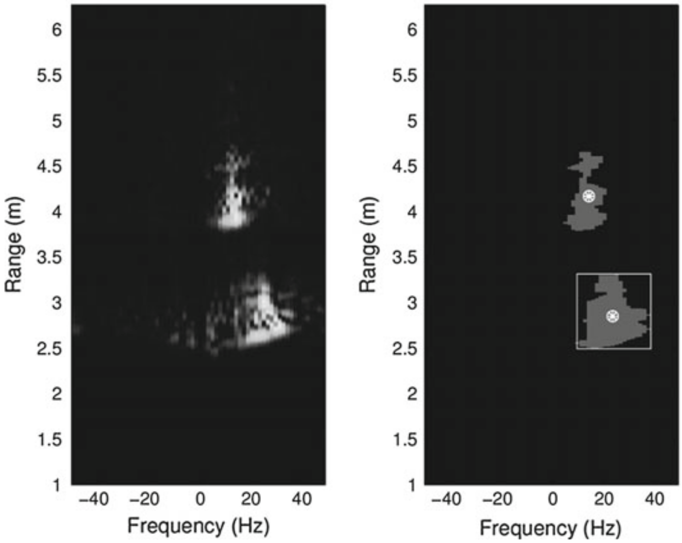

Fig. 4 Micro-Doppler spectrogram (left image) of two subjects moving in the same direction. The two related micro-Doppler signatures were segmented and the one closest to the radar sensor was selected (right image) for vital sign measurement

signatures were detected, the one closer to the radar sensor was considered for measurement of vital signs, as shown in Fig. 4 (right side).

3.2.2 Measurement of Vital Signs via EMD

Given a non-linear, non-stationary signal, such as a radar signal that conveys modulated RR and HR, the EMD is an effective time-frequency analysis technique, allowing to break down the signal into a set of IMFs among which RR and HR are included. The extraction process of IMFs is performed by the following steps: (1) computing of upper (joining maxima) and lower (joining minima) envelopes of the signal by using cubic splines; (2) estimation of the first component by subtracting the local mean of the two envelops from the original signal; (3) hence, the last computed component is treated as the original signal and the process is repeated until the envelopes become symmetric with respect to zero mean and no more components can be extracted.

3.3 Experimental Setup

The experimental setting was a laboratory room of 5.8 m × 3.8 m, shown in Figs. 5 and 6, in which two participants performed seven ADLs, namely cooking (CO), sleeping (SL), watching TV (WA), feeding (FE), dressing (DR), locomotion (LO), post fall (PF). The physical characteristics of the two participants are reported in Table 1. The radar sensor was placed in positions S1 and S2 at the two different heights from the floor of $H1 = 1.4$ m and $H2 = 2.5$ m. Note that the S2 position was beyond a drywall panel having thickness of about 8 cm. In addition, two time of-flight (TOF) cameras SwissRanger SR4000 [41] were placed on the wall at a height of 2.4 m (positions T1 and T2), in order to collect ground-truth data related to activities carried out by the participants.

The ADLs were performed at various distances with respect to the radar sensor. Referring to Fig. 5, firstly the positions marked on the X axis (equally spaced of 0.5 m) were tested for all ADLs. Secondly, the remaining positions were tested for only WA, LO and PF activities, since these last are more likely to happen in random positions.

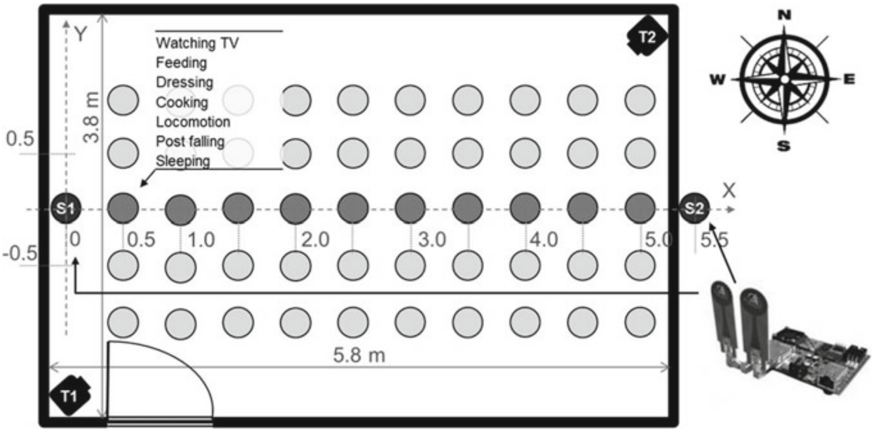

Fig. 5 Experimental setup: layout of the marked positions in which ADLs were performed, positions of the radar sensor inside (S1) and outside (S2) the room, and positions of TOF cameras (T1 and T2)

Each ADL was performed by the two participants orienting their face (or head for SL and PF activities) toward the four cardinal directions (North, East, South, West), starting from a static position and then progressively increasing the motion velocity until activity completion. Further details regarding assumed posture, involved movements and body's parts are summarized in Table 2. During the data collection, each participant was wearing a WWS (Wearable Wellness System) t-shirt [42] equipped with various sensors providing ground truth measurements for RR, ECG and body's movements (thanks to an embedded tri-axial accelerometer).

The TOF cameras, wall-mounted in position T1 and T2 (Fig. 5) at the height of 2.4 m from the floor, were used to efficiently annotate the starting and ending timestamps of each simulated action, i.e., change of body posture, as well as the occupancy level of the room, i.e., number and position of persons, as shown in Fig. 7. Firstly, the people present in the room were automatically detected and counted, by using a high-performing approach which does not need to track one person at a time (i.e., tracking-free approach), but on the contrary it is able to detect and track all persons' location at the same time on the basis of an agglomerative clustering method [43]. Secondly, starting and ending times of each performed action were automatically identified by decomposing (classification task) the action into a sequence of hierarchical postures [44] on the basis of high-discriminative features extracted from TOF range data [45].

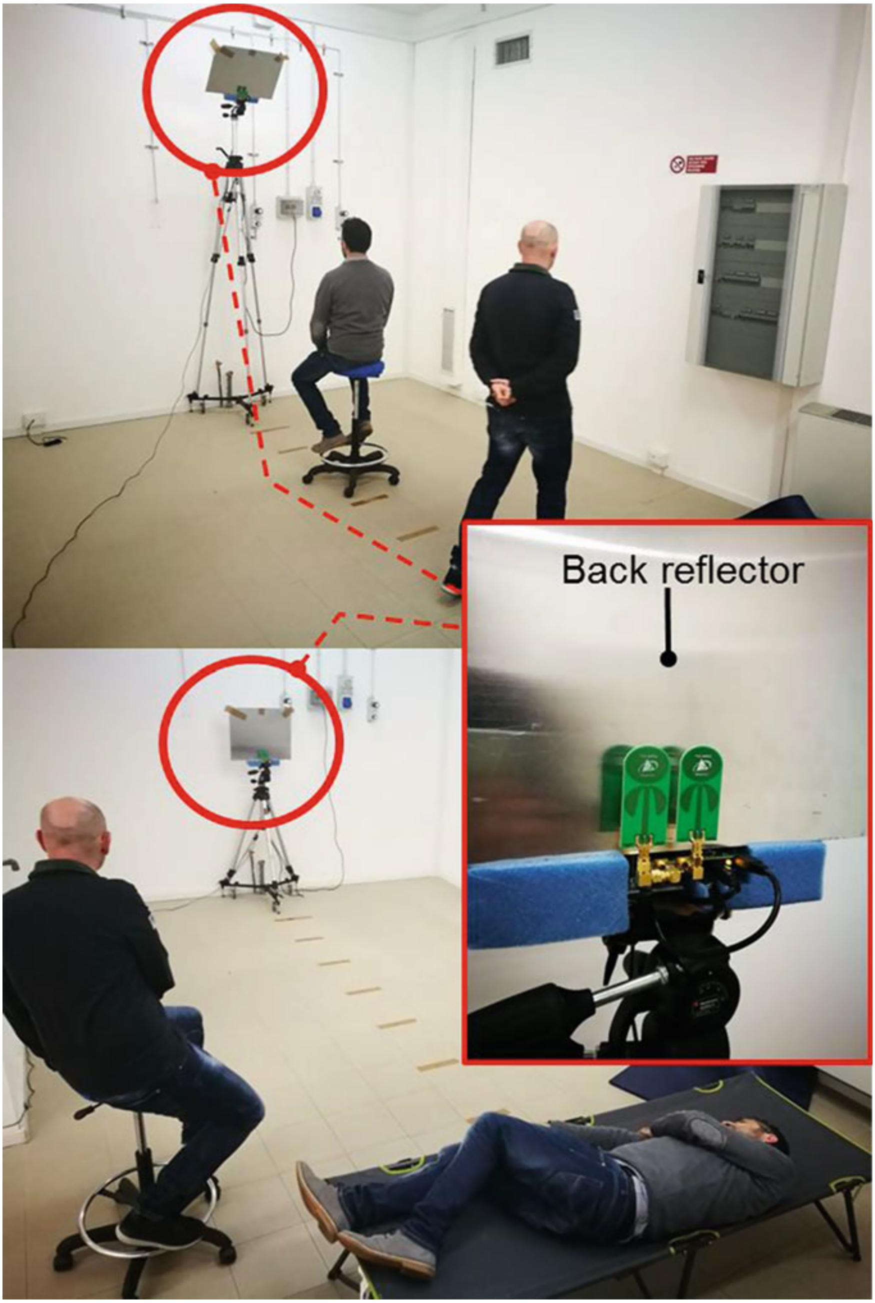

Fig. 6 Experimental setup. Pictures taken during data collection. It is also visible the radar sensor mounted at two different heights and its back reflector

Table 1 Participants' data

Gender	Age	Weight (kg)	Height (cm)	Chest circumference (cm)
Male	35	70	173	96
Male	45	84	184	104

Table 2 Further details of performed ADLs

ADL	Posture	Movement description	Body's parts
Cooking (CO)	Standing	Slightly moving hands mimicking the act of cooking	Superior limbs
Dressing (DR)	Sitting on the bed	Slightly moving arms, legs and torso mimicking the act of dressing	Whole body, but mainly superior limbs
Feeding (FE)	Sitting on the chair	Slightly moving hands/arms mimicking the act of eating/drinking	Superior limbs
Locomotion (LO)	Standing	Slightly walking	Whole body, with slight oscillation of superior limbs
Post fall (PF)	Lying down on the floor	Remaining motionless on the floor after a simulated fall	Mainly static position, with slight movement of the head
Sleeping (SL)	Lying down on the bed	Almost always motionless, sometimes turning to the opposite side	Whole body
Watching TV (WA)	Sitting on the chair	Almost always motionless, sometimes moving torso forward/backward or arms up/down	Torso, superior limbs

4 Results and Discussion

The detection performance was validated in terms of accuracy with respect to the ground truth. The validation was conducted in two phases, without and with a second moving person in addition to the monitored one within the radar FOV. The best coverage of the room was achieved with the radar sensor mounted at height H1, hence all reported results are referred to this height mounting.

Regarding the case with the only monitored subject present, the median accuracy of RR and HR detections are reported in Figs. 8 and 9, respectively. In general, the HR detection was more sensitive to movements than the RR one (especially to chest movements), resulting detectable only up to 2 m from the sensor. Beyond this limit, the movement compensation stage was not able to restore the SNR loss at the necessary level to separate the cardiac signal from the much stronger respiratory one.

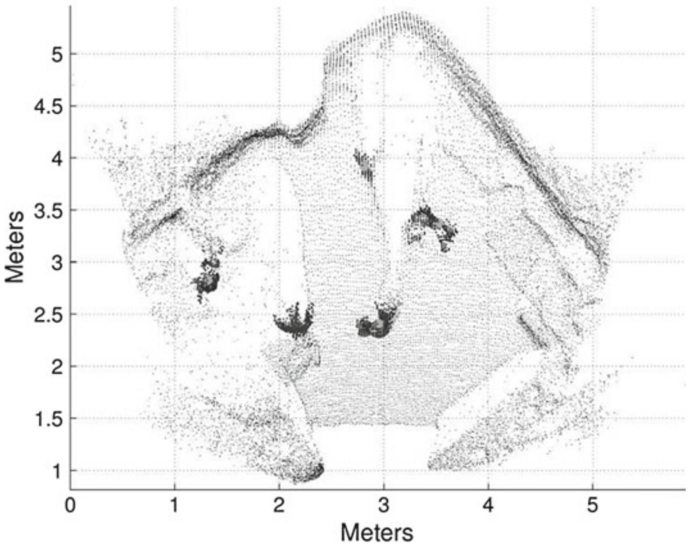

Fig. 7 TOF-based occupancy detection and posture recognition in a room with five people present

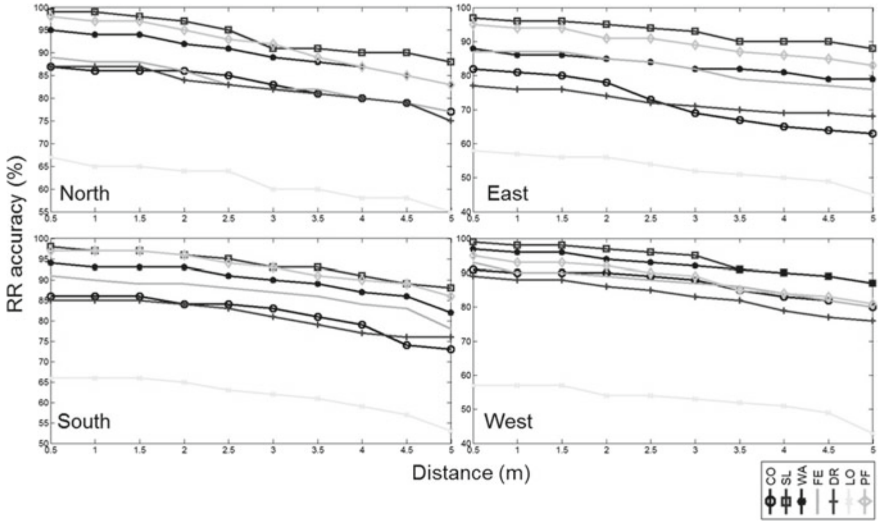

Fig. 8 Accuracy of RR detection at varying of distances and ADLs. The only monitored subject was present in the scene

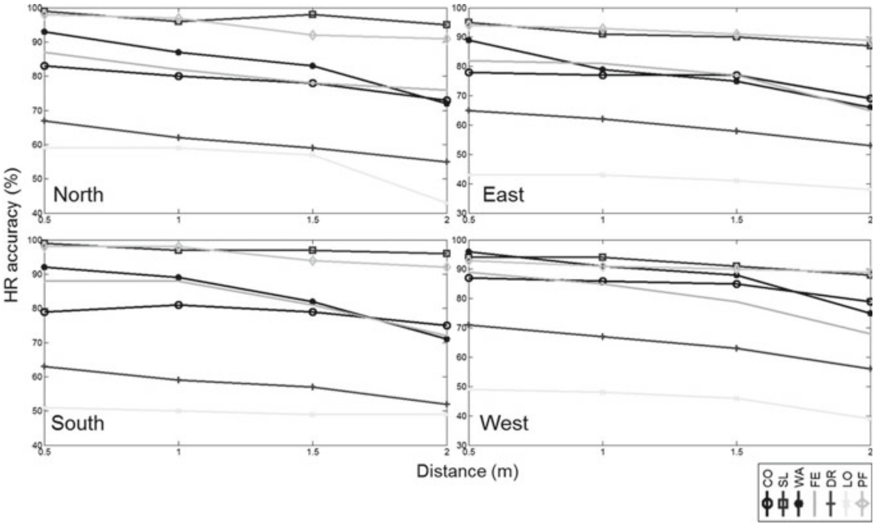

Fig. 9 Accuracy of HR detection at varying of distances and ADLs. The only monitored subject was present in the scene

Obviously, in both RR and HR cases, the best accuracy was achieved in correspondence of ADLs without too much movements, e.g., SL, PF and WA. This explains the poor performance observed during the LO activity in comparison to the other ADLs. The same applied, although at a lesser extent, in the case of the DR activity, due to the occurrence of chest oscillations.

Some differences were found also in dependence of the monitored subject's orientation. Especially in the case of HR, the most favorable orientation was toward the sensor, i.e., West and East for S1 and S2 sensor positions, respectively. The subject's position with respect to the sensor FOV (of about 100°) was also relevant, since the detection accuracy decreased as the subject moved away from the X axis (Fig. 5).

Regarding the second validation phase, with a second moving subject present in the radar FOV, the movement compensation stage was robust enough as long as the distance between the two subjects was greater than 1 m. The corresponding RR and HR accuracies are reported in Figs. 10 and 11, respectively. As one can appreciate by comparing the plots reported in Figs. 12 and 13, the overall detection performance was not significantly affected by the presence of a second moving person in the same environment. As previously mentioned, the validation has been also carried out by positioning the radar sensor in S2, i.e., outside the room, in order to investigate the TW sensing capability. In this circumstance, the clutter signal generated by the interposed wall was effectively suppressed by the clutter removal stage, and the RR resulted detectable, without loss in accuracy, within distances up to 4 m with respect to the sensor. Instead, regarding the HR, the maximum detection range dropped to about 1 m away from the sensor, without sensible accuracy loss.

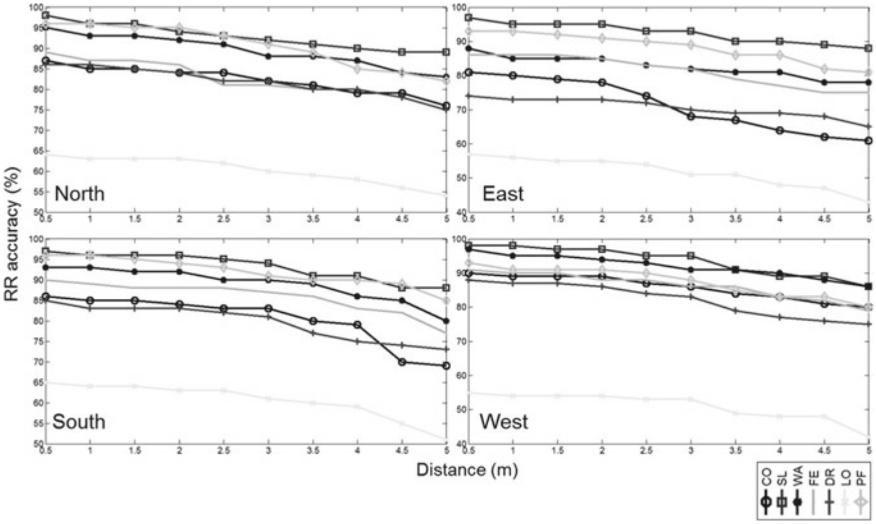

Fig. 10 Accuracy of RR detection at varying of distances and ADLs. Another person was present in the scene beside the monitored subject. The second person was walking/standing/sitting within a minimum distance of 1 m

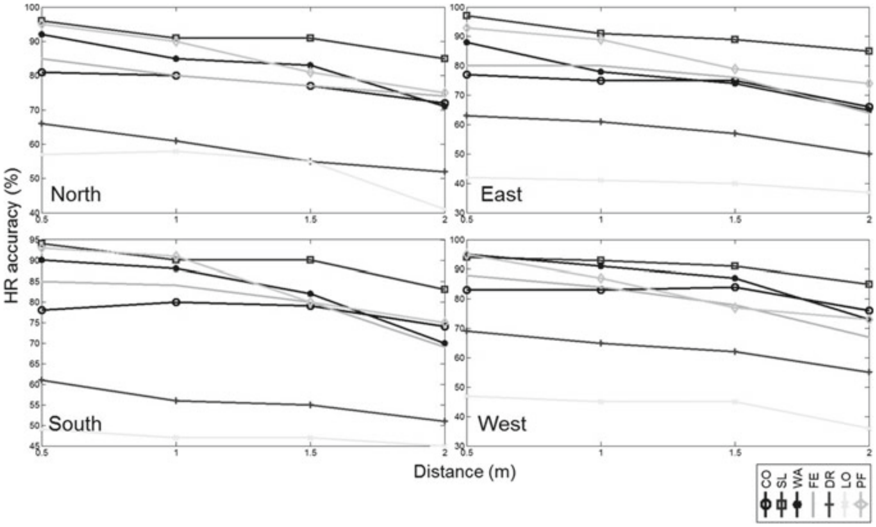

Fig. 11 Accuracy of HR detection at varying of distances and ADLs. Another person was present in the scene beside the monitored subject. The second person was walking/standing/sitting within a minimum distance of 1 m

The comparison of the present study with other similar ones is not straightforward. To the best of the authors' knowledge, no published study has been carried out previously aiming to validate the radar-based detection of vital signs in assisted

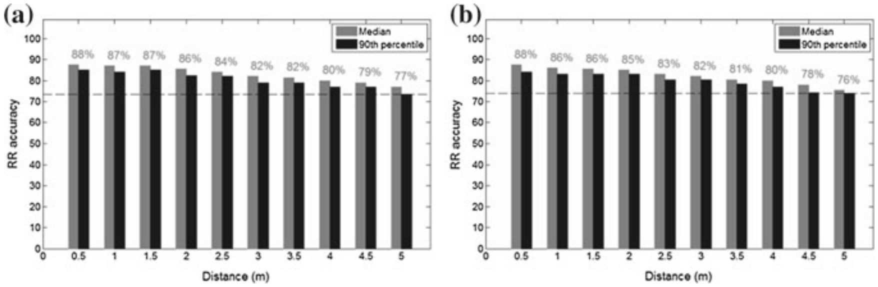

Fig. 12 Accuracy of RR detection in presence (**a**) and absence (**b**) of a second person

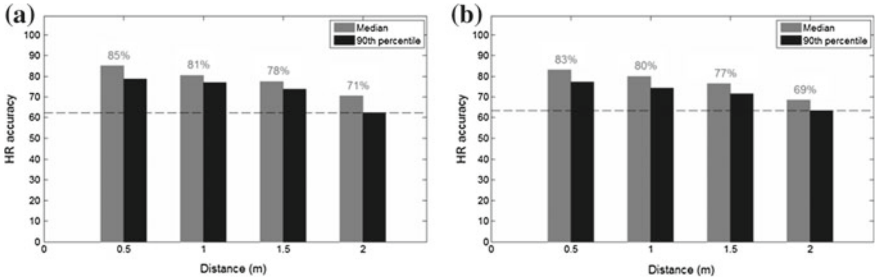

Fig. 13 Accuracy of HR detection in presence (**a**) and absence (**b**) of a second person

living scenarios under realistic conditions, i.e., performing ADLs. The only similar study is [31], in which however the suggested radar-based system was validated only for quasi-static activities, such as, typing on a laptop or using a cell phone.

Consequently, the high accuracy reported by that study cannot be considered as representative of real-life assisted living scenarios.

5 Conclusion

The aim of this study was to investigate the contactless detection of vital signs using an IR-UWB radar sensor in assisted living contexts. At this purpose, an algorithmic framework including a movement compensation stage was presented and the related experimental results reported. The presented framework was realistically evaluated by considering the detection of vital signs during the execution of various ADLs and also in presence of a second moving subject. Furthermore, the vital signs detection was evaluated at different distances, orientations and FOV positions with respect to two radar sensors, also in TW modality. The achieved results show that vital signs can be still detected also during ADLs, but with accuracy varying greatly depending on the level of movements and involved body's parts. Moreover, the radar returns caused by movements of the second subject were effectively compensated without significant loss of accuracy. In conclusion, the authors believe that this study provides a better understanding of opportunities and limits posed by radar technology for vital signs monitoring in assisted/smart living applications.

The ongoing work is focused on further investigating the movement compensation by using machine learning techniques (e.g., convolutional neural networks) and additional sensing modalities (e.g., inertial and vision) in conjunction with radars. The future work includes also the detection and tracking of vital signs (including heart rate variability) of multiple target subjects for assisted/smart living applications.

Acknowledgements This work was carried out within the project "ACTIVE AGEING AT HOME" funded by the Italian Ministry of Education, Universities and Research, within the National Operational Programme for "Research and Competitiveness" 2007–2013.

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