Respiration and heartbeat rates estimation using IR-UWB non-contact radar sensor recordings: A pre-clinical study

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Abstract
Sleep study is of major importance for the assessment of sleep apneas, sleep stages or the diagnosis of sleep disorders. Although there exists a variety of tools for the evaluation of sleep, including the gold standard polysomnography (PSG) or high-tech wearable devices, the last decade there is also an increasing interest in the use of ultra wide-band (UWB) radar sensors for non-contact medical studies. The objective of this study is to develop a pre-clinical environment for the measurement of two important vital signs of the human functions, i.e., the respiratory and heartbeat rates, through UWB radar recordings of chest motion. For this purpose, at first we composed a simulating chest and heart motion architecture which represents these two basic body functions in parallel. After that, with the employment of a UWB-radar, we performed extensive recordings of simulator's displacements, and we concluded to the mathematical estimation of the respiratory and heartbeat rates, compared to the initial frequencies given to the simulated procedure. Our experimental results prove that we can estimate both rates in an accurate manner and even if these pre-clinical tests are made under ideal conditions, the UWB-radar can further be used for clinical assessment, with promising perspectives.

Keywords
IR-UWB radar, respiratory rate estimation, heartbeat rate estimation, simulated data

1. Introduction

Vital signs such as the respiration and heartbeat rates are among the most important signals that provide significant information to the clinicians, for medical assessment. Impulse response ultra wideband (IR-UWB) radar sensors have gained the researchers interest as they constitute a non-contact manner of detecting the vital signs [1]. Sleep is among the most vital human body procedures. Indeed, there exist many people who suffer from sleep disorders, such as apneas, abnormal breathing or abnormalities to the sleep stages, which lower their sleep quality.

The traditional manner of monitoring the sleep is through the well-established polysomnography (PSG) tool. However, PSG requires numerous leads to capture the whole body activity during sleep, which raise the patients' discomfort, due to the restricted movement [2]. Moreover, most of the times in order to evaluate the patients' sleep quality, the examinations should be of long duration, resulting to long recordings and thus, making their analysis difficult. On the other hand, IR-UWB radar sensors have been proven able tools for the study not only of the sleep apneas but also for the detection of sleep stages [3].

The purpose of this study is to evaluate the IR-UWB radar's ability to capture the motion of a simulator, constructed by the members of our laboratory, which simulates the chest and heart motions. More specifically, our experimental procedure is to locate the radar in front of the simulator, under various experimental conditions, and evaluate how accurate are the radar's respiratory and heartbeat rates estimation, compared to the fixed given values of simulator's motion, i.e., to the experimental conditions. As the environmental conditions of our experiments were ideal, implying that no other target existing in the room and the noise was limited, the mathematical approaches followed for the estimation of the vital signs were simple, fast, and well-established.

2. Mathematical background

The vital signs' information includes the respiration and heartbeat of the human target. This information is contained in the periodic expanding and contracting of the chest cavity. However, the first step is to describe how we take the vital signals via the radar's acquisitions. After that, we can estimate the quantities of interest, i.e., the

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respiratory rate and heartbeat.

2.1. Estimation of vital signs

The IR-UWB tool, via the radar pulses, aims to detect and quantify the periodic expanding of the chest. Thus, an important parameter in the construction of the vital signal is the distance between the radar antenna and the human chest, which changes over time. Previous work has proved that the distance could be represented as follows,

$$d(t) = d_0 + a_r \sin(2\pi f_r t) + a_h \sin(2\pi f_h t) \quad (1)$$

where, d_0 is the nominal distance, a_r, a_h are the mean values over the range of possible displacements of the chest cavity that caused by respiration and heartbeat activities, respectively. Moreover, as f_r, f_h we denote the respiratory and heartbeat frequencies, respectively, which are the quantities that we want to estimate.

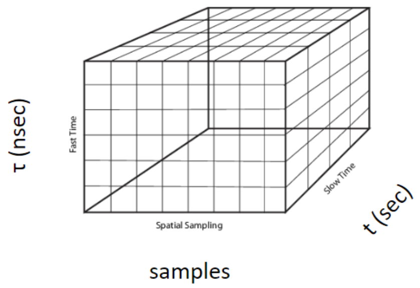

Figure 1: The radar cube: As slow time τ we denote the number M of bins, whilst the fast time t is counted in seconds.

The radar's output is a 2-dimensional matrix, $\mathbf{S} \in \mathrm{R}^{\mathrm{K}\times\mathrm{M}}$, where as K we denote the number of samples in sample space and M the radar's bins in fast time (i.e., $M = 297$ in our case). Our purpose is to estimate the radar's signal in slow time, i.e., regarding the real time t, as this is depicted in Fig. 1. In order to reduce the computational time of the radar's we select the bin m_{opt} out of the $m = 1, \dots, M$, which has the maximum variance among all the bins. As a consequence, this leads to a unique recording $\mathbf{r}$, which is derived from:

$$\mathbf{r}(t) = \frac{1}{\sqrt{K}} \sum_{k=0}^{K-1} \mathbf{s}(t - kT_s, m_{opt}) \quad (2)$$

where T_s is the period of sampling.

The next step is to analyze the following function. Specifically, the radar's signal $\mathbf{r}$ consists of the vital signal $\mathbf{x}_{f_r,f_h}(t)$ accomplished by additive noise $\mathbf{n}(t)$. However, in our experimental case the "clean" signal $\mathbf{x}$ is already denoised as our experiments are held under ideal circumstances.

The $\mathbf{x}$ vital signal, it is a combination of two quantities, as shows the following equation, i.e., it contains the effects of both respiratory and heartbeat:

$$\mathbf{x}_{f_r,f_h}(t) = \frac{1}{\sqrt{K}} \sum_{k=0}^{K-1} \mathbf{u}(t - kT_s - t_k(f_r, f_h)) \quad (3)$$

where, as t_k we denote the following delay:

$$t_k(f_r, f_h) = \frac{d_0}{v} + \frac{a_r \sin(2\pi f_r t)}{v} + \frac{a_h \sin(2\pi f_h t)}{v} \quad (4)$$

with, v denoting the electromagnetic wave speed and as $\mathbf{u}$ we denote the decluttered signal (i.e., after loop-back filtering on the raw signal $\mathbf{r}$. The f_r and f_h are the rates of respiratory and heartbeat, respectively.

Respiration Rate (RR): Regarding the RR, the most well-established method of its computation is through the power spectrum. Thus, we first apply the Fourier transform to the extracted signal $\mathbf{r}$ and then we take its power spectrum. as this is presented in Fig. 2. As it is

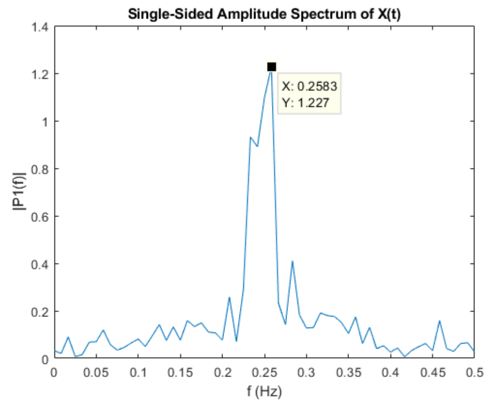

Figure 2: Single-sided Amplitude Spectrum of the decluttered radar signal $\mathbf{x}$(t).

observed in Fig. 2, the frequency which corresponds to the highest spectrum's amplitude is the respiratory rate. It is worth to notice that, the respiratory rate was set to the range $0.2Hz - 0.4Hz$, in the simulated experimental processes.

Heartbeat Rate (HR): The HR is a more difficult quantity to be estimated, as the heartbeat is captured more difficult than the respiratory from the chest motion through the radar. However, in terms of our analysis, as the environment was ideal and the evaluation of the rates estimation through the radar was based on simulated data, the HR derived from the highest value of the the power spectrum's amplitude, but in to the range $0.8Hz - 1.4Hz$.

Both of the mentioned processes are usually accomplished by a lowpass filter, for the noise reduction and the more accurate estimation of the RR and, again, before the application of the Fourier transform, the radar signal passes through a highpass filter for the HR estimation.

2.2. Simulator description

In order to implement the algorithms for estimating heart and respiration rates using the UWB radar, a ground truth was necessary. To this approach we created an artificially predefined dataset based on the physiological principles of the heart/breathing system. Because UWB radar technology is based on detecting the reflectivity and displacement of a collection of body points from the radar, such an approach is a mechanical system for simulating chest wall motion that incorporates both respiratory and heart rate. As for the respiratory rhythm, this is evident from the apparent movement of the chest during breathing which according to this movement ranges from 4-12mm, with a frequency range of 0.2-0.34Hz (12-20 breaths per minute). However, the movement of the chest surface, in addition to the assessment of the respiratory rate, also contributes to the assessment of the heart rate since, depending on the phase of the heart's operation, a displacement of 0.2-0.5mm is induced on the chest surface with a frequency range of 1-1.34Hz (60-80 beats per minute) [4].

In this direction, a mechanical approach to the displacement of the thoracic surface is the system illustrated in Fig. 3. This system consists of two stepper motors with a discrete resolution of 200 steps/rev (steps/rotation) which, in combination to an "8-step micro-stepping mode", through the stepper driver, can reach a resolution of 1600 steps/rev. The rotary movements of the motors are converted into linear movements via a trapezoidal screw with an 8mm "Lead" which corresponds to a maximum resolution of 0.005mm per step. The operation of the system has been configured in such a way that it is possible to adjust the amplitude and oscillation of the moving part or even implement a non-periodic motion using a "look-up table" based on the desired amplitude and speed of motion. The range of motion is calculated by the number of rotations, while the frequency of oscillation is calculated by the time it takes the moving part to make a cycle, i.e., the period. The whole system was designed and printed in pieces by a 3D printer.

A pre-defined set of control functions was implemented in order to create scenarios for breathing and heart rate. For instance, we can create scenarios for steady or dynamic frequency regarding breathing rates and heart rates, as well as for emulating special events like abnormalities on heart/respiratory rates (e.g. apnea event). The emulator communicates through a simple serial interface and its functions include: stop motion, forward motion, backward, increase/decrease step time, increase/decrease distance, normal/abnormal breathing and, breathing with apnea and abnormal frequency.

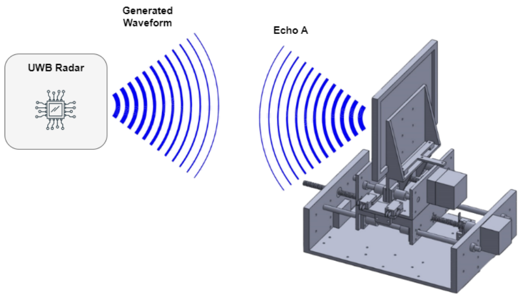

Figure 3: The radar operating principle.

3. Experimental Evaluation

3.1. IR-UWB radar characteristics

Ultra-Wideband (UWB) radar technology is capable of accurately detecting vital signs such as respiration and heart rate, making it a valuable tool for monitoring the health and well-being of individuals in medical and fitness applications. The LT102 radar module is a ready-to-use UWB radar system for indoor environments that combines high-quality antennas, advanced signal processing capabilities, and communication interfaces into a single unit. It is designed to comply with regulatory standards and is customizable for various applications such as presence detection and breath analysis. The LT102 module is powered through a USB connection and uses a USB full speed (virtual com port) for communication and also has an auxiliary connector that can be used as general-purpose input/outputs (GPIOs) or as an additional communication interface [5].

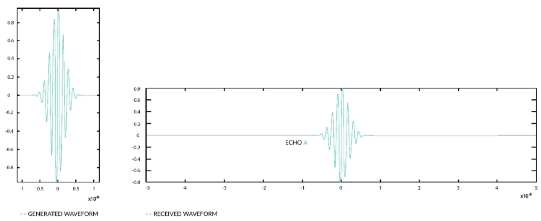

Figure 4: The basic principle and the wave forms: a) generated pulse at transmitter (left) and b) generated echoes from target (right).

3.1.1. Operating Principle

The LT102 system uses the direct readout of backscattered pulses as its operating principle. The system emits pulses (Fig. 3) which travel through space and hit any targets within the active area of the radar. These targets then reflect a portion of the incoming energy (echoes) back to the radar module (Fig.4). The receiver then converts the incoming signal into digital data, which is provided to the micro-controller unit (MCU) for processing according to the specific application.

3.1.2. General Specifications

The table below lists the general specifications of the device. These include the typical detection range, maximum power consumption, operating frequency, integrated antenna, and communication interfaces.

Table 1
General Specifications

Specification	Value
Detection range	10 meters
Maximum power consumption	500mW
Operating frequency	6.5GHz to 8.5GHz
Integrated Antenna	Aperture ±60° by ±60°
Communication interfaces	USB full speed, SPI, UART
Dimensions	36mm x 68mm

3.1.3. Electrical Specifications

The Electrical Specifications table provides the range of operating conditions and requirements for the device.

Table 2
Electrical Specifications

Specification	Min.	Typ.	Max.
Operating frequency	6.5GHz	7.29GHz	8.5GHz
Temperature Range	-40°C	-	+85°C
Supply voltage (AuxIO)	3.0V	3.3V	3.6V
Supply voltage (USB)	-	5V	-
Current consumption	-	-	100mA
Range resolution	-	6mm	-
VIL	-	-	0.3 Vdd
VIH	0.7 Vdd	-	-
Rseries (AuxIO protection)	-	220 Ohm	-
Operating frequency	6.5GHz	7.29GHz	8.5GHz
Temperature Range	-40°C	-	+85°C

3.2. Experimental Results

Regarding our experimental procedure, multiple simulated radar-based recordings were extracted. Analytically, in Table 3, we present the conditions under which our experiments were carried out.

Table 3
Experimental Conditions of the Simulator

Exp. ID	Angle (degrees)	Distance (cm)
1	0	45
2	0	60
3	0	90
4	0	120
5	45	45
6	45	60
7	45	90
8	45	120
9	90	45
10	90	60
11	90	90
12	90	120

Specifically, all of our experimental measurements were of 120 seconds duration, with a sampling frequency equal to 8.9. According to the simulator's frequency of "chest" and "heart" motions, they were set equal to 0.25 Hz and 1.34 Hz, respectively.

Table 4
Experimental Estimations

Exp. ID	RR (Hz)	HR (Hz)
1	0.2670	1.2905
2	0.2670	1.3305
3	0.2670	0.9568
4	0.2670	1.3795
5	0.2225	1.3573
6	0.2225	1.3350
7	0.2225	1.3350
8	0.2225	1.3795
9	0.2225	1.3795
10	0.2225	1.3795
11	0.2225	1.3795
12	0.2225	1.3350

In Table 4, we present the estimated respiratory and heartbeat rates derived from our algorithmic process, based on the signals acquired through the interaction of the simulator and the radar sensor. As mentioned in the methodology, the estimation of the RR and HR was based on the application of the Fourier transform and then, by taking the power spectrum. The respiratory rate was derived by limiting the frequencies to the range 0.2-0.4Hz whilst, the heartbeat rate was computed by, first, passing the radar signal through a highpass filter of a passband frequency equal to 0.8Hz and then, taking extracting the power spectrum. The frequency range to which we searched for the highest signal's energy was from 0.8 to 1.4 Hz.

Based on the estimations we observe the following:

1. The RR estimations are more accurate than the HR's.
2. In 0 degrees the procedure proved to be more robust.
3. As the angle changes, both estimations have higher absolute error.
4. As the radar diverges from the simulator, both estimations are less accurate.

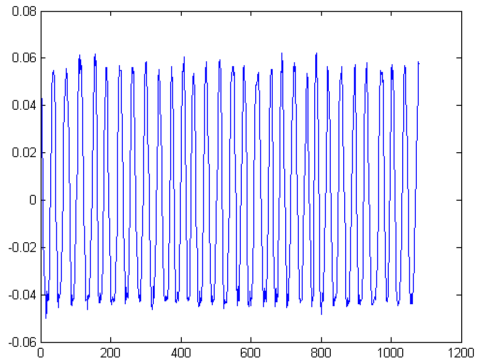

Figure 5: Radar signal for the experimental case 1.

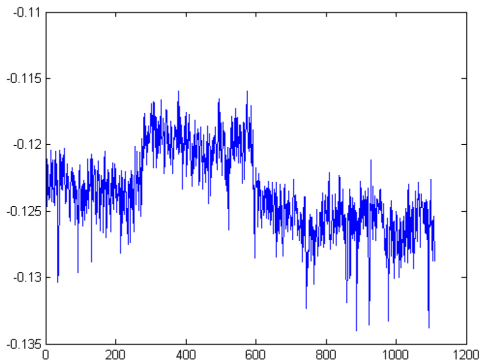

Figure 6: Radar signal for the experimental case 12.

Overall, the mean absolute error (MAE) over all the RR estimations is equal to 0.022 whereas, the HR's is equal to 0.0556. Finally, in Fig. 5 and Fig. 6 we observe the radar sensor's measurements 1 and 12, respectively. Comparing these two signals, which exist in sample domain, we observe that the most well-acquired signal concerns the experimental conditions where the target is close to the radar and in 0 degrees angle.

4. Conclusions

In this study we aimed to evaluate the IR-UWB radar sensor's capabilities on capturing the RR and HR frequencies in different experimental conditions. Specifically, we examined a variety of different experimental scenarios, which concerned radar's recordings from simulated motions of chest and heart. In terms of our evaluations, we constructed a simulator of moving functions, which had the ability to change angle and distance. This tool constituted the radar's target. To conclude, through our experimental evaluations we observed that the target's angle and distance from the radar play significant role to the robust and accurate estimation of RR and HR. Finally, the acquired signals are also affected by the conditions under which the target exists.

Our future goal is to examine the IR-UWB radar sensor on clinical evaluations. Our purpose is to examine if we can monitor sleep through the radar and pass to clinical assessment, concerning the sleep apneas and the sleep stages. To this end, the PSG tool will be the comparative method.

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