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PRIMARY RESEARCH

Contactless vital signs monitoring using Doppler Radar sensor

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Abstract
Contactless vital signs monitoring, such as respiration and heartbeat, can be a significant tool for applications in the fields of health care, surveillance and emergency. Among vital signs detection methods, Doppler Radar (Radio Detection and Ranging) has shown promising performance in various applications. Doppler Radar detects vital signs by transmitting a Radio Frequency (RF) signal towards the human body. Transmitted RF signal is phase modulated by the periodic movements caused by different body parts including chest and heart movements. Then, the Radar receiver captures the reflected signal and demodulates it to extract the vital signs' components. Since RF signals could easily be affected by every movement in the environment, studies in this area have reported limited accuracy, especially for heartbeat detection. This study presents a novel solution for this problem by developing a non-contact, non-invasive and unconstrained vital sign monitoring system. A low-cost prototype system using 24 GHz Continuous Wave (CW) Doppler radar is developed. By sampling the Radar signal for every 40 milliseconds, a time series signal is generated, and then is further divided into 30 seconds-length windows. First, for each window, an adaptive threshold method is used to filter noises generated either by random body movements or electronics artifacts. Then, convolution with a plank taper window -the frequency bands are taken as [0.7, 2.5] for the heartbeat, and [0.1, 0.5] for respiration- is applied. Finally, a peak detection algorithm is used to calculate heartbeat and respiration rates. Experiments are performed according to different daily life scenarios considering different sides of healthy subjects at different distances, up to 2 meters, from the system. A total of 100 minutes of recordings from 10 healthy subjects were used to validate the proposed system and its ability to measure vital signs for different subjects. The proposed system achieves 97.7 accuracies for respiration detection and 95.3 accuracy for heartbeat detection. The accuracy is determined by comparing the system results in highly accurate biometric sensors. By the end of this study, it has been proved that with this very low-cost design, a highly accurate vital signs detection system can be developed. Such a system could be utilized as a fundamental subsystem in a variety of applications; especially those designed for daily home usage.

I. INTRODUCTION

Detecting and monitoring vital signs, such as respiration and heartbeat, could be a significant tool for applications in the fields of health care, surveillance and emergency [1]. In the medical field, vital signs are mostly detected by sensor-based medical devices like Electroencephalography (EEG), accelerometer and pressure sensors. Although such sensors provide a highly accurate results, they are less preferred for daily usage due to their need for direct contact with the body, which makes the user uncomfortable. On the other hand, systems that are based on sensors that do not have a physical connection with the subject have gotten high consent from the community for their ease of use, non-contact and home usage compatibility. Among contactless vital signs detection methods, Doppler Radar has shown promising performance in various applications, such as daily health monitoring, human tracking, and hidden subjects' detection [2, 3, 4]. Such applications do not require contact or spatial preparation and can penetrate through walls.

The initial works in non-contact vital signs detection using microwaves and the Doppler effect was in 1975 by proving

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that respiratory rate could be obtained from a human and animal subject at 0.3 m distance [5]. Later, in [6], it was shown that by microwave radar, not only respiration signal, but also heartbeat related signal can also be obtained.

Since then, many radar-based vital signs extraction technologies are presented. These technologies mainly utilized different radar types, such as Ultra-Wide Band (UWB) radars, Frequency Modulated Continuous Wave (FMCW) radars, and CW Doppler radars. Each of these technologies has its own advantages and disadvantages. UWB and FMCW radar types provide high-resolution measurement to detect the distance between the subject and the system. Therefore, with these radars, vital signs for more than one subject could be extracted [7, 8]. Meanwhile, the large bandwidth increases the complexity of the system's hardware. UWB radar-based systems are less practical in terms of low-power operation [9, 10], whereas FMCW and CW radar-based systems allow low-power operation. Although CW radar does not provide range resolution [11], it provides less complex hardware architecture and higher measurement accuracy [12]. Thus, CW radar is considered as better option for non-contact vital signs detection applications in single subject cases, regardless the coverage range.

Doppler Radar detects vital signs by transmitting an unmodulated RF signals towards the human body. Transmitted RF signal is phase modulated by the periodic movements caused by the body, chest and heart. The Radar receiver captures the reflected signal and demodulates it to extract the vital sign components [13].

The chest wall motion caused by the heartbeat has an amplitude range of 0.2–0.5 mm and frequency range of 1–1.34 Hz (60–80 beats per minute) [14]. Whereas, chest wall motion caused by respiration ranges from 4–12 mm [15] with a frequency range of 0.2–0.34 Hz (12–20 breaths per minute) [14]. Obviously, these motions at happen in very small scale. Since RF signal prone to be easily affected by different motions in the environment, studies in this area have reported limited accuracy, especially for heartbeat detection. This study presents a novel solution for this problem by developing a non-contact, non-invasive and unconstrained vital sign monitoring system. An advanced digital signal processing technique are developed to extract vital signs in different conditions; including the presence of body movement. Respiration and heartbeat signals is successfully extracted from signals reflected from subjects at distances of up to two meters from the system.

II. VITAL SIGNS MEASUREMENT WITH DOPPLER RADAR

Radar systems are used to extract speed, distance and direction of objects using electromagnetic waves [16]. In microwave Doppler monitoring, the Radar transmits a single tone with frequency *f*. The signal is then reflected from objects in the coverage area. Considering a stationary person's chest with periodic movements, Radar receives a signal similar to the transmitted one, with its phase modulated by the time-varying chest motion. Since the chest motion is caused by heartbeat and respiration, demodulating the phase provides heart and respiration rates. Taking $\Phi(t)$ as the phase noise inside the microwave oscillator. Transmitted signal *s(t)* and received signal *r(t)* are represented in Equations 1 and 2 respectively.

$$s(t) = cos(wt + \Phi(t)) \tag{1}$$

$$r(t) = cos(wt + \Phi(t) + \Delta\theta) \tag{2}$$

where $\Delta\theta = 4pi * x(t)/\lambda$ is the phase shift caused by the chest motion. Here *x(t)* is the time varying displacement of the chest wall, and λ is the wavelength of the transmitted signal. When the change in the displacement *x(t)* is small compared to λ, the phase change will be small. In this case, phase modulated signal can be directly demodulated by mixing it with a portion of the original signal [14], we have Equation 3:

$$sin(\omega t+\Phi(t)+\Delta\theta)*cos(\omega t+\Phi(t)) = sin(\Delta\theta)+HFT \tag{3}$$

where *HFT* is high-frequency terms and $sin(\Delta\theta) \approx \Delta\theta$ for small $\Delta\theta$ [17]. Null points occur in CW Doppler Radar systems when the received signal and the local oscillator are either in-phase or 180 degree out of phase [18]. Demodulated waveform $\delta\theta$ carries information about the vital signs of the object which the signal is reflected from. Most of Radar sensors use *I/Q* demodulation topology to overcome the null detection problem [19]. It provides two outputs; in-phase and quadrature signals with 90-degree phase difference represented in Equations 4 and 5.

$$I(t) = cos(\frac{4\pi x(t)}{\lambda} + \Phi(t) + \Phi) \tag{4}$$

$$Q(t) = sin(\frac{4\pi x(t)}{\lambda} + \Phi(t) + \Phi) \tag{5}$$

III. SYSTEM DESCRIPTION

A practical, low-cost and easily implemented prototype system is designed. A block diagram of the prototype components is presented in Figure 1. The system uses a dual-channel Doppler radar transceiver (New Japan Radio product NJR4262) as the main sensor. NJR4262 is a low-cofvst K-band 24-GHz continuous-wave Doppler radar transceiver with a built-in mixer to eliminate common components between transmitted and received signals [20]. The transceiver outputs only phase components of the received wave, which include the static distance, body, respiratory and heartbeat movements. To overcome the null problem two output signals are provided; In-phase (*I*) and Quadrature (*Q*) signals with 90-degree phase difference. Transceiver outputs are then passed through an analog bandpass filter to pass frequencies related to heartbeat and respiration, and attenuate undesired frequency components. For this purpose, a second order active band pass filter using inverting operational amplifier is designed, the lower cut-off frequency (*fC1*) and upper cut-off frequency (*fC2*) are selected as 0.1 Hz and 7Hz, respectively. The gain of the passed frequencies is 34db which is about 50 amplification levels. Finally, *I* and *Q* signals are converted from analog to digital. Since Arduino ADC provides resolution at 10 bit and to guarantee higher sampling resolution, a 16 Bit ADC (ADS1115 module) is used for converting the signal. The digital signal is then analyzed using different signal processing techniques. Analyzing processes has been done in MATLAB 2019b environment.

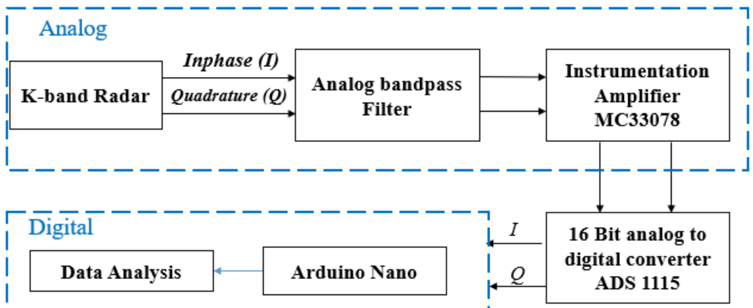

Fig. 1. Electronic circuit design

IV. METHODOLOGY

Time series signals with 25 Hz sampling rate are generated by sampling Radar output signals for each 40 milliseconds. The Arduino sketch uses Interrupt Service Routine (ISR) to accurately limit the sampling interval to 40 milliseconds (25 Hz). This sample rate was chosen to avoid 50-60 Hz components that may originate from power lines. The signal is further divided into 30 seconds-length windows with 50% overlap. First, each window is pre-processed to remove the DC artifact and avoid the null point problem. Then, movements related to different body parts are filtered. Finally, heartbeat and respiration signals are extracted. Processing details are explained in the following.

A. Pre-Processing

Null point problem is proven to be more reliable with small amplitude measurements [21]. Thus, to avoid null-point problem and calculate more accurate estimation of displacements in the reflected wave, more efficient combination of *I(t)* and *Q(t)* is required. For this purpose, several approaches have been proposed [22, 23, 24]. The most commonly used method is arctangent demodulation, also referred as direct phase demodulation, which is mathematically represented as:

$$ATAN(t) = arctan(\frac{Q(t)}{I(t)}) \tag{6}$$

Additionally, the static distance existed as a Direct Current (DC) component in the baseband signals causes a linear transform on *I* and *Q* components. For more accurate phase demodulation, DC offset is removed by extracting the mean value of each window [25].

B. Sensing Physical Movements

Body movements manifests as tossing, turning, changing posture, and involuntary limb movements. These movements affect the signal by increasing its variance and power, which in turn affects heartbeat and respiration extraction accuracy. Thus, filtering such noises generated either by random body movements or electronics artifacts from the signal is an important step before getting to vital signals extraction step. For this purpose, an adaptive threshold method is developed. First, for each window, two local thresholds are calculated to generate a boundary in which only vital signals could be located. The thresholds are calculated as: mean(window) + 3* Std (window) for the upper limit and mean(window) - 3* Std (window) for lower limit. Then, data samples or epochs that are out of the determined

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range, bigger or smaller than the threshold, are considered as artifacts and removed from the signal. Finally, a linear interpolation is applied to up-sample the signal and fill the gaps caused by extracting data points with new predicted ones. This step is completed using MATLAB griddedInterpolant method.

C. Heart and Respiration Rates Extraction

Two Finite Impulse Response (FIR) bandpass filters are designed using Planck-taper window with length of 30 second and 0.1 edge decay. Planck-taper window coefficients are given by [26]:

$$a(k) = \begin{cases} 0, \ k=0 \\ \frac{1}{e^{z_a(k)+1}}, 0 < k < \epsilon(N-1) \\ 1, \epsilon(N-1) \leq k \leq (1-\epsilon)(N-1) \\ \frac{1}{e^{z_b(k)}+1}, (1-\epsilon)(N-1) < k < N-1 \\ 0, \ k = N-1 \end{cases} \tag{7}$$

$$z_a(k) = \epsilon(N-1)\left(\frac{1}{k} + \frac{1}{k-\epsilon(N-1)}\right) \tag{8}$$

$$z_b(k) = \epsilon(N-1)\left(\frac{1}{N-1-k} + \frac{1}{(1-\epsilon)(N-1)-k}\right) \tag{9}$$

Where N is the length of the filter, $0 < \epsilon \leq 0.5$, is the edge decay which controls the size of the top portion of the window, and $k = 0, 1, ..., N-1$. Since all possible values for heartbeats are between 45 and 150 cycles/min and for respirations are between 9 and 24 cycles/min, the frequency bands are selected as [0.7, 2.5] for the heartbeat, and [0.1, 0.5] for respiration. Figure 2 presents designed filter response for heartbeat signal extraction on the left, and the filter response for respiration signal extraction on the right.

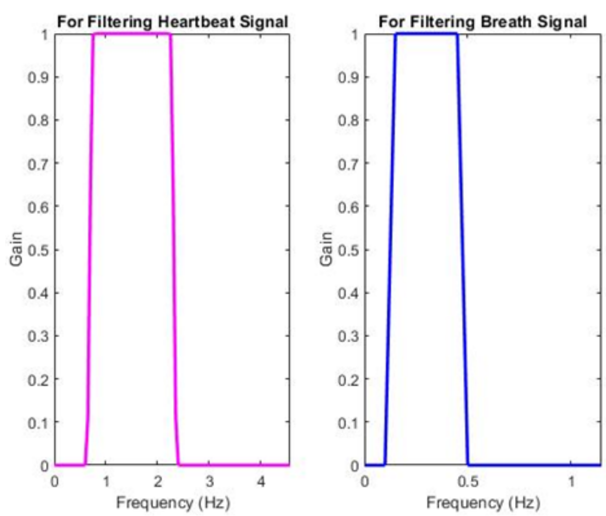

Fig. 2. FIR bandpass filters' frequency domain response

V. REFERENCE SENSORS

To validate the efficiency of this work, two additional biometric sensors are used to compare their results with our developed algorithms' results. Both reference sensors are sampled with a single Arduino with the same sample rate as the radar (40 milliseconds/25 Hz).

A. Breath Rate Reference Data

By means of piezoelectric sensor-a device that uses the piezoelectric effect to measure changes in pressure, acceleration, temperature, strain, or force by converting them to electrical charges, shown in Figure 3-(a)-the pressure caused by chest movement during breathing is measured. Then, the signal is synchronized with the radars signal and divided into windows with same length.

B. Heart Rate Reference Data

Pulse Sensor is used to get reference heart rate data. The Pulse Sensor is low-cost optical heart rate sensor (PPG) for Arduino and other microcontrollers [27]. Pulse Sensor has spot pressure which gives a live clean heartbeat waveform shown in Figure 3-(b). Then, simply, by counting peaks we get the heart beats.

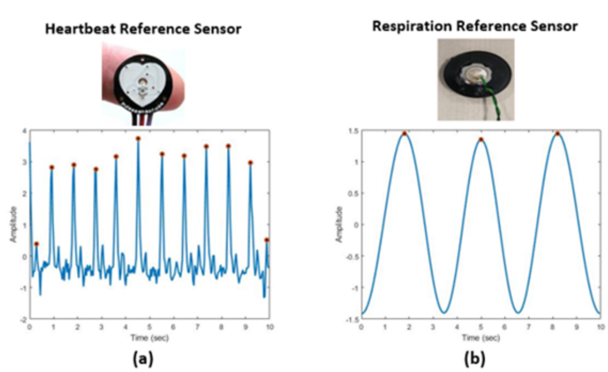

Fig. 3. Reference sensors and signals

VI. EXPERIMENTAL RESULTS

In order to make the system more robust, experiments are performed according to different daily life scenarios such

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as sitting, standing, laying down and sleeping, considering different positions of the subject including front, back and side. Although the best results are taken when the system is facing the subject's chest with no body movements, such ideal case is hard to be guaranteed for home usage device. The distance between the system and the subject is set in range up to 2 meters. Since gathered signal carries respiration and heartbeat signals as well as all the movements in the environment, first step in signal processing is cancelling these movements and all unwanted components. The difference between demodulated signal before and after artifact cancellation in the time domain for 3.5 minutes window is presented in Figure 4.

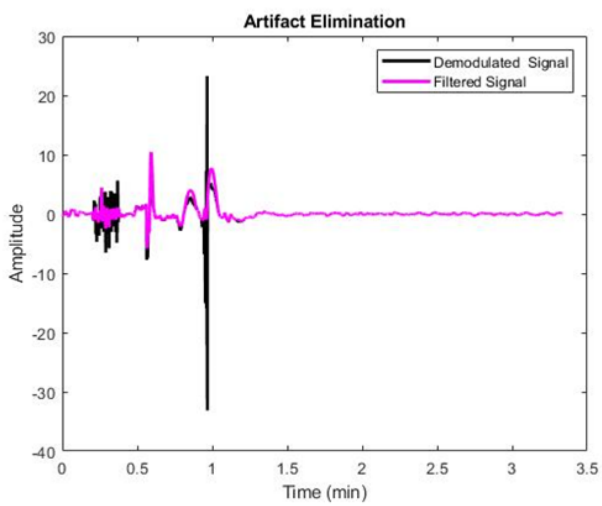

Fig. 4. Demodulated signal before and after artifact cancellation

After identifying and replacing epochs with noise and body movements, using the above described method, the remaining epochs were processed to extract the respiratory and heart rates. The signal is examined in 30 seconds length windows. A moving window with 30 seconds length and 15 second overlap is used. Each window is passed throw two algorithms with different parameters. One for extracting respiration signal and another is for extraction heartbeat signal. A time domain comparison between reference signal (above) and extracted respiration signal (bellow) is shown in Figure 5 Similarly, reference and extracted heartbeat signals are shown in Figure 6.

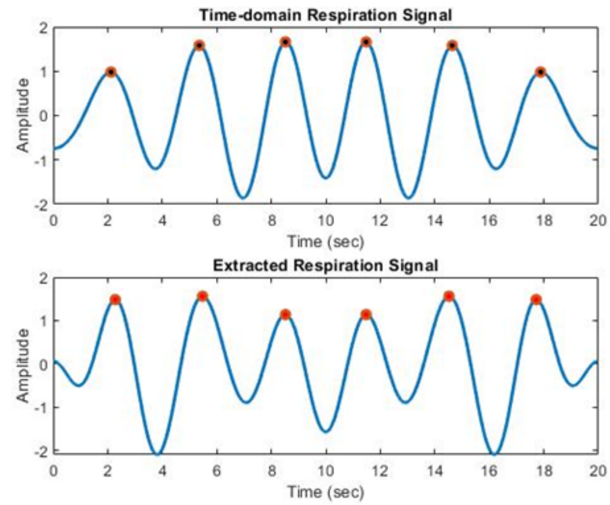

Fig. 5. Extracted and reference respiration signals

A total of 100 minutes of recordings from 10 healthy subjects (6 males and 4 females) were used to validate the proposed system and its ability to measure vital signs rates. During experiments, Radar has been located in two different locations: first location is on the ceiling with 230 cm height from the floor, and 180 cm height from the bed or chair. Second location is on the chest level toward the subject. For each Radar location, two states of the subject have been tested: sitting and lying down. Considering that such project is developed for home usage purposes, daily life scenarios such as Radar facing the chest, Radar facing the back and radar facing the subject's side have been evaluated for each state.

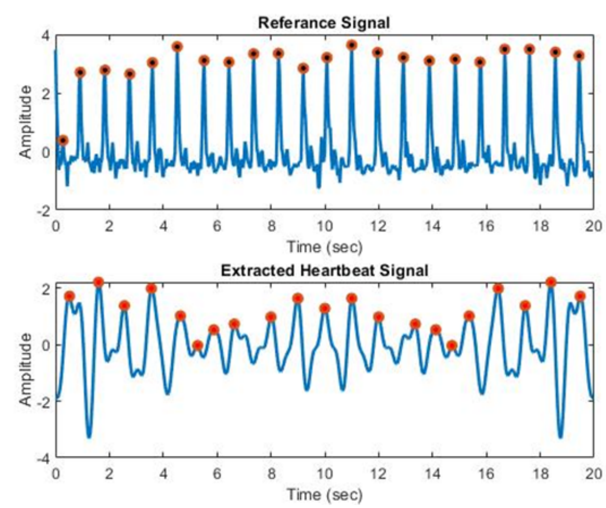

Fig. 6. Extracted and reference heartbeat signals

Absolute mean error and accuracy percentage are used to evaluate the methods' performances. Accuracy percentage is basically calculated by measuring the closeness between predicted rates and the rates measured using reference sen-

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sors mathematically shown by Equation 10.

$$\text{Accuracy} = \frac{\text{HR}_{\text{ref}} - |\text{HR}_{\text{ref}} - \text{HR}_{\text{Radar}}|}{\text{HR}_{\text{ref}}} \times 100(\%) \quad (10)$$

whereas Mean Absolute Error (MAE), simply finds the absolute difference between predicted and actual rates, and then finds the mean of all errors, as it is in Equation 11.

$$MAE = \frac{1}{n}\sum_{j=1}^{n}|y_j - \hat{y}_j| \quad (11)$$

This method is suitable for evaluating results, since in this study less predictions and more predictions have similar effects.

By comparing the system results to highly accurate biometric sensors, the proposed system achieves 97.7 accuracy for respiration detection and 95.3 accuracy for heartbeat detection with the best scenario case when the radar is facing a siting subject's chest. Achieved error and accuracy values for different measurement sets are presented in Table 1.

TABLE 1
MAE AND ACCURACY RESULTS FOR DIFFERENT TEST SETS

Radar Position	Subject State	Radar Heading	Respiration Rate		Heartbeat Rate	
			MAE	Acc.	MAE	Acc.
Ceiling	Sitting		3.5	82.7	13	81.7
	Lying down	Chest	2.2	90.7	3.3	94.8
		Back	2.7	84.8	3.1	95.8
		Side	2.6	85.6	2.3	95.6
Chest level	Sitting	Chest	0.8	97.7	2.5	95.3
		Back	2.8	85.5	6.8	92.1
		Side	2.5	87.3	4.5	94.6
	Lying down	Chest	2.1	90.7	3.3	94.4
		Back	2.4	89.1	7.2	88.7
		Side	2.3	87.0	6.1	88.9
Average			2.39	88.11	4.76	92.2

VII. CONCLUSION

In this paper methods for signal processing of Doppler signals have been outlined with major focus on extracting vital signs from signals that include random body movements. A very low-cost non-contact system design with methods for signal separation and vital signs detection have been developed. Considering various daily life scenarios from up to two meters away, proposed system has proved highly accurate performance for both the heart rate and respiratory rate. Finally, considering the robust performance that has been proved, future work will focus on utilizing this contactless physiological data acquisition system as a fundamental subsystem in a variety of applications; especially those designed for daily home usage for elder people such as classifying their daily activities and detect any possible danger events could happen like fall, hysteria or fainting.

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