Contactless Vital Signs Tracking with mmWave RADAR in Realtime

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***Abstract*—Heart rate and breathing rate are vital signs that are crucial for measuring a person's well-being, stress and emotions. In this work, we leverage commodity mmWave RADAR based on frequency modulated continuous wave (FMCW) developed by TI to contactlessly measure the vital signs of humans in real-time. First, we measure the variations in chest displacement (caused by heartbeat and breathing), then transfer the processed output to the PC via the UART data port, and finally, display it in real-time using the MATLAB GUI.**

***Index Terms*—mmWave, Vital Signs, Heart Rate (HR), Breathing Rate, FMCW.**

I. Introduction

Recently, frequency modulated continuous wave (FMCW)-based mmWave RADARs have gained a significant popularity owing to its low-cost, ultra low power requirement, and their ability of detecting the angle, range, and velocity simultaneously [1]. Because of these features they have been used for diverse range of applications including, object recognition and detection, place recognition, motion estimation, simultaneous localization and mapping (SLAM), *etc.* [2].

The FMCW-based mmWave RADARs have extremely high frequency (EHF), and their wavelength is measured in millimeters (mm). For instance, the commodity mmWave RADARs built by Texas Instruments (TI) have a frequency ranging from $76 \sim 81$ GHz, and their corresponding wavelength is 4 mm [3]. Due to such a smaller wavelength, it can easily detect infinitesimal motions in terms of mm resolution, e.g., chest displacement due to breathing and heartbeat.

II. Background

FMCW-based mmWave RADAR synthesizes the FMCW. The frequency of FMCW (*a.k.a.* chirp signal) increases linearly with time. The transmitted chirp signal $s(t)$ is expressed as:

$$s(t) = \exp^{j\left(\omega t + \pi \frac{B}{T_c} t^2\right)} \tag{1}$$

where ω is the angular velocity of the carrier frequency (f_c), and is equal to $2\pi f_c$. B is the bandwidth of the transmitted chirp and T_c is the chirp duration. This transmitted chirp strikes with the objects and produces various scatters reflection. The receiving antenna capture the reflection $r(t)$, which is given as:

$$r(t) = \exp^{j\left(\omega (t-\tau) + \pi \frac{B}{T_c} (t-\tau)^2\right)} \tag{2}$$

here τ is the delay encountered by the received signal after reflection and is equal to $2R/c$, where R is the range (or distance) of the detected object, and c denotes the speed of light.

Since the mmWave RADAR contains both the $s(t)$ and $r(T)$, it mixes them together and creates an intermediate signal. This intermediate signal is also called beat signal $b(T)$:

$$b(t) = s(t)r(T) \approx \exp^{j\left(4\pi \frac{BR}{cT} t + \frac{4\pi}{\lambda} R\right)} \tag{3}$$

where $4\pi(BR/cT)$ term represents the beat frequency f_b, which is useful for calculating the velocity of the target object; and $(4\pi/\lambda)R$ represents the beat phase ϕ_b, which is used for calculating the tiny vibration of an object (*i.e.,* variation of distance in time). We can alternatively write Eq. 3 as follows:

$$b(t) = \exp^{j(f_b t + \phi_b)} \tag{4}$$

In this work, we leverage ϕ_b for measuring chest vibration due to the breathing and heart rate. In particular, the small movement of the chest causes the phase changes *i.e.,* $\Delta\phi_b$ from where the changes in displacement *i.e.,* ΔR can be derived by manipulating the ϕ_b term of Eq. 3 as follows:

$$\Delta R = \frac{\lambda}{4\pi} \Delta\phi_b \tag{5}$$

The TI's off-the-shelf FMCW-based mmWave RADAR, for example, has a wavelength of 4 mm. Assume that the chest vibration induced by the heart rate changed the phase by π radians, then using Eq. 5, the change in distance ΔR would be approximately 97.4 mm.

III. Methodology

In this work, we used mmWave RADAR developed by Texas Instruments (TI), named as IWR1443BOOST [4]. This device has three transmitting antennas and four receiving antenna. This device converts the beat signal (*i.e.,* IF signal after the mixer) from analog to a digital form using its Analog to Digital converter (ADC). The signal processing steps for extracting the vital signal are explained as follows:

Range Estimation. Each frame in our implementation has a single chirp. Each modulation sweep contains a couple of

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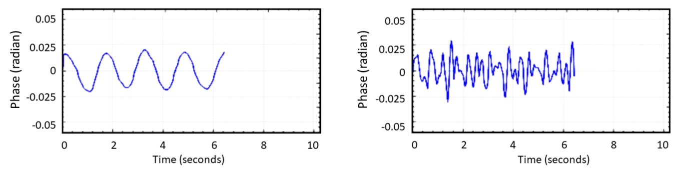
frame transmission (or chirp transmission[1]). Multiple modulation sweeps stacks on the top of each other and forms a matrix, where the column is fast-time axis and the row is slow time axis. Firstly, the Fast Fourier Transform is applied to each entity of the matrix (i.e., the digitized beat signal) to obtain the range-bins. This transforms the entire column into the range profile. Although there are multiple rang-bins in each range profile, however, the target's range-bin corresponds to the one with maximum variation (or highest value). To obtain the accurate displacement profile, the angle between two consecutive phases must be less than π radians. To do so, the phase unwrapping is applied, which restricts such jumps within -π and π, by adding them multiples of $\pm 2\pi$. Finally, the phase drifts are eliminated using the phase difference procedure, which computes the consecutive values of unwrapped phases and replace the outliers of the phase difference by the interpolated value.

Breath rate extraction. The phase values acquired from the preceding operation are passed through a band-pass filter, *i.e.,* Bi-Quad IIR filter which is serially cascaded. Based on the assumption in [5], [6] for resting adults whose breathing rate ranges between 12 $\sim$ 16 breaths per minute, we used the cutt-off band-limits for allowing the band-pass frequencies in between 0.1 and 0.6 Hz. With these limits, we could capture the movement of chest from 6 to 36 breathes per minute[2]. The output of the band-pass filter is saved in a buffer, where a couple of spectral estimation techniques are applied namely the FFT and inter-peak interval estimation for breathing signals. Finally, the breathing rate decision is made using the confidence metric of spectral estimation.

Heart rate extraction. For measuring the heart rate the band-pass filter is applied with band-limits of 0.8 $\sim$ 4.0 Hz which could capture 48 $\sim$ 240 beats per minutes (BPM). Since, the movement of chest due to heart rate is very small, and could be easily corrupted by the motion of individual. We handle this by monitoring the energy of the data contained in one second; if the energy of the data segment exceeds a certain level, it is discarded. In case of no motion detection, the cardiac waveform is stored in a buffer, and the spectral estimation techniques such as FFT, auto-correlation and estimation based on inter-peak intervals are applied to it. Lastly, based on the confidence metric decision, the heart rate is estimated.

IV. Evaluation

For configuring the TI mmWave sensor (IWR1443BOOST), we used one chirp per frame, and obtained 100 ADC samples per chirp. The chirp duration T_c was set as 50 microseconds. Furthermore, the IF (or beat signal) sampling rate was set as 2 MHz. Although this device could support 3 transmitter (TX) and 4 receiver (RX) antenna, however, due to the limitation of maximum UART data rate transfer, we used only 1 TX and 1 RX antenna pair. The frame periodicity was set as 50 milliseconds (*i.e.,* 20 fps). The real-time processing window was configured as 10 seconds which was updated every second. The memory required for the buffering process was 16 kB. Lastly, we used the maximum achievable bandwidth of this device (*i.e.,* 4 GHz from 77 GHz to 81 GHz).



(a) Breathing Waveform. (b) Heart Beating Waveform.

Fig. 1. Real-time Vital Signs on MATLAB GUI

Figures 1(a) and 1(b) show the real-time vital signs tracking for breathing and heartrate. The window resolution is 10 seconds where the output of vital signs is updated every second. During the measurements, any motion by the user can corrupt the vital signs readings. In the current implementation, we mitigate it by defining a threshold; if the energy of the motion signal exceeds that threshold, the vital signs measurement for that segment of time is discarded.

V. Conclusion and Future Work

In this workshop paper we have provided the preliminary evaluation of the TI sensor for tracking the vital signs in real-time. It should be noted that we have used hard-coded thresholds for cut-off limits of the band-pass filters based on the assumptions used in the current studies [5], [6]. Furthermore, we used UART data port for transmitting the real-time data from the mmWave sensor to the PC for visualization purposes, and due to its lower throughput we had a couple of limitations on using MIMO and multiple chirps per frames etc. In future, we would tackle these issues by using a high speed data transfer tool called DCA1000EVM in conjunction with IWR1443BOOST, to transmit the data at higher speed (at the rate of Gbps) via Ethernet port. Furthermore, we would make our system more robust to errors due to human motion by leveraging the periodic similarity of heart rate signals for training the machine learning (or deep learning) models. We also envision to use vital signs monitoring alongside other relevant data acquisition sensors (e.g., camera) for tracking the emotional stress of a driver for avoiding accidents.

[1] As in our implementation we have a single chirp per frame in order to keep a lower throughput for UART transmission, therefore the frame and chirp size is same. Note that it is also possible to transmit multiple chirps per frame.

[2] Almost double limits of that assumed in [5], [6].

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