Detection of Stationary Human Targets by Capturing Doppler of Heart Beat using a Portable SFCW through Wall Radar

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Abstract

Heart-beat detection has found many applications in military and rescue at disaster relief sites. Detection of micro motion of human heart beat is achieved using a C-band dual synthesizer heterodyne receiver based step frequency continuous wave (SFCW) portable through wall radar (TWR). SFCW radar can help separate Doppler signatures in down-range, thus enabling it to look for multiple human targets. This paper focuses on the experimentation of a technique that uses multiple sweeps of stepped frequency continuous-wave signal and moving target indication (MTI) filter to obtain the range and Doppler frequency of human vital signs, in the presence of an interfering wall or other complex environments. The Doppler detection logic is implemented in Field Programmable Gate Array (FPGA). The experimental results are reported.

I. INTRODUCTION

Mechanical vibrations or rotations of structures on a target may introduce frequency modulation on the radar return signal. The modulation due to this vibration or rotation is referred as micro-Doppler phenomenon. For example, human physical activity is a complex motion that is comprised of movements of individual body parts, including head, torso, leg, arm and foot. When human is walking, the movements of different components of human body generate a number of different frequency shifts in the radar returned signal, also called Doppler frequency shifts. It should be noted that only the velocity in the radial direction contributes to Doppler frequency shift [2]. Positive Doppler frequency is generated if radar target moves toward the radar while negative one is rendered if radar object moves backward from the radar sensor. Several radar technologies are usually used to detect the Doppler frequency shift due to human movement, including continuous wave (CW), frequency modulated CW (FMCW), pulse compression, and pulse radar [4]. M. Pieraccini, etc. utilized a 2.42 GHz continuous-wave microwave transceiver to detect breathing and heartbeat of people buried in snow and the feasibility is proved by experiments. I. Immoreev and S. Ivashov researched on Ultra-Wideband (UWB) pulse radar in high accuracy remote monitoring moving objects at short distances, and they showed the applications in medicine and in psychophysiology for remote measuring of patient's heart activity and respiration. Q. Zhang, etc. worked on the imaging of moving target with rotating parts by Linear Frequency-Modulated (LFM) radar signal, and the simulation results have been presented to illustrate the effectiveness of the proposed method. In this paper, the stepped-frequency continuous-wave is adopted for several advantages of it. Firstly, by stepped-frequency continuous-wave, the range detection and micro-Doppler signature extraction can be achieved simultaneously. Secondly, the implement and the waveform control of stepped-frequency continuous-wave are easy. Finally and most importantly, in the radar system of stepped-frequency continuous-wave, some processing methods of narrowband signal can also be used to process wideband signal [6].

The SFCW-UWB transceiver has been realized using dual PLL-VCO based sweeping synthesizers which constitute heterodyne architecture of TWR. Minute phase variations in received echo, caused by human respiration and heart beat during waveform dwell, are captured in processing hardware after digital down-conversion. Digital heterodyne architecture is chosen for limiting receiver bandwidth (to few KHz across IF), ensuring I/Q balance, and optimal performance of the analog to digital converters.

The paper is structured as follows: Section II formulates the echo due to the heart beat of stationary human target into a mathematical form. Section III presents the Doppler processing of SFCW for micro Doppler extraction. Section IV explains the implementation of the logic in a FPGA based DSP hardware and the results obtained. Section V provides the conclusion with prospects of future work.

II. HEART BEAT ECHO MODEL

The stepped frequency has a pulse repetition time of T, i.e. the step frequencies are repeated for every T. For one swept period, the stepped-frequency continuous-wave signal is [1], [9]

$$T(t_F) = \sum_{n=0}^{N_f-1} Re\left\{e^{j2\pi(f_0+n\Delta f)t_F}\, rect\left(\frac{t_F - \frac{T_d}{2} - nT_d}{T_d}\right)\right\} \quad (1)$$

where N_f is the number of frequencies, f_0 is the start frequency, Δf is the step frequency, T_d is the dwell time, which is the time spent on each frequency, and $t_F \in [0, N_f T]$ is the fast time which means the time within one swept period. For one swept period, it is considered that the echo has a constant time delay, τ. And consider the target's complex reflection coefficient, $|\Gamma|e^{j\varphi}$ the echo signal can be expressed as

$$S(t_F) = T(t_F - \tau) = |\Gamma|e^{j\phi} \sum_{n=0}^{N_f-1} Re\left\{e^{j2\pi(f_0+n\Delta f)(t_F-\tau)}\, rect\left(\frac{t_F - \frac{T_d}{2} - nT_d - \tau}{T_d}\right)\right\} \quad (2)$$

Baseband version of (2) can be expressed as,

$$S_b(t_F) = |\Gamma|e^{j\phi} \sum_{n=0}^{N_f-1} Re\left\{e^{-j2\pi(f_0+n\Delta f)\tau}\, rect\left(\frac{t_F - \frac{T_d}{2} - nT_d}{T_d}\right)\right\} \quad (3)$$

$S_b(t)$ now is a stair cased sine wave where each step corresponds to the response measured at each frequency. The amplitude and phase is determined by the reflection coefficient of the target while the frequency of the sine wave is proportional to the delay τ. If the signal is sampled in the middle of each step, we get a complex array.

$$S[k] = |\Gamma|e^{j\phi}cos(2\pi(f_0 + k\Delta f)\tau) \quad (4)$$

where $k = 0, 1, 2, \ldots N_f\text{-}1$

This can be rewritten as a frequency domain representation

$$S(f_k) = |\Gamma|e^{j\phi}\, rect\frac{f-f_c}{B} cos(2\pi f\tau) \quad (5)$$

where, $f = f_0, f_0 + \Delta f, \ldots f_0 + (N_f - 1)\Delta f$ B represents the bandwidth of the transmitted signal, while $f_c = \frac{f_{max}+f_0}{2}$ is the center frequency of the waveform. $S(f_k)$ presents the stepped-frequency continuous-wave baseband signal model of one swept period. For extracting the micro-Doppler signature like heart beat, multiple swept periods are adopted and then the time delay of echo is considered time-variant. The distance between radar receiver and the micro-motion target can be considered as

$$r(t_s) = r_0 + A_H sin(\omega_H t_s + \varphi_H) \quad (6)$$

where, $t_s = 0, N_f T, 2N_f T, \ldots$ is the slow time which means the time of swept periods, r_0 is the average distance and A_H, ω_H, φ_H are amplitude, angular frequency and initial phase. Thus, the time delay of target can be expressed as

$$\tau(t_s) = \frac{2r(t_s)}{c} = \frac{2[r_0 + A_H sin(\omega_H t_s + \varphi_H)]}{c} = \frac{2r_0}{c} + \frac{2[A_H sin(\omega_H t_s + \varphi_H)]}{c} = \tau_0 + \tau_H(t_s) \quad (7)$$

where τ_0 denotes the time delay of the average distance and $\tau(t_s)$ is caused by the heartbeat of the stationary human target.

III. SFCW DOPPLER PROCESSING

The equivalent time-domain signal of one swept period can be obtained by IFFT [1], [9], [10]

$$s'(t_F) = IFFT[S(f_k)] = \frac{1}{2}|\Gamma|e^{j\phi}B\{sinc[B(t_F - \tau)]e^{j2\pi f_c(t_F-\tau)} + sinc[B(t_F + \tau)]e^{j2\pi f_c(t_F+\tau)}\} \quad (8)$$

where, the number of IFFT points equals to the number of range gates. $s'(t_F)$ includes the range information of human body. For extracting the life characteristic, multiple $s'(t_F)$ of different sweeps will be used,

$$s'(t_F, t_s) = \frac{1}{2}|\Gamma|e^{j\phi}B\{sinc[B(t_F - \tau(t_s))]e^{j2\pi f_c(t_F-\tau(t_s))} + sinc[B(t_F + \tau(t_s))]e^{j2\pi f_c(t_F+\tau(t_s))}\} \quad (9)$$

Signal $s'(t_F, t_s)$ contains the time delay $\tau(t_s)$ which includes the micro-Doppler signature in both the envelope and the phase. Here, only the time delay in the phase is used to extract the micro-Doppler signature. Consider the time delay in the range gate where there is micro-motion target is about τ_0. Then suppose $t_F = \tau_0$ and rewrite Eq. (9) as

$$s'(\tau_0, t_s) = \frac{1}{2}|\Gamma|e^{j\phi}B\{sinc[B\tau_H(t_s)]e^{-j2\pi f_c \tau_H(t_s)} + sinc[B(2\tau_0 + \tau_H(t_s))]e^{j2\pi f_c(2\tau_0+\tau_H(t_s))}\} \quad (10)$$

where, $B\tau_H(t_s) \approx 0$ and $B(2\tau_0 + \tau_H(t_s)) \gg 1$. So $sinc[B\tau_H(t_s)] \approx 1$ and $sinc[B(2\tau_0 + \tau_H(t_s))] \approx 0$. Then,

$$s'(\tau_0, t_s) = \frac{1}{2}|\Gamma|e^{j\phi}Be^{-j2\pi f_c \tau_H(t_s)} = \frac{1}{2}|\Gamma|e^{j\phi}Be^{-j\frac{4\pi f_c A_H sin(\omega_H t_s + \varphi_H)}{c}} \quad (11)$$

The exponential term in eq. (11) is expanded using Fourier series as

$$e^{-j\frac{4\pi f_c A_H \sin(\omega_H t_s+\varphi_H)}{c}} = \sum_{n=-\infty}^{\infty}\left\{J_n\left(\frac{4\pi f_c A_H}{c}\right)e^{-jn\varphi_H}e^{-jn\omega_H t_s}\right\} \tag{12}$$

where, $J_n(x)$ is the nth order Bessel function of the first kind, an interesting Fourier-series based representation of the phase modulated signal can be obtained by substituting eq.(12) into eq.(11) and is described as

$$s'(\tau_0, t_s) = \frac{1}{2}|\Gamma|e^{j\phi}B \sum_{n=-\infty}^{\infty}\left\{J_n\left(\frac{4\pi f_c A_H}{c}\right)e^{-jn\varphi_H}e^{-jn\omega_H t_s}\right\} \tag{13}$$

$s'(\tau_0, t_s)$ contains a constant component at m = 0, the component with vibration angular frequency of target , ω_H and the harmonics with ω_H. The intensities of these harmonics are defined by f_c and A_H .For micro-motion target, A_H can be considered almost invariable, and the appropriate radar parameters can be set to make the intensities of harmonics much lower than one of the component with ω_H. So the vibration frequency can be obtained by FFT on $s'(\tau_0, t_s)$ after the constant component is removed by MTI filter. For the range gate where there is static object, the echo's time delay is considered always time-invariant, and the spectrum will show no frequency component after MTI filtering. So the micro-motion target can be detected and meanwhile, the vibration frequency of the target is extracted.

The processing steps are presented as follows

Step 1 Transform L = 256 continuous swept periods base band signal to time domain by IFFT to obtain $s'(t_F, 0)$, $s'(t_F, NT)$,..... $s'(t_F, (L-1)NT)$

Step 2 Construct a matrix R with $s'(t_F, (i-1)NT), 1 \leq i \leq L$

$$R = \begin{bmatrix} s'(1,1) & s'(1,2) & \cdots & s'(1,1024) \\ s'(2,1) & s'(2,2) & \dots & s'(2,1024) \\ \vdots & \vdots & \vdots & \vdots \\ s'(256,1) & s'(256,2) & \cdots & s'(256,1024) \end{bmatrix} \tag{14}$$

Each row means the values of $s'(t_F)$ for one swept period, and each column means the values of different sweeps in the same range gate.

Step 3 Pass the data of each column in R through the MTI filter to suppress target-like returns produced by clutter (wall reflections, static part of human body, etc. in our case), and allow returns from moving targets to pass through, with little or no degradation. The recursive MTI filter gives a flat frequency response in the frequency of interest. The transfer function is

$$H(z) = \frac{Y(z)}{X(z)} = \frac{1 - z^{-1}}{1 - Kz^{-1}} \tag{15}$$

X(z) is the input to the MTI filter whereas *Y(z)* is the MTI filter output, *K* is the gain factor which controls the frequency response.

Step 4 Compute FFT along each column of the matrix generated in Step 3 to generate the Range-Doppler (RD) plane**.** Scale the range axis as (Range bin number) $* \frac{C}{2B}$ and the frequency axis as (Frequency bin number) $* \frac{PRF}{L}$

Utilizing the RD plane, micro-motion target can be detected.

IV. IMPLEMENTATION & RESULTS

A TWR based on heterodyne architecture has been realized using fractional-N PLL based synthesizer-VCO combination [3]. Objective of the design was to detect human targets at least up to 15m beyond various types of walls of better than 9" thickness. Both Tx and Rx synthesizers sweep through 1GHz of bandwidth with 5MHz step size, whereas the Rx synthesizer is separated from the Tx by an IF of 10.7MHz. The reference and echo signals at IF are passed through crystal filters of 1MHz bandwidth, thus limiting the receiver bandwidth to 1MHz. The radar provides a resolution better than 15cm, and has an unambiguous range of 30m

Figure 1. Algorithm for micro-Doppler processing

To optimize hardware requirement for the receiver, digital IQ detection is used for determining phasor relation between reference and echo channels. Only one ADC per channel is required when digital phase detection is employed. Signals at IF are oversampled by a factor of 4 using 16-bit ADCs, and samples in every frequency dwell coherently integrated for minimizing effects of synthesizer phase noise. A multi-channel, signal processing hardware unit with FPGA and DSP combination was designed. This setup is now utilized for SFCW micro-Doppler processing and imaging.

Figure 2. Multi-channel signal processing hardware[3]

The SFCW parameters used for the experiment is detailed below

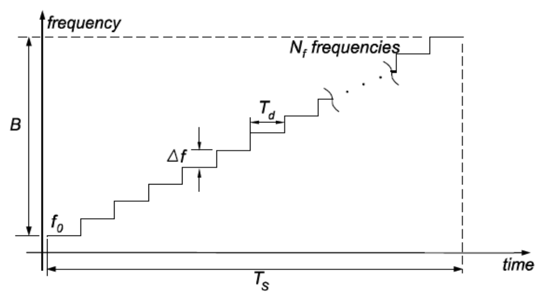

Figure 3. SFCW waveform in time vs. frequency

	Frequency band	C band
B	Sweep Bandwidth	1 GHz
Δf	Frequency step	5 MHz
T_d	Dwell time	100 µs
N_f	Number of frequency steps	200
T_s	Total scan time	20 ms
T_{off}	Tx Off time	24 ms
f_{adc}	ADC sampling frequency (4 * IF)	42.8 MHz
R_{unamb}	Unambiguous range	30m
N_{fft}	Number of FFT points	1024
PRF	$\frac{1}{T_s + T_{off}}$	22.73 Hz
L	Number of sweeps	256
f_H	Heart beat frequency	1.1 Hz
2 x 2	Antenna Type	Patch array

The laboratory experiment setup and the observed results are explained

A. *Application 1 : Military*

In military or hostage situations, the application is to find human targets behind the wall. The experiment was started with heart beat detection of stationary human targets behind a 9 inch thick concrete wall. The results are promising. Human targets as far as 8 meters behind the wall were detected. Moving target detection was achieved in our previous work, better than 20 meters through 9" concrete wall [3].

Figure 4. Setup for through wall applications

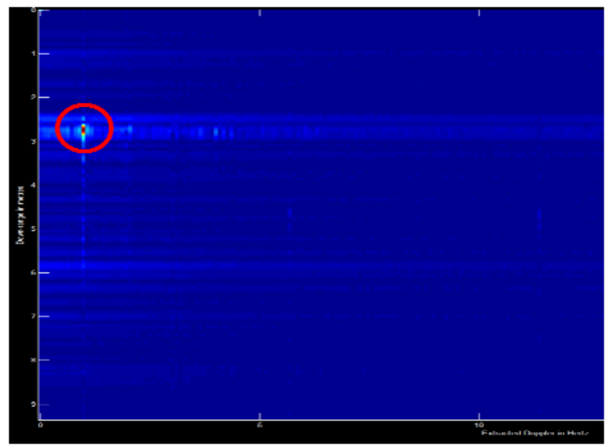

Figure 5. Single target at 2.8m behind wall

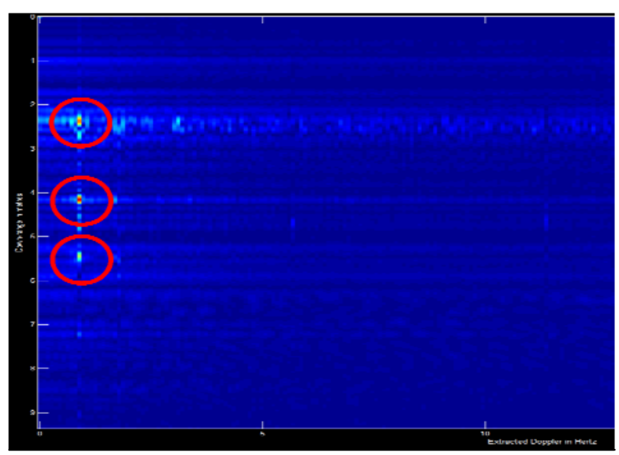

Figure 6. Three targets at 2.4m, 4.1m and 5.4m behind wall

B. Application 2 : Search and rescue at disaster relief sites

In search and rescue operations, the application is to extract and to classify human vital signs like heart beat for detection of trapped human victims in complex environments such as in earthquake disaster site. The experiment started with capture of heart beat Doppler of human targets behind the rubble. The case has to be extended to increased depth of rubble to emulate the real scenario of human subjects buried in a collapsed building.

Figure 7. Setup for rescue applications for buried human targets

For this setup, it was able to capture heart beat Doppler as far as 4m through the rubble. The image as seen in figure 8, shows a smear along Doppler axis, and also multi-path reflection.

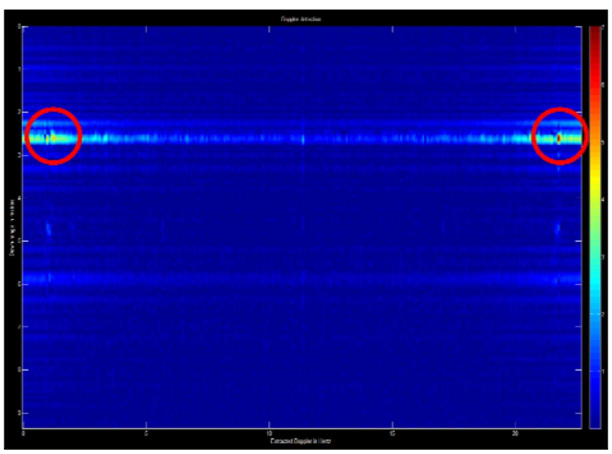

Figure 8. Single target at 2.6m behind rubble

V. CONCLUSIONS

The results demonstrate that the combination of SFCW radar as the hardware and advanced signal-processing algorithms as the software has potential for efficient vital sign detection and location in military as well as search and rescue for trapped victims in complex environment. Applying the MTI to remove the direct wave and the background clutter, the spectral analysis with the FFT can separate and extract heartbeat frequency from human life signals effectively in experimental data.

This work has shown promising results for stationary human being detection through opaque barriers. The technique has been validated by testing the radar with different types of wall (both thickness, and materials). It has been observed that gross human movements like waving of hands, walking etc can be clearly detected even at greater distances from the wall compared to heart beat. Classification of heart beat against gross movements necessitates advanced spectral analysis techniques like Short Time Fourier Transform (STFT) to reflect the time–frequency characteristic of multiple micro-Doppler shifts.

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