Simultaneous Location and Parameter Estimation of Human Vital Sign with MIMO-FMCW Radar

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***Abstract*—Simultaneous location and parameter estimation of vital sign signal captured with a MIMO-FMCW radar sensor system is presented. The suggested system is able to deal with safety inspection emergency counter-terrorism and fire rescue. Micro-Doppler information, estimated from received signal, is used to classify heart and breath frequency of human. The Capon BF measurement algorithm is used to estimate accurate angles. The received signal synthesize precise angle information to get position of target. Measured data collected from MIMO-FMCW radar received encouraging results after these algorithms. Results of human object with deferent range or angle show effectiveness to achieve great estimation performance.**

***Index Terms*—Non-contact vital sign detection; Simultaneous Location and Parameter Estimation; MIMO-FMCW Radar; Capon Beam Forming**

I. Introduction

Recent progress in microwave radar for noncontact vital sign measurement techniques on Frequency Modulated Continuous Wave (FMCW) radar have been made with growing interests in health-care and biomedical science. When the operating frequency increased from microwave to millimeter range,smaller size objects can be discovered. Besides, millimeter waves provide wider frequency bands and lower RF interference compared with other kinds of waveform.The FMCW radar has the advantage of small size, light weight, low power consuming and enabling real time processing[8]. So it is more efficient in suboptimal environment like home health care and detection of sudden infant death syndrome occurrence. Taking advantages of high resolution in range and angle measurement of Multiple Input Multiple Output (MIMO) FMCW radar enable to detect the position of humans. Therefore, this kind of radar has been employed in this work[4].

Several researches have already proposed enormous theoretical signal processing analysis of FMCW radar [3]. A deep learning framework is developed to extract vital sign parameters, and shows the effectiveness in assisted living scenarios [1], By considering the additional range and angular information with incoherent integration along the Doppler dimension, the research gain insights into the Heart and breath frequency.[9] .

In this work, the employment of MIMO-FMCW radar is suggested to mitigate position and vital sign of human simultaneously. The remaining work is organized as follows. The location and parameter estimation problem are briefly presented in subsection II-A and the MIMO-FMCW radar echo model of human vital sign is proposed in subsection II-B. The range profile and range-azimuth heat-map are formed in subsection II-C. Meanwhile the dual low-pass filters of the phase difference of peaks among radar frames are utilized to estimate respiration and heartbeat rate in section II-D. Section III gives the experiment and echo signal processing result, which demonstrates the proposed method. The conclusion is drawn in section IV.

II. Vital Sign Location and Parameter Estimation

A. Problem Description

As Fig. 1 shows that non-contact vital sign and location detector use MIMO-FMCW radar to get human respiration and heartbeat. Combining the frequency modulation and multiple input multiple output technology, modern MMW radar could be easily utilized in indoor applications such as elderly health care monitoring, robot simultaneously location and mapping, etc. Indoor human vital sign monitoring is a very typical application of MMW radar by using micro-Doppler extraction. The location function of radar are also the fundamental function of a radar device. But jointly location and vital sign parameter such as respiration and heartbeat rate by using single radar device seems to be a very challenging problem.

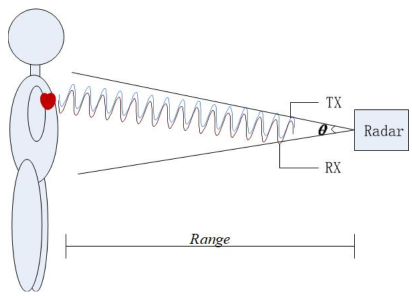

Fig. 1. Demonstration of Human Vital Sign Detection

A simultaneous location and parameter estimation is presented by using multiple channel echos. The range and azimuth of human object are estimated by finding peaks over the range azimuth heat-map which are calculated by range pulse compressing and azimuth Capon beam forming. Meanwhile the vital sign parameters are extracted by locating the peaks of the power spectrum which is the Fast Fourier Transformation(FFT) of the output from the dual low-pass filter of range peaks's phase difference between frames of radar echo. The experiments validate the proposed method.

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B. Radar Echo of Human Vital Sign

As to FMCW radar waveform, the transmitted complex analytic signal for one frequency modulation period is given by

$$s\left(\tilde{t},\eta\right)=e^{j\left[2\pi f_0\left(\tilde{t}+\eta\right)+\pi K\tilde{t}^2+\phi_0\right]} \tag{1}$$

Where $\tilde{t}$ is fast time such that $\tilde{t}\in[0,T]$, η is slow time which corresponding to the start of each modulation. f_0 is carrier frequency, $K=\frac{B}{T}$ is chirp rate, ϕ_0 is initial phase, B is the bandwidth of transmitted signal, T is the duration of frequency modulation.

Suppose a human whose chest is at the range of $R(\eta)$ and azimuth $\theta(\eta)$ from the MMW radar. $R(\eta)$ and $\theta(\eta)$ are assumed constant in fast-time. The delayed time of τ_m is received from $R(\eta)$ and the array spatial delay.

$$\tau_m=\frac{2R(\eta)}{c}-(m-1)\frac{d\sin\theta(\eta)}{c} \tag{2}$$

Where $m=1,2,...,M$ is the channel of the received signal.

The received signal for the chest is a delayed version of $s\left(\tilde{t},\eta\right)$. After time of τ_m, scattered echo by human object can be expressed as

$$r_m\left(\tilde{t},\eta\right)=\sigma(\eta)\cdot s\left(\tilde{t}-\tau_m,\eta\right)+v_m(\tilde{t},\eta) \tag{3}$$

$$=\sigma(\eta)\cdot e^{j\left[2\pi f_0\left(\tilde{t}+\eta-\tau_m\right)+\pi K\left(\tilde{t}-\tau_m\right)^2+\phi_0\right]}+v_m(\tilde{t},\eta) \tag{4}$$

Where σ depends on the target radar cross section and the range of human body to radar device. $v_m(\tilde{t},\eta)$ is thermal noise in receive channel m which is independent between channels.

C. Range and Azimuth Estimation

For FMCW radar, the base band signal $x_m\left(\tilde{t},\eta\right)$ can be get by,

$$\begin{aligned}x_m\left(\tilde{t},\eta\right)=&r_m\left(\tilde{t},\eta\right)\cdot s^*\left(\tilde{t},\eta\right)\\ \approx&\sigma(\eta)\exp\left\{-j4\pi\frac{R(\eta)}{\lambda}\right\}\cdot\exp\left\{-j2\pi f_R\tilde{t}\right\}\\ &\cdot\exp\left\{j2\pi(m-1)\frac{d}{\lambda}\sin\theta(\eta)\right\}+v_m(\tilde{t},\eta)\end{aligned} \tag{5}$$

In Eq.(5) the high order phase items of $\tilde{t}^2$ are omitted for they are much smaller than 1 1. where $\exp\left\{-j4\pi\frac{R(\eta)}{\lambda}\right\}$ is phase caused by intra chirp Doppler, $\exp\left\{-j2\pi f_R\tilde{t}\right\}$ is a sinusoidal signal modulated by object range and azimuth and $\exp\left\{j2\pi(m-1)\frac{d}{\lambda}\sin\theta(\eta)\right\}$ is spatial modulation phase. Here f_R is the frequency caused by the range shift between echo signal and transmitted signal.

$$f_R=\frac{2KR(\eta)}{c} \tag{6}$$

The range profile could be done by committing Fourier transformation of $x_m(\tilde{t},\eta)$ along fast time $\tilde{t}$, which could lead to $X_m(f,\eta)$,

$$\begin{aligned}X_m(f,\eta)=&\mathcal{F}_{\tilde{t}}\left\{x_m\left(\tilde{t},\eta\right)\right\}\\ =&\sigma(\eta)\cdot\exp\left\{-j4\pi\frac{R(\eta)}{\lambda}\right\}\cdot\delta\left[f-f_R\right]\\ &\cdot\exp\left\{j2\pi(m-1)\frac{d}{\lambda}\sin\theta(\eta)\right\}+V_m(f,\eta)\end{aligned} \tag{7}$$

where $V_m(f,\eta)$ is the Fourier transform of noise signal $v_m(\tilde{t},\eta)$.

The MIMO radar has n_{TX} transmitted antenna(TX) and n_{RX} received antenna(RX), so the system has $M=n_{\text{TX}}\times n_{\text{RX}}$ equivalent channels. Then the stacked multiple channel signal can be expressed as follows,

$$\mathbf{X}(f,\eta)=\left[X_1(f,\eta),\cdots,X_M(f,\eta)\right]^{\text{T}} \tag{8}$$

Let $\mathbf{S}(\omega)$ represent the steering vector of equivalent spatial array of MIMO radar,

$$\mathbf{S}(\omega)=\begin{bmatrix}1 & \exp\left\{j2\pi\frac{d}{\lambda}\sin\omega\right\} & \cdots & \exp\left\{j2\pi(M-1)\frac{d}{\lambda}\sin\omega\right\}\end{bmatrix}^{\text{T}} \tag{9}$$

where the superscript T means the transpose operation. The following superscript H refers to conjugate transpose operation of vector or matrix.

For just one radar frame, L chirps are transmitted. So let $\eta=l\cdot T\,(l=0,1,...,L-1)$ and we get

$$\mathbf{X}(f)=\begin{bmatrix}X_1(f,0) & X_1(f,T) & \cdots & X_1(f,(L-1)T)\\ X_2(f,0) & X_2(f,T) & \cdots & X_2(f,(L-1)T)\\ \vdots & \vdots & \cdots & \vdots\\ X_M(f,0) & X_M(f,T) & \cdots & X_M(f,(L-1)T)\end{bmatrix} \tag{10}$$

Then the range-azimuth heat map of vital sign signal will be

$$\mathbf{Y}(f,\omega)=\frac{1}{\mathbf{S}^{\text{H}}(\omega)\,\mathbf{R}_{\mathbf{X}}^{-1}S(\omega)} \tag{11}$$

Where correlation matrix $\mathbf{R}_{\mathbf{X}}=\mathbf{X}(f)\cdot\mathbf{X}^{\text{H}}(f)$

The range and azimuth of the human reflector can be extracted from the frequency and spatial frequency corresponding to the peaks on the range-azimuth heat-map.

$$(f^*,\omega^*)=\arg\max_{f,\omega}\mathbf{Y}(f,\omega) \tag{12}$$

And we have the range and azimuth estimation as follows,

$$\hat{R}=\frac{c}{2K}f_R^* \tag{13}$$

$$\hat{\theta}=\omega^* \tag{14}$$

$(\hat{R},\hat{\theta})$ is corresponding range and azimuth when $Y(f,\omega)$ take its peak. Meanwhile, for the peak on range-azimuth heat map, we could have obtained their phase of intra-chirp or intra-frame, which can be expressed as follows.

$$Z(\eta)=\left[\mathbf{S}^H\left(\hat{\theta}\right)\cdot\mathbf{X}(f^*,\eta)\right]=A\exp\left\{-j4\pi\frac{R(\eta)}{\lambda}\right\}+V_m(\eta) \tag{15}$$

D. Simultaneous Vital Sign Parameter Extraction

For vital sign, information is contained in $R(\eta)$ [10].

$$R(\eta) = \hat{R} + a_r \cos(2\pi f_r \eta) + a_h \cos(2\pi f_h \eta) \tag{16}$$

Where $\hat{R}$ is estimated range of vital sign without translations, a_r and a_h are vibration amplitude of respiration and heartbeat respectively, $f_r$and f_h are frequency of them.

So vital sign signal in the peak of range-azimuth heat-map can be expressed as

$$\begin{aligned} Z(\eta) =& \tilde{A} \cdot \exp\left\{-j\frac{4\pi}{\lambda} a_r \cos(2\pi f_r \eta)\right\} \\ &\cdot \exp\left\{-j\frac{4\pi}{\lambda} a_h \cos(2\pi f_h \eta)\right\} + V_m(\eta) \end{aligned} \tag{17}$$

where $\tilde{A} = A\exp\left\{-j\frac{4\pi}{\lambda}\hat{R}\right\}$ is the constant phase.

Here shows that phase contact the frequency of heartbeat and respiration.

$$\phi(\eta) = a_r \cos(2\pi f_r \eta) + a_h \cos(2\pi f_h \eta) \tag{18}$$

The heartbeat and respiration phase can be separated by two band-pass filter.

$$\begin{aligned} \Delta_r(\eta) &= BPF_r[\phi(\eta)] = a_r \cos(2\pi f_r \eta) \\ \Delta_h(\eta) &= BPF_h[\phi(\eta)] = a_h \cos(2\pi f_h \eta) \end{aligned} \tag{19}$$

Then we have

$$\begin{aligned} \hat{f}_r &= \arg\max_f |\mathcal{F}_\eta\{\Delta_r(\eta)\}| \\ \hat{f}_h &= \arg\max_f |\mathcal{F}_\eta\{\Delta_h(\eta)\}| \end{aligned} \tag{20}$$

Finally both the location and vital sign parameters for the object in the field of view can be extracted. They can be listed as

$$\mathbf{x} = \left(\hat{R}, \hat{\theta}, \hat{f}_r, \hat{f}_h\right) \tag{21}$$

As the fluctuation range of chest cavity caused by human respiration and heartbeat is very small, this paper use micro motion information of changes in the frequency domain to extract vital signs. MIMO radar can develop the accuracy in measure orientation of object. The received signal needs several important steps to gain accurate results, so there is the overall implementation flow chart which is shown in Fig.2.

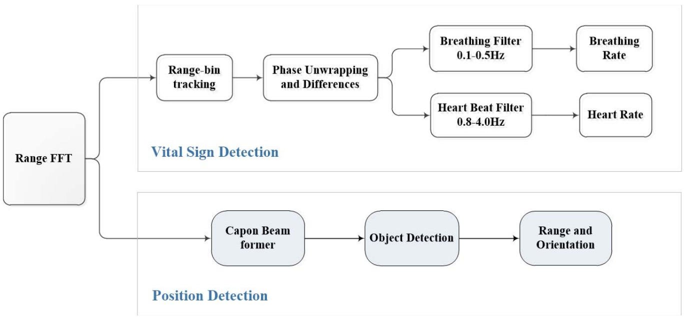

Fig. 2. Simultaneous Location and VS Parameter Estimation Flowchart

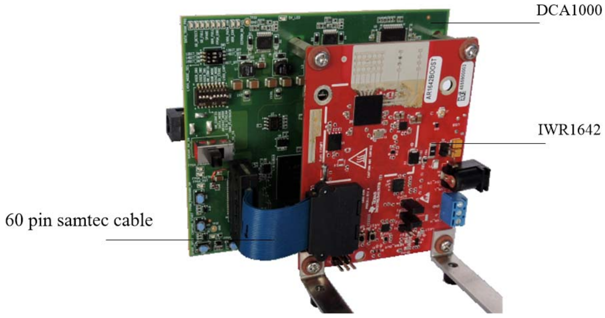

Fig. 3. FMCW-MIMO Radar and Data Capture Board

III. Experiment And Result

The experiments adopt the development board of IWR1642 [7] and DCA1000 EVM [6] from Texas Instruments(TI) company for capturing the raw ADC data. The DCA1000 EVM receives the LVDS data from IWR1642 device and transmit the data to PC via the ethernet interface. Connect the IWR1642 and DCA1000 as shown in Fig. 3. All components are part of the kit. The TI manual has detailed introduction of the IWR1642 mmWave sensor, which is FMCW radar with 2 TX and 4 RX. Table I shows the important parameters of the IWR1642 .In the scenario 1 of experiments, an adult remained stationary, and stands at a distance of 0.7323 meter from the radar with angle of 29° . In the scenario 2 , this man stands at a distance of 0.5126 meter from the radar with angle of 0° . Table II shows the results. As we can see, the location and vital sign estimation are quite accurate according to the ground true settings.

TABLE I
Parameters of the IWR1642 MIMO-FMCW radar.

Parameters	**Value**	**Parameters**	**Value**
Start frequency	77GHz	ADC sampling rate	2MHz
Band width	4GHz	Slow time axis sampling	20Hz
Chirp duration	50us	Samples per chirp	100samples

TABLE II
Location and parameters Estimation of human being in scenario 1 and 2.

Parameters	**scenario 1**	**Parameters**	**scenario 2**
Range	0.5126m	Range	0.7323m
Azimuth	0°	Azimuth	29°
Breath	14time/min	Breath	12time/min
Heartbeat	83time/min	Heartbeat	88time/min

The obtained range bin corresponding to the maximum value, phase information is extracted for the slow time axis. Then phase unwrapping is used to limit the phase range to$[-\pi, \pi]$. Two band pass filters are used to separate the heartbeat signal and the respiratory signal. After that, the heartbeat and respiratory signals are separated. Fig. 4 and Fig. 5 show the results when a man behaves in deferent scenario , the Distance-azimuth heat map shows location while the Vital sign detection result show breath and heartbeat

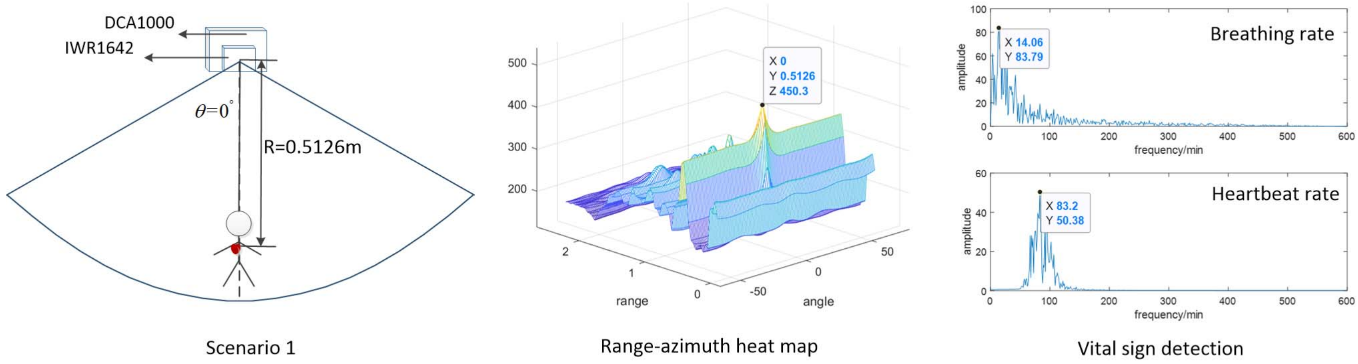

Fig. 4. Result of scenario 1.

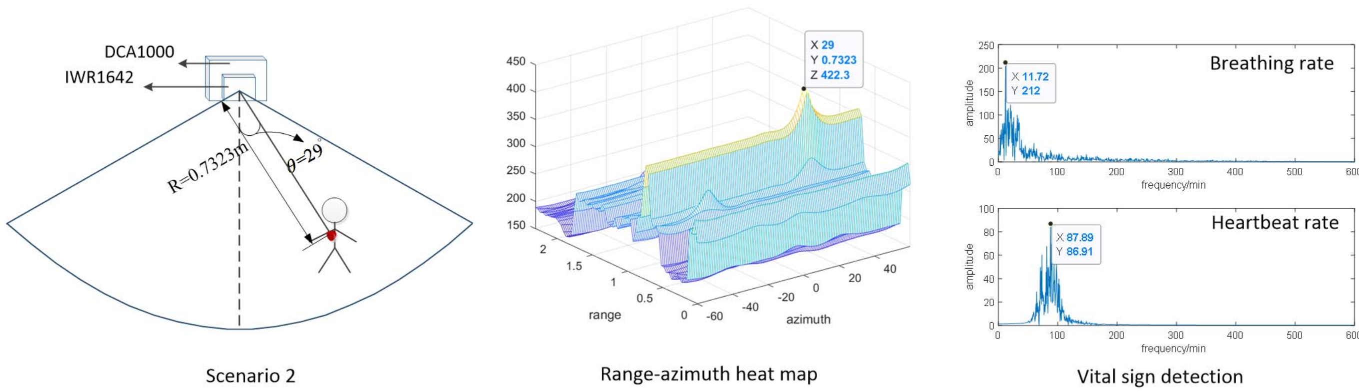

Fig. 5. Result of scenario 2.

frequency. Comparing two deferent experimental scene, it is obvious that this algorithm can extract of multiple vital signs of location and parameter Simultaneously.

IV. Conclusion

The non-contact sign detector utilizes the MIMO-FMCW radar for non-contact human breathing and heartbeat detection. Since the chest fluctuation caused by human breathing and heartbeat is very small, usually less than the distance resolution of the radar, it is difficult to extract the human breath and heartbeat in the one-dimensional distance image. However, the small change of the distance usually causes change of the MIMO-FMCW radar in the frequency domain. Therefore, this study extracts the heartbeat and breath information by find the change of phase between different frames. This study uses real radar data to verify the algorithm. Compared with smart bracelet, the result is right. It means that the MIMO-FMCW radar can be used to evaluate vital sign of human being.

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