FMCW Radar-based Vital Signal Monitoring Technique Using Adaptive Range-bin Selection

Mingeon Shin, Yongchul Jung, Jongho Kim, Kwangseok Choi, Kwangho Lee, Haram Ju, Kangi-Il Cho, Sungho Lee
Convergence Signal SoC Research Center, Semiconductor and Display Dept.
Korea Electronics Technology Institute (KETI)
Bundang, Seongnam, Gyeonggi-do 13509, Korea
Email : slee@keti.re.kr

***Abstract*— This paper aims to propose a signal processing technique for non-contact sensing of vital signs such as respiration and heart-rate using FMCW radar. Existing studies have limitation of only detecting vital signs for a fixed target, but in this study, we propose vital signs sensing technique for a moving target. We propose a novel algorithm that tracks the optimal distance information through the correlation between the distance information from the moving target and the magnitude and energy density of the phase information that responds to vital signs. The novel algorithm is based on signals from FMCW radar sensors that can extract range information from moving objects. The proposed algorithm is verified through a compact module through a 60GHz commercial FMCW radar sensor and a radar signal processor. The experimental results show that the proposed algorithm has a 4.5 bpm error in heart rate, while conventional techniques have an error of 11.4 bpm.**

Keywords—FMCW radar, Vital sensing, Target bin selection, radar signal processing, Radar SoC.

I. Introduction

Recently, detecting non-contact vital signs technique has been applied to various monitoring devices for sleeping monitoring, driver state, and health monitoring. A frequency modulated continuous wave (FMCW) radar sensors have an advantage in that regular movements such as breathing and heart rate signals can be detected through the frequency shift of the reflected radio waves [1-2]. However, most studies so far have only been able to detect signals in static target, because the noise factor caused by human movement and motion artifact make hard to extract vital signs..

In this study, a new signal processing technique that can extract respiratory and heart rate signals for moving target is proposed. Using the characteristics of the FMCW radar that detects the distance of the target, the method of extracting the distance information with the greatest correlation while simultaneously observing the phase shift of each distance information and the absolute magnitude of the phase signal is a technique that enables precise target tracking has been proposed.

II. Vital Signal Modeling in FMCW Radar

FMCW radar modulates a frequency over time using an electromagnetic wave. Thus, depending on the distance of target, the time for the echo signal to receiver is time delayed, which is downmixed by the modulated frequency and received as an Intermediate Frequency (IF) signal. The higher the target frequency, f of the received IF signal, the higher the distance value of the target. This is the same as (1). S is the slope of the frequency to be modulated when transmitting electromagnetic waves, d is the distance between the radar and the target, and c is the speed of light.

$$f = \frac{S2d}{c}. \tag{1}$$

It transmits electromagnetic waves that modulate several times over time and measures speed using the frequency value that changes by the Doppler effect of the IF signal reflected on the target. This speed measurement method using FMCW radar uses a phase difference of the same frequency bin, i.e. range bin, of the IF signal. The $\Delta phase$ of the IF signal changes according to the small displacement of a target in addition to the change due to the doppler effect [3]. This phase change amount may be expressed as (2) and is related to the electromagnetic wave wavelength band of the radar system. Δd_s represents a small displacement of the target, and λ is a FMCW radar transmission frequency wavelength. In the case of target movement greater than the range resolution, the frequency bin of the target is changed, and in the case of target movement smaller than the range resolution, the phase of one frequency bin is changed. The small displacement change due to the vital sign can be obtained by obtaining the phase using the complex signal value of the fast Fourier transform (FFT) result [2]. The small displacement is the same as in (3). The FMCW radar detects a vital signs by using such a $\Delta\omega$ of range bin [4].

$$\Delta\omega = \frac{4\pi\Delta d_s}{\lambda}. \tag{2}$$

$$\Delta d_s = \frac{\lambda}{4\pi} \times unwrap\left(\arctan\frac{Q}{I}\right). \tag{3}$$

A. Difficulty targeting in vital sign monitoring

In order to estimate the vital sign, it is necessary to select a range bin where a person is located and then extract the phase of the corresponding frequency tone. In the FMCW radar system, the frequency bin obtained by FFT of the IF signal becomes the range bin. Mathematically, when radar has an elevation field of view (FOV) of 45 degrees, the distance between radar and humans is 50 cm, the length of the upper body area is 30 cm, and the radar range resolution is 2.5 cm, human body causes more than three range bin. However, echo signals are observed at more range bin than that due to the human body being curved and spectral leakage. Therefore, when it is necessary to detect a vital sign after targeting one range bin based maximum magnitude value search method in FFT result, the following problems exist.

1) *Scalloping loss due to mismatch between target location and FFT bin.*

2) *Frequency instability due to constant small movements of the target.*

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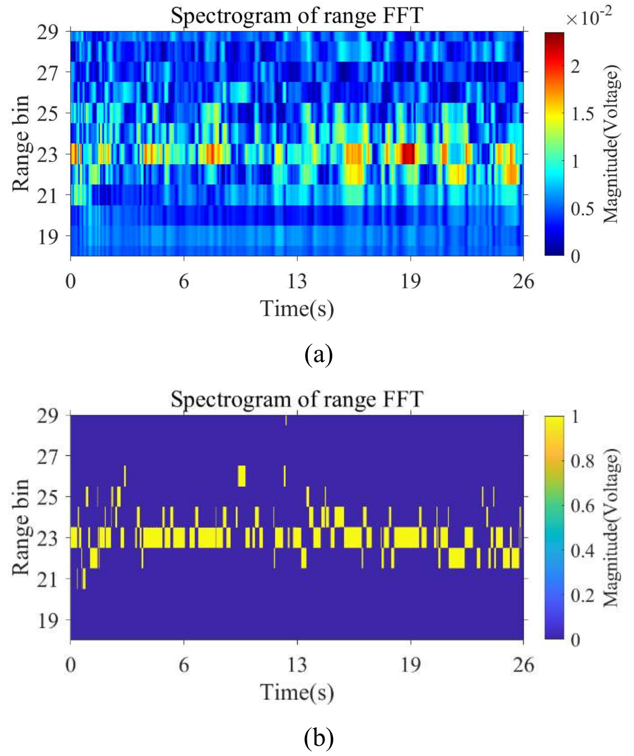


Fig. 1. (a) Raw range spectrogram in vital sign monitoring and (b) Normalize the maximum value for each chirp signal.

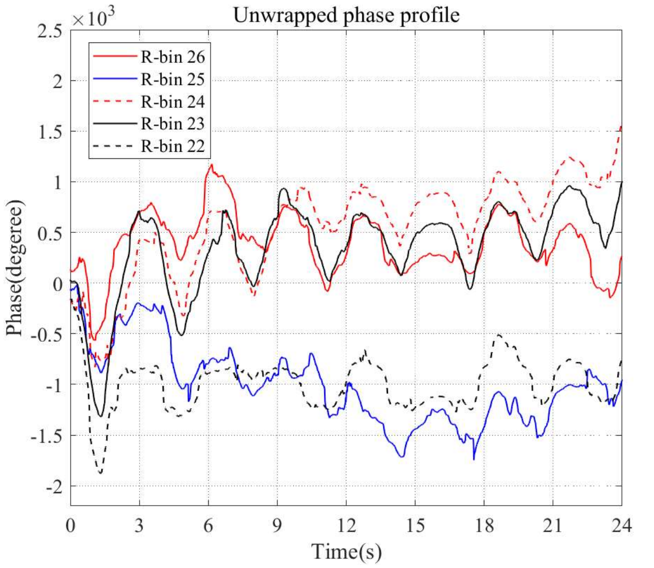


Fig. 2. Small displacement signal of each range bin. Vital signals present at various range bins due to the size of the human body.

3) *Multiple range bins resulting due to human body regions having an area greater than the range resolution.*

This problem can be seen in Fig. 1. As shown in Fig. 1, the range bin where the person is located cannot catch the target using the maximum Radar Cross Section (RCS) due to the movement of the human body. In addition to the issue that the index of the Peak range-bin is not the same over time, as shown in the data of the 0 to 3 second interval in Fig.1(b), there are difficulties in measuring vital signs in multiple range bins, as shown in Fig. 2.

To solve the issues, this paper proposes a signal processing technique that increases the accuracy of vital sign estimation by targeting the correct range bin, which is explained in Chapter 3.

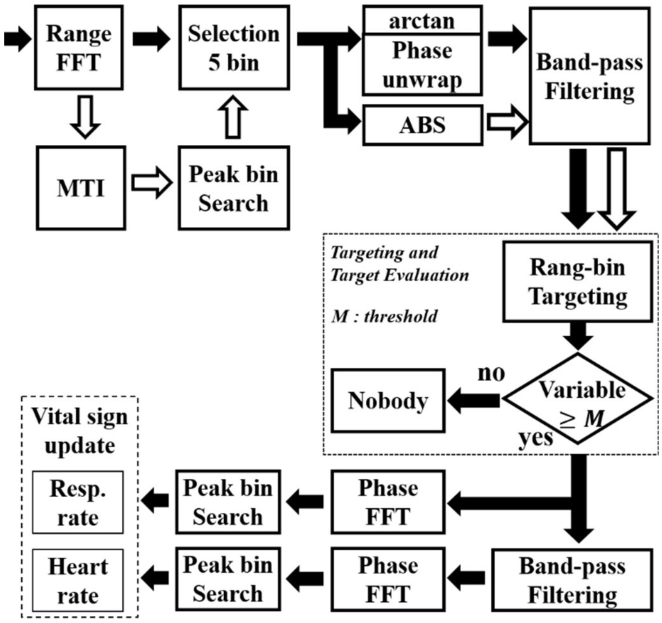


Fig. 3. Proposed signal processing chain for vitals sign estimation.

It is necessary to increase the accuracy of vital sign estimation by applying the adaptive range bin selection technique [5].

III. Proposed Signal Processing

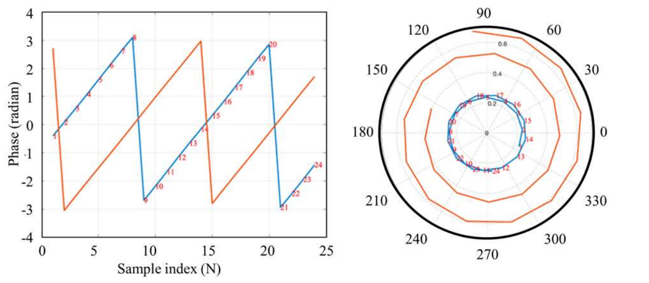
A novel signal processing chain is introduced to detect vital signs based on FMCW radar, which improves vital sign estimation accuracy while tracking a target. In contrast to the traditional method, we propose an unwrap process that adjusts the jump threshold and a method of selecting a range bin in which vital signs exist. The signal processing chain is shown in Fig. 3. The signal processing flow can be divided into four main categories, which are as follows.

1) Radar clutter reduction : The moving target indicator (MTI) filter and the selection five bins step attenuate the stationary clutter signal caused by a stationary object with a high RCS value in the room. The MTI filtered signal is converted into a frequency domain through a Fourier transform. After that, a range bin in which the magnitude has a peak value is selected. Two bins on each side of the peak range bin are selected, and as a result, five range bins are selected as vital signs range bins.

2) Small displacement measure : Absolute(ABS) value operation, arctan operation, and proposed unwrap process are used to calculate the small displacement of a specific range bin.

3) Range bin Evaluation : Bandpass filtering, proposed range bin targeting, and variance value calculation step are to determine the presence or absence of vital signs in the target of the range bin, and the range bins with the higher vital signs are selected from the five range bins. If the target is a person, the phase profile's variance value must be greater than a specific threshold M because the phase changes over time. The presence of a person is determined using a point that does not have a stopped phase value with a heartbeat.

4) Vital sign Estimation : Finally, the frequency of micro-movement is estimated through FFT, and the heart rate and respiration rate are estimated. Although this phase FFT estim-



(a) (b)

Fig. 4. Simulationed Phase profile with linearly increasing values, (a) time domain, (b) Polar coordinate system. The orange lines has a decreasing signal strength. The blue lines has a constant signal strength.

ation method has an observation window of 10 seconds or more [6], it has the advantage of being less sensitive to heartbeat fluctuations. It has the advantage of estimating faster than the zero-crossing method [7]. This study uses an estimation method using the phase FFT method.

A. Unwrap using the Vital phase jump threshold

In the FMCW radar, the change in the small distance appears as a phase difference. Therefore, these phase values are wrapped 360 degrees. Since the phase value of the IF signal specific frequency bin is proportional to the distance, the phase value increases and the RCS value decreases as the distance increases. This is shown in Fig. 4. A conventional unwrap procedure is calculated with a jump threshold that the difference between the previous and subsequent data is 360 degrees [8].

In the case of increasing the phase to a small step value at a high sampling frequency, as shown in Fig. 4, the corresponding unwrap process is appropriate. However, if the sampling frequency is low, it may jump from point 7 to point 15 in Fig. 4(a) and deviate from the logic of the unwrap process and fail to unwrap. Therefore, we propose an unwrap procedure that sets the jump threshold considering the phase sampling frequency.

Generally, small displacements of the human body moving back and forth occur due to heartbeat and breathing. Chest wall displacements from 0.01 mm to 0.5 mm are due to heartbeat, and from 1 mm to 20 mm are due to respiration [9]. When Δd_s is 20 mm due to heartbeat and breathing, the phase of the IF signal increases or decreases by about 51 radians at 61GHz Radar system. By modeling the FMCW radar signal, the phase of the IF signal that changes for each transmission repetition frequency may be known. The change in small displacement due to breathing and heart rate is the same as $\Delta x_b, \Delta x_h$, which can be calculated by Equation (4)(5).

$$x_h(t) = 2 \times d_{sh} \cos(2\pi f_h t + \theta_h),$$

where $0 < 2 \times d_{sh} < 0.5\,, 0 < 2 \times f_h < \frac{150}{60}$.

$$\Delta x_h = x_h\left(t + \frac{1}{f_s}\right) - x_h(t) = \frac{2 d_{sh} f_h}{f_s} \tag{4}$$

$$x_b(t) = 2 \times d_{sb} \cos(2\pi f_b t + \theta_b),$$

where $0 < 2 \times d_{sb} < 0.5\,, 0 < 2 \times f_b < \frac{30}{60}$.

$$\Delta x_b = x_b\left(t + \frac{1}{f_s}\right) - x_b(t) = \frac{2 d_{sb} f_b}{f_s} \tag{5}$$

d_{sh}, d_{sb} : Small displacement by heartbeat, respiration.

f_h, f_b : Heart rate and respiration rate.

θ_h, θ_b : The onset phase of Small displacement caused by the heartbeat, the respiration.

Using the modeling signal, assuming a maximum heart rate of 150 bpm and a maximum respiration rate of 30 bpm, and Pulse repetition frequency (PRF) is 80 Hz, the $\Delta\omega$ per chirp signal is 73 degree. The proposed unwrap procedure uses this $\Delta\omega$, which is calculated to (6). The proposed PRF-unwrapping procedure uses these $\Delta\omega$ value as the jump threshold value. The algorithm 1 explains the process.

$$\Delta\omega_h = \frac{8\pi d_{sh}}{\lambda}, \qquad \Delta\omega_b = \frac{8\pi d_{sb}}{\lambda}.$$

$$\Delta\omega = \Delta\omega_h(t) + \Delta\omega_b(t).$$

$$\omega_h\left(t + \frac{1}{f_s}\right) - \omega_h(t) = \frac{\Delta\omega_h f_h}{f_s}.$$

$$\omega_b\left(t + \frac{1}{f_s}\right) - \omega_b(t) = \frac{\Delta\omega_b f_b}{f_s}.$$

$$\Delta\omega_{max} = \frac{8\pi(d_{sb} f_b + d_{sh} f_h)}{\lambda f_s}. \tag{6}$$

Algorithm 1. PRF-Unwrapping Procedure

R_{idx} is the index of detected rang bin;
P(r, t) is phase-time matrix of raw phase value with arctan calculation
  r is range bin index, t is time domain;
$tol = \Delta\omega_{max}$; tol is jump threshold in wrapped phase shift.
$\theta(t)$ = P(R_{idx}, :);
for t = 1:1:3s
  if $\theta_{t+1} - \theta_t > 2\pi - tol$ ***then***
    $\theta_{t+1} = \theta_{t+1} - 2\pi$;
  else if $\theta_{t+1} - \theta_t < 2\pi - tol$ **then**
    $\theta_{t+1} = \theta_{t+1} + 2\pi$;
  else ;
end

B. Proposed range bin targeting

We propose a method using signal intensity and decorrelation of RCS profile M(t) and phase profile P(t) to target the range bin where vital sign exist. As the distance of the target increases, the RCS increases and the phase rotates in the decreasing direction. Ideally, the phase profile and echo RF power are inversely proportional, but when the frequency changes due to the limitations of frequency resolution, the signal magnitude may decrease. Therefore, we use the absolute value of the correlation between the two signals. When the respiration signal is large, the amplitude of the phase

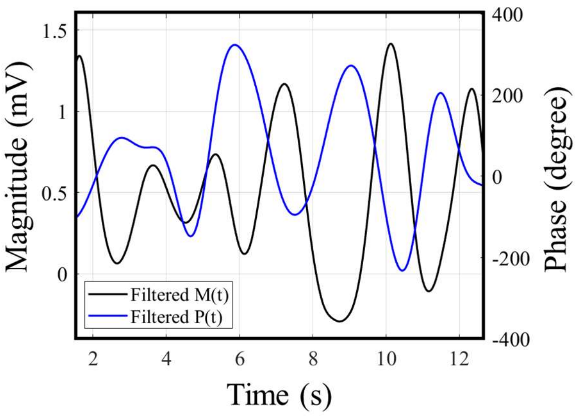


Fig. 5. Band pass filtered M(t), P(t) signals of vital sign range bins.

profile and the RCS profile increases, and this signal intensity can be obtained as the square of the variance. One range bin is selected using this correlation and signal intensity.

Fig. 5 shows the M(t) and P(t) signals that are bandpass-filtered by the frequency band of the respiration rate. Using the correlation and intensity of these filtered signals, we select a range bin in which vital signs exist. There have been previous studies using signal intensity for vital range-bin targeting. We can see from this study that the RCS size varies due to the decrease in distance due to breathing [10]. The phase noise of the FMCW radar system also effects the magnitude of the IF signal, so filtered magnitude-time signal is used. This M(t) and P(t) is bandpass filtered to the breathing band. And then, Using these two signals, the Phase Deviation and magnitude-phase Decorrelation (PPD) coefficient value is calculated through the procedure shown in (7), and the range bin with the highest PPD value is targeted.

$$PPD(t) = abs\left(\frac{cov[M(t),P(t)]}{\sigma_m \sigma_p} \times \sigma_m^2 \sigma_p^2\right)$$

$$= abs\left(\frac{\Sigma_i^n \left(\frac{(M(i)-\mu_m)(P(i)-\mu_p)}{n}\right)}{\sqrt{\Sigma_i^n \frac{(M(i)-\mu_m)^2}{n}}\sqrt{\Sigma_i^n \frac{(P(i)-\mu_p)^2}{n}}} \times \frac{\Sigma_i^n \alpha M(i) \Sigma_i^n \beta P(i)}{n}\right)$$

$$= abs\left(\frac{\Sigma_i^n M(i)P(i)}{\sqrt{\Sigma_i^n (M(i))^2}\sqrt{\Sigma_i^n (P(i))^2}} \times \frac{\Sigma_i^n \alpha M(i) \Sigma_i^n \beta P(i)}{n}\right). \quad (7)$$

C. *Proposed radar SoC for real-time processing*

In order to accelerate high computational complexity in vital signal processing, it is implemented as SoC, as shown in Fig. 6 using ADC raw data from a 60GHz FMCW radar sensor, radar signal processing operation is performed through a MTI filter, variable-points FFT, and constant false alarm rate (CFAR) core. Also, finite impulse response (FIR) filter, FFT, and arctangent calculation in vital signal processing have high computational complexity. Therefore, to accelerate the computation of vital signal processing, FIR filter and coordinate rotation digital computer (CORDIC) based arctangent were implemented as the Radar SoC, and the FFT was shared with the Radar signal processor.

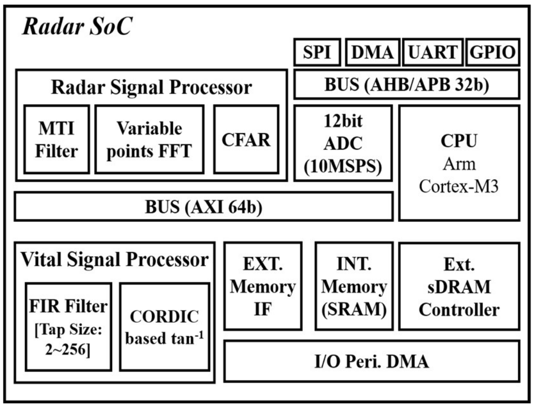


Fig. 6. The proposed Radar SoC structure.

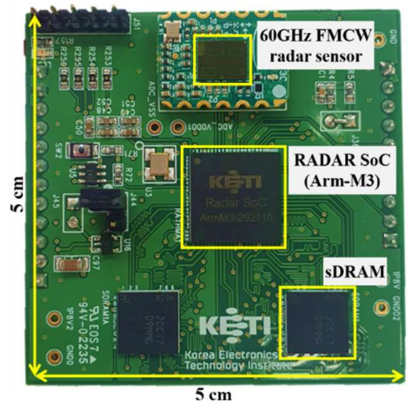


Fig. 7. FMCW radar module using KETI radar SoC

IV. Experimental Results

To measure vital signs, 60GHz BGT60TR13C FMCW radar chip from *Infineon Technologies AG* in Fig. 7 was used for the radar sensor, and a self-developed radar signal processor from *Korea Electronics Technology Institute (KETI)* was utilized to control the sensor and perform a part of signal processing (MTI filtering, Windowing, Clutter reduction, FFT, arctan calculation, Un-wrapping functions). The radar sensor can detect human target over 1.5 meter away. Thus, the experiment was carried out in an environment in which targeting person moving freely from a distance of 1 meter or more.

TABLE I. System Parameter of FMCW Radar

System Parameter	Value	Unit
Central Frequency	61	GHz
Bandwidth	6	GHz
PRF [a]	80	Hz
Chirp duration	276	us
Sampling rate of IF signal	3800	kHz
Tx Power	4.675	dBm
Rx IF signal Gain	45	dB
HPF Cutoff Frequency	70	kHz
Number of Tx antenna	1	Ch
Number of Rx antenna	3	Ch

PRF: Pulse repetition frequency. (*Chirp Repetition Frequency*).

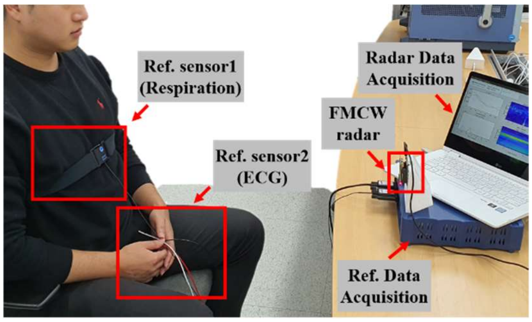


Fig. 8. Photographs of the experimental setup for vital rates estimation.

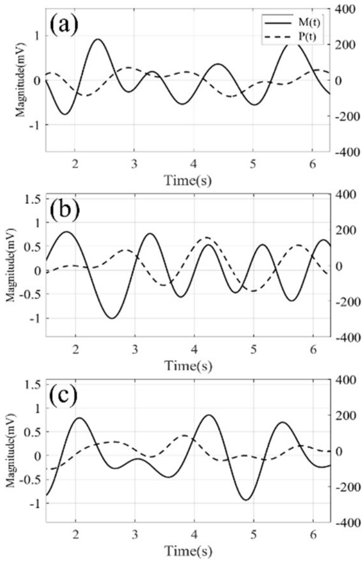


Fig. 9. Measured vital signs M(t), P(t) signals of Peak range bin and near range bins. Rang bin 23 is selected using the PPD coefficients. (a) range bin 22, (b) range bin 23, (c) range bin 24.

Table I shows the parameters of the FMCW radar system. The speed resolution is determined according to the frequency modulation specification and PRF of the chirp signal, and the maximum detection distance is determined according to the RF transmission output and ADC sampling rate. The corresponding parameter adjusts the IF signal gain (dB) according to the characteristics of the sensor signal.

A. Evaluation methods

Based on the measured vital signs using FMCW RADAR, performance comparisons were made with the range bin selection technique using Pearson correlation coefficients between M(t) and P(t), similar to the magnitude-phase coherency (MPC) index method [11]. Pearson correlation is as shown in Equation (8).

$$\rho(A,B) = \frac{1}{N}\Sigma_i^n\left(\frac{A_i-\mu_A}{\sigma_A}\right)\left(\frac{B_i-\mu_B}{\sigma_B}\right) \qquad (8)$$

In order to know the measurement accuracy of the vital signs, BIOPACK device (NS-1073) was used as a reference device , and the measurement environment is shown in Fig. 8. The measurement was performed for 42 seconds, and it was estimated to be vital sign and range bin targeting every 3 seconds of frame time. Fig. 9 shows the vital signs P(t) and M(t) measured when the range bin is targeted. The range bin was selected based on the PPD coefficient value using the two measured signals. To measure the heart rate and respiratory rate, the frequency of the corresponding phase signal was estimated through the FFT of the unwrapped phase signal. Each spectrum of vital sign has a higher SNR and estimates the heart rate, as shown in Fig. 10, whereas for Pearson correlation-based range bin select without considering Signal Intensity, the heart rate estimation is a mixture of multiple frequency tones. When selecting range bin, if the signal strengths of M(t) and P(t) are weak, both signals become DC signals, resulting in a higher correlation coefficient, and the corresponding range bin may be selected accordingly, indicating that the wrong range bin is selected. In the respiration estimation of the technique using the Pearson correlation coefficient in Fig. 11, 40 bpm is estimated at 45 seconds because the vital signs was estimated by selecting the wrong range bin. When the PPD technique is used, it can be seen that higher accuracy is shown compared to the technique using the Pearson correlation coefficient.

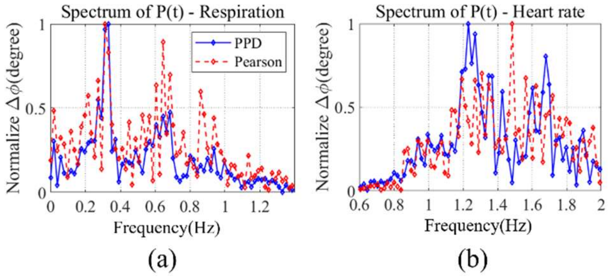


Fig. 10. (a) Respiration estimation result and (b) heart rate estimation result.

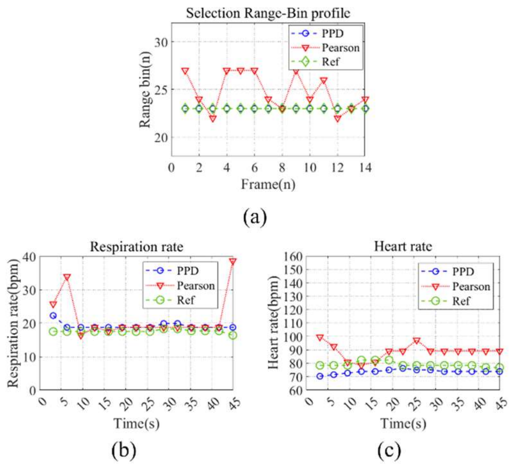


Fig. 11. (a) Respiration estimation result and (b) heart rate estimation result.

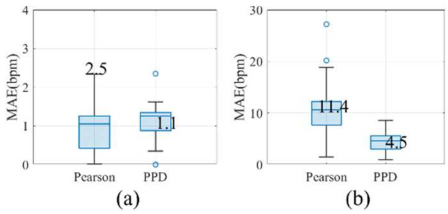
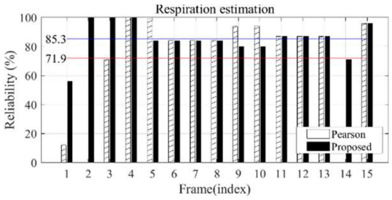
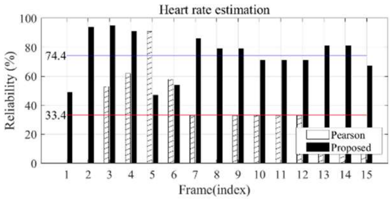


Fig. 12. Comparison techniques for range bin selection, and (a) respiration rate estimation error, (b) heart rate estimation error.

In order to compare the performance of the range bin selection technique, a vital signs estimation error rate was used. The error rate Mean Absolute Error (MAE) compared to 13 estimated values at 3 seconds to 42 seconds when the vital signs estimated value of the reference equipment was calculated. As Fig. 12 shows, PPD techniques have a 4.5 bpm error in heart rate estimation, while conventional techniques have a high error of 11.4 bpm.



(a)



(b)

Fig. 13. Reliabilty of vital estimaion according to range bin selection technique, (a) respiration rate estimation, (b) heart rate estimation.

TABLE II. COMPARISON OF VITAL SIGNS ESTIMATION

Ref.	Algorithms	Window length	RR (%)	HR (%)	ERR (%)
[12]	FFT-TWV	5 s	-	-	3.4
[13]	FTPR	10 s	-	-	9.5
[14]	FTPR-TWV (WT)	3 s	-	92	
[8]	RBS (power variation) DC compensation	12.8 s	94	80	-
[11]	RBS (magnitude-phase coherency)	15 s	83.7	70.7	-
Ours	RBS (PPD) PRF-Unwrap	3s	85.3	74.4	

TWV: Time-window-variation technique.
FTPR: Frequency–time phase regression algorithm.
WT : Wavelet Transform.
RBS : Range bin selection

Vital signs estimation reliability through the proposed algorithm was calculated. Fig. 13 shows vital signs reliability for each frame. The respiration estimation reliability is the ratio of 8 bpm to the difference between the estimated vital sign and the reference value. The heart rate estimation reliability is the ratio of 16 bpm to the difference between the estimated vital sign and the reference value. The ratio value of the error bpm was determined in consideration of the phase FFT frequency estimation performance. At these ratio values, respiratory estimation reliability is 85.3% and heart rate estimation reliability is 74.4%. The performance of the proposed vital signs estimation system was compared with other work, and in Table II. These works have different measurement conditions, such as measuring a person lying down [8] or measuring a person sitting down [11]. It should also be noted that the measures of the vital signs estimation performance accuracy are different. In [8], the accuracy is high, but there are disadvantages in that the measurement condition was measured while the person was lying down and the observation time was long. Compared with the previous works [11], Our study can accurately measure absorption and heart rate with only 3 seconds of radar signal data.

V. CONCLUSION

This paper presents a novel algorithm for selecting range bins to extract vital signs from FMCW radar signals and an unwrap technique for extracting phases by considering the PRF of radar systems. Depending on the need for real-time data processing in sensor systems rather than centralized computing, we implemented a low-power edge processing system using a self-developed radar SoC. Vital signs estimation performance depends on the range bin selection. Experiments have shown that the proposed technique for selecting range bins has better performance than conventional methods. Based on the new algorithmic technique, respiratory estimation performance is 85.3%, and heart rate estimation performance is 74.4%.

ACKNOWLEDGMENT

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REFERENCES

[1] M. Stephan and A. Santra, "Radar-Based Human Target Detection using Deep Residual U-Net for Smart Home Applications," 2019 18th IEEE International Conference On Machine Learning And Applications (ICMLA), 2019, pp. 175-182, doi: 10.1109/ICMLA.2019.00035.

[2] Arsalan, Muhammad, Avik Santra, and Christoph Will. "Improved contactless heartbeat estimation in FMCW radar via Kalman filter tracking." IEEE Sensors Letters 4.5 (2020): 1-4.

[3] Zhang, Dan, Masahiko Kurata, and Takayuki Inaba. "FMCW radar for small displacement detection of vital signal using projection matrix method." International Journal of Antennas and Propagation 2013 (2013).

[4] Pramudita, Aloysius Adya, et al. "Radar System for Detecting Respiration Vital Sign of Live Victim Behind the Wall." IEEE Sensors Journal 22.15 (2022): 14670-14685.

[5] Hu, Yaokun, and Takeshi Toda. "A novel adaptive range-bin selection method for remote heart-rate measurement of an indoor moving person using mm-wave FMCW radar." IEICE Communications Express 10.5 (2021): 277-282.

[6] A. Santra, R. V. Ulaganathan, T. Finke, A. Baheti, D. Noppeney, J. R. Wolfgang, and S. Trotta, "Short-range multi-mode continuous-wave radar for vital sign measurement and imaging, " in 2018 IEEE Radar Conference (RadarConf18), April 2018, pp. 0946–0950.

[7] W. Hu, Z. Zhao, Y.Wang, H. Zhang, and F. Lin, "Noncontact accurate measurement of cardiopulmonary activity using a compact quadrature doppler radar sensor, " IEEE Transactions on Biomedical Engineering, vol. 61, no. 3, pp. 725–735, March 2014.

[8] M. Alizadeh, G. Shaker, J. C. M. D. Almeida, P. P. Morita and S. Safavi-Naeini, "Remote Monitoring of Human Vital Signs Using mm-Wave FMCW Radar," in IEEE Access, vol. 7, pp. 54958-54968, 2019, doi: 10.1109/ACCESS.2019.2912956.

[9] A. D. Droitcour, "Non-contact measurement of heart and respiration rates with single chip microwave Doppler radar, " Ph.D. dissertation, Stanford Univ., Stanford, CA, USA, 2006.

[10] L. Anitori, A. de Jong, and F. Nennie, "FMCW radar for life-sign detection," in Proc. IEEE Radar Conf., May 2009, pp. 1-6.

[11] Choi, Ho-Ik, Heemang Song, and Hyun-Chool Shin. "Target range selection of FMCW radar for accurate vital information extraction." IEEE Access 9 (2020): 1261-1270.

[12] Tu, Jianxuan, and Jenshan Lin. "Fast acquisition of heart rate in noncontact vital sign radar measurement using time-window-variation technique." IEEE Transactions on Instrumentation and Measurement 65.1 (2015): 112-122.

[13] Nosrati, Mehrdad, and Negar Tavassolian. "High-accuracy heart rate variability monitoring using Doppler radar based on Gaussian pulse train modeling and FTPR algorithm." IEEE Transactions on Microwave Theory and Techniques 66.1 (2017): 556-567.

[14] Pan, Haipeng, Yongyang Zou, and Minming Gu. "A spectrum estimation approach for accurate heartbeat detection using Doppler radar based on combination of FTPR and TWV." EURASIP Journal on Advances in Signal Processing 2022.1 (2022): 1-22.