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A Resolution Enhancement Technique for Remote Monitoring of the Vital Signs of Multiple Subjects Using a 24 Ghz Bandwidth-Limited FMCW Radar

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ABSTRACT This study proposes a novel signal processing method for detecting the vital signs of multiple adjacent subjects using a 24 GHz frequency modulated continuous wave Doppler radar. Radar-based vital signs sensors have attracted significant attention because of their contactless and unobtrusive mode of measurement. However, limited-bandwidth, fixed-beam systems have been restricted to single subjects because a high resolution is required to detect the vital signs of multiple adjacent subjects. As the range resolution is determined by the frequency bandwidth, a novel method is proposed that doubles the effective frequency bandwidth by using a modified waveform. The proposed method can distinguish between two subjects sitting 40 cm apart, overcoming the 60 cm Rayleigh resolution for a frequency bandwidth of 250 MHz. The computational complexity of the proposed method is considerably low when compared with high-resolution algorithms such as the multiple signal classification algorithm. Furthermore, the method easily suppresses stationary clutter by using phase deviation. To validate the performance of the proposed method, experiments were conducted with two subjects lying side by side on a bed. The results indicate the excellent performance, with enhanced range and high detection accuracy. This method has many potential applications, including monitoring infants and sleep apnea patients.

INDEX TERMS Multiple subjects, vital signs, FMCW radar, range resolution enhancement, mutual interference rejection.

I. INTRODUCTION

Monitoring vital signs, such as heartbeat and respiration, not only provides information on the health status of patients but facilitates daily health management for the general public. Most existing sensors for vital signs monitoring are based on contact-type sensors. Contact sensors have good accuracy with a reliable contact status [1]–[3]. However, these sensors can cause a feelings of pressure and stress due to their unavoidable need for a physical connection to the subject, which restricts behavior. In contrast, microwave-based sensors do not require physical contact with the human body [4]–[12], and because they can measure vital signs without the subject's awareness, they can be applied to various healthcare scenarios.

In practical applications, radar-based noncontact sensors cannot be applied to multiple subjects [13]–[16]. With the the resolution limit determined by the bandwidth (B) of the system, $c/2B$ (where c is the speed of light), obtaining the vital signs of the target subjects requires detecting the positions of the subjects first. Then the vital signs can be extracted at each position. Consequently various solutions have been developed using a frequency modulated continuous wave (FMCW) Doppler radar that provides the range and velocity of the target [17]–[20]. For detection of the vital signs of two subjects, several methods have been proposed that

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combine an FMCW Doppler radar with a beam steering method [21]–[23]. In these studies, the combination of the FMCW Doppler radar and beam steering enabled determination of the two-dimensional position of each subject. After obtaining the target position using the FMCW radar, the vital signs were extracted using continuous wave (CW) radar. Because the two subjects were in different directions, the received signal had vital signs information on each target in each direction. In essence, this method can detect the vital signs of multiple subjects in different directions but cannot extract the vital signs signals of subjects that are in the same direction.

One simple solution to distinguish between two subjects in the same direction is the use of a wide bandwidth for improved range resolution [24]–[26]. Peng et al. extracted the vital signs of two subjects spaced 20 cm apart by using a frequency bandwidth of 1 GHz (range resolution 15 cm) [24]. Furthermore, a super resolution algorithm was proposed for multiple subjects [27]. The multiple signal classification (MUSIC) algorithm can provide superior resolution for a given bandwidth, thus overcoming the theoretical resolution limit. Consequently, the vital signs of the two subjects spaced 40 cm apart were extracted using a bandwidth of 250 MHz, though the theoretical resolution was 60 cm. However, it is difficult to suppress the clutter effect that arises when using the MUSIC algorithm because it does not utilize phase information. Furthermore, real-time detection of vital signs using the MUSIC algorithm is challenging due to the high computational complexity of its eigenvalue decomposition (EVD) and parametric sweep procedures [28], [29].

In this study, a new signal processing method based on a band-limited 24 GHz FMCW Doppler radar is proposed for detecting the vital signs of two adjacent subjects lying in the same direction. The proposed method considers three major issues: (1) resolution, (2) clutter, and (3) computational load. For resolution enhancement, a simple mathematical approach was used to increase the effective frequency bandwidth. To verify the improvement in resolution, the resolution limit of the proposed method was evaluated through experiments that varied the space between two subjects. For evaluation of clutter mitigation performance, target identification experiments were performed using a haman being and a copper plate, which has a much larger radar cross section (RCS). To assess computational complexity, the computational speed of the proposed method was compared with that of the MUSIC algorithm. Furthermore, to demonstrate the feasibility of the proposed method in practical applications, experiments were conducted with two subjects lying side by side on a bed. The results show excellent performance.

II. THEORY AND METHODS

Radar-based sensors can be combined with a daily healthcare system, but real-world application requires that the multiple-subject issue be resolved. For example, when two subjects are lying on a bed as shown in Fig. 1, it is necessary to recognize individual subjects and extract the vital signs of each subject. In this section, a novel signal processing method is proposed for improving the range resolution beyond the theoretical limit.

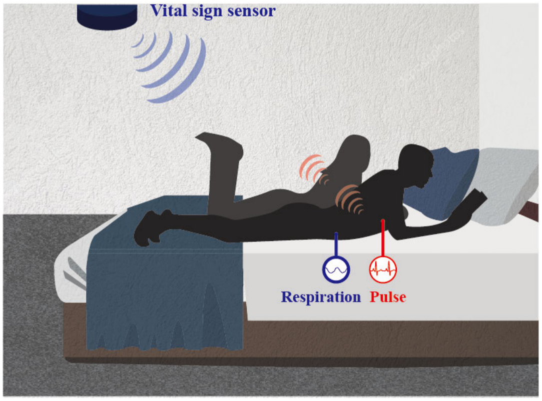


FIGURE 1. Configuration of an IoT healthcare system.

A. CONVENTIONAL SIGNAL PROCESSING

An FMCW Doppler radar can be used to obtain location and movement information on a target [17]. The operating principle of the FMCW Doppler radar is illustrated in Fig. 2. Chirp signals that linearly sweep a frequency range are sequentially transmitted during a pulse repetition interval (PRI). A reflection of the transmitted signal is received with a time delay proportional to the target range and the baseband signal, which contains a beat frequency is formed from the output of the mixer and a low-pass filter. The beat frequency provides the range information and is determined by the frequency difference between the transmitted and received signals. Baseband signals form a column matrix for each PRI period, and these matrices are then stacked. The time series data on each column matrix is transformed into a frequency spectrum by using fast Fourier transform (FFT), and the range information is deduced from the beat frequency. The target position is tracked via the peak values of the column matrix, and the vital signs are obtained from the phase deviation of the row matrix at each position. The beat signal of the k-th period can be expressed as follows:

$$s_b(r,\tau) = \sum_{n=1}^{N} \alpha \exp\left[j2\pi f_c t_n(\tau)\right] \operatorname{sinc}\left[\frac{2B}{c}(r-R_n)\right], \quad t \in \{(k-1)T,\ kT\}, \quad (1)$$

where N is the number of the target; the variable r is the range; τ is the so-called "slow time"; α is the amplitude of the n-th target, which is a function of RCS and range; B is the frequency bandwidth; c is the speed of light; $t_n = 2R_n/c$ is the round trip delay time; R_n is the range of the n-th target; f_c is the carrier frequency; and T is the modulation period. In (1), the Rayleigh range resolution of the FMCW Doppler radar is $c/2B$ and is determined by the bandwidth.

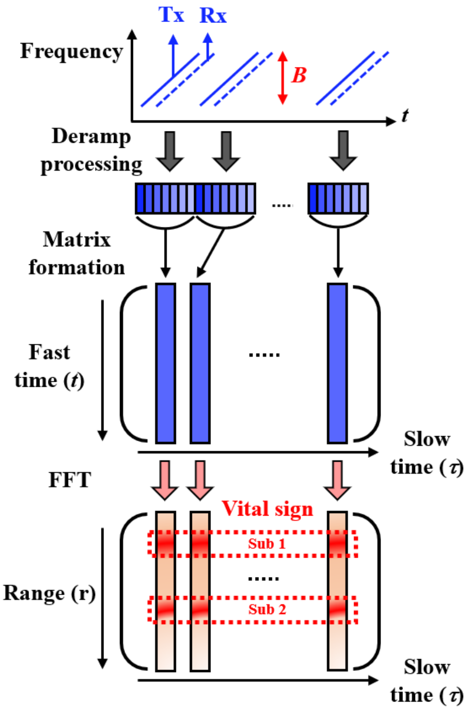
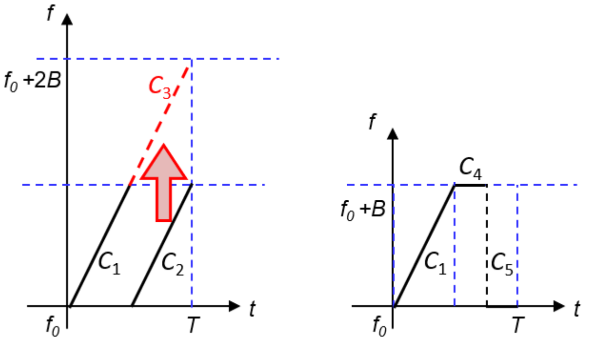


FIGURE 2. Fundamental principles of the FMCW radar.



(a) (b)

FIGURE 3. Principle of the proposed method: (a) concept and (b) modified waveform.

B. PROPOSED METHOD

To enhance the resolution of the radar sensor, the frequency bandwidth should be increased. In this section, a mathematical approach for increasing the effective frequency bandwidth of a system using a given bandwidth is presented. The primary purpose of this method is to exploit the fact that vital signs signals vary slowly in comparison with the modulation frequency.

In Fig. 3(a), when signal C_2 is converted to signal C_3, it has the same effect as having twice the frequency bandwidth in the chirp signal. To convert C_2 to C_3, the phase information corresponding to the bandwidth, B, is required. Consequently, the waveform of the frequency modulation is altered as shown in Fig. 3(b). The phase difference between two single-tone waves with frequency $f_0 + B$ (C_4) and f_0 (C_5) can provide phase information that corresponds to the bandwidth B. Furthermore, the phase difference during PRI is negligible due to the low-frequency nature of vital signs. This allows the possibility of replacing C_1 with C_2. In essence, signal C_3 can be reconstructed using C_1, C_4, and C_5. Signal C_3 can be formulated as follows:

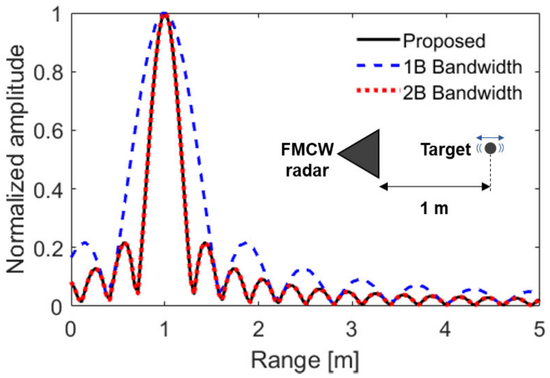


FIGURE 4. Simulation results of range estimation for a single point scatterer.

$$\begin{aligned}\exp\left[j\phi_{C_3}\right] &\approx \exp\left[j\phi_{C_2}\right]\cdot\exp\left[j\phi_{C_4}\right]\cdot\exp\left[-j\phi_{C_5}\right]\\ &\approx \exp\left[j\phi_{C_1}\right]\cdot\exp\left[j\phi_{C_4}\right]\cdot\exp\left[-j\phi_{C_5}\right],\end{aligned} \tag{2}$$

where ϕ_{C_k} represents the phase information of section C_k in Fig. 3. Fig. 4 illustrates the simulation results for a single point scatterer. It is clear that the proposed method improves range resolution, yielding the same effect as when using twice the frequency bandwidth. However, when there are two point targets, the improvement in the range resolution of the proposed method is limited due to the additional terms generated by the multiplication of ϕ_{C_1}, ϕ_{C_4} and ϕ_{C_5}. The signals ϕ_{C_1}, ϕ_{C_4} and ϕ_{C_5} are each composed of the sum of two signals from the two targets. Consequently, unwanted additional terms are generated from the multiplication operations. Detailed derivations of the formulae are presented in the supplementary material. Finally, the beat signal of the proposed method for two targets can be expressed as follows:

$$S_{b,\text{proposed}}(r,\tau) = x + w, \tag{3}$$

$$x = \sum_{n=1}^{2} \varphi_n \cdot \operatorname{sinc}\left[\frac{4B}{c}(r - R_n)\right], \tag{4}$$

$$w = \sum_{n=1}^{2} \beta_n \cdot \varphi_n \cdot \operatorname{sinc}\left[\frac{2B}{c}(r - R_n)\right], \tag{5}$$

where φ_n is the phase information of the n-th target, and β_n is a complex coupling coefficient determined by the bandwidth and range difference that consists of the signal component x with a resolution of $c/4B$ and the noise component w with a resolution of $c/2B$. In essence, the desired signal, x, has the resolution of a signal with twice the bandwidth, while the noise signal, w, has the same resolution as the original signal. When the error rate, w/x, increases, the resolution is

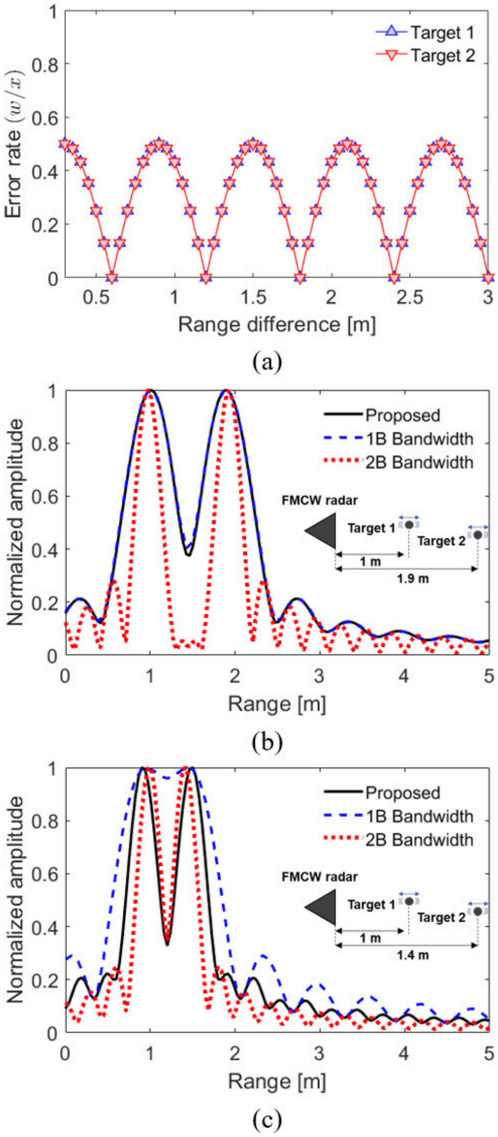


FIGURE 5. **Simulation results for two point scatterers: (a) error rate according to the interspace, (b) range estimation with a range difference of 90 cm, and (c) range estimation with a range difference of 40 cm.**

degraded and the error rate fluctuates periodically because β_n depends on the bandwidth and the range difference, as shown in Fig. 5(a). To verify the effect of the error rate, the simulation was carried out at the maximum error rate. When two targets had a range difference of 90 cm, the proposed method has an almost identical effect as the original bandwidth signal, as shown in Fig. 5(b). With the proposed method, the maximum error rate limits improvement of the resolution. However, it can clearly distinguish between two targets with a range difference of 40 cm at an error rate lower than the maximum value, which is beyond the Rayleigh resolution of 60 cm.

Range estimation errors are generated by the unwanted noise signal w, as shown in Fig. 6. Because the errors are within 10 cm, there is no significant effect on range estimation. Furthermore, a range error of approximately 10 cm can be compensated for by phase extraction by using the range integration method [27]. Thus, the range estimation error of the proposed method does not affect the accuracy of vital signs monitoring.

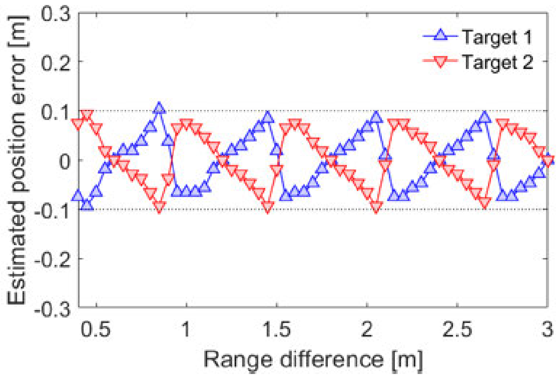


FIGURE 6. **Range estimation error varying with range difference.**

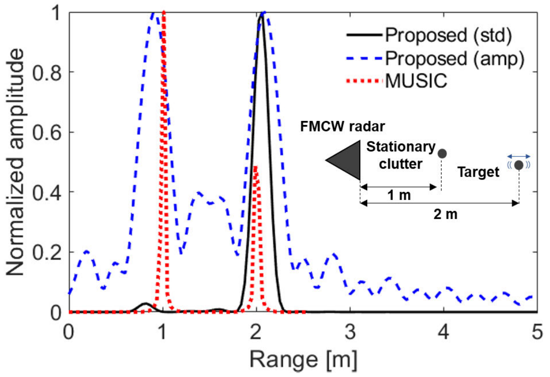
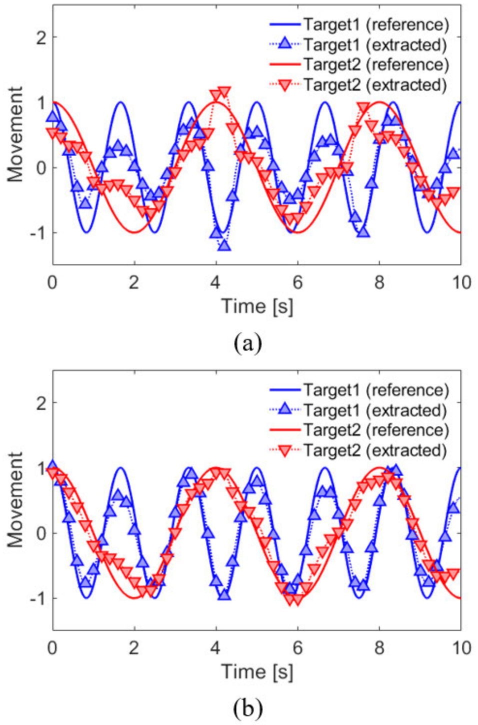


FIGURE 7. **Simulation results for stationary clutter and a vibrating point scatterer.**

C. CLUTTER MITIGATION

There are a few methods for improving resolution with a limited frequency bandwidth. Typical methods include subspace-based algorithms, such as MUSIC and the estimation of signal parameters via rotational invariant techniques (ESPRIT). These methods are robust for noise and exhibit high-resolution performance. However, because they require parametric sweep, they also impose a large computational burden. Furthermore, because they cannot provide phase information, it is difficult to detect vital signs in the presence of separate stationary clutter. In comparison, the proposed method has low computational complexity and can distinguish stationary clutter because it utilizes the standard deviation of phase information from the FFT.

To demonstrate the performance of the proposed method, it was assumed that a stationary clutter object was located 1 m from the detector and a vibrating point scatterer was located 2 m away. The MUSIC algorithm detected both the stationary clutter and vibrating point scatterer, as shown in Fig. 7, while the proposed method can also detect both targets using only amplitude information. However, using the standard



(a)

(b)

FIGURE 8. Effect of mutual interference rejection: (a) extracted results from a single point and (b) extracted results for a 30 cm range.

deviation of the phase information can mitigate strong clutter and clearly detect the intended subject.

D. MUTUAL INTERFERENCE REJECTION

When two subjects are closer than the Rayleigh resolution limit, the mutual interference becomes considerably strong. This makes it difficult to detect the correct vital signs even if the targets are clearly identified and the phase information properly extracted from the respective positions of the targets. In essence, mutual interference rejection is critical in the detection of accurate vital signs.

The beat signal is the sum of the sinc functions in (1). Because the phase information on the n-th subject is extracted from the beat signal $S_b(R_n, \tau)$, the phase information from the other subjects, which would be a source of mutual interference, is generated in proportion to the amplitude of the sinc function. Thus, the amplitude of mutual interference increases as the distance between the subjects decreases. To eliminate mutual interference, the proposed method extracts the vital signs at a range of about 30 cm and not at a single point [27]. Fig. 8 shows the simulation results for two vibrating point targets located at 1 m and 1.3 m. The phase information extracted from a single point produces an incorrect vital signal due to mutual interference, as shown in Fig. 8(a). However, the phase information obtained using the range integration method can be used to clearly detect vital signs signals with improved noise rejection, as shown in Fig. 8(b).

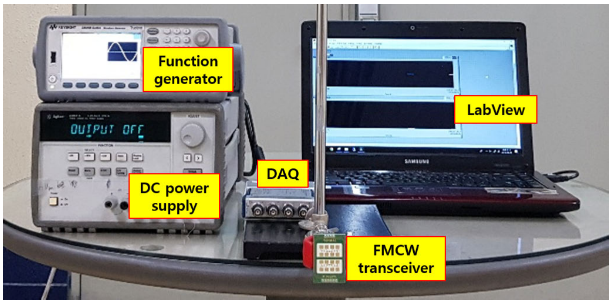


FIGURE 9. Measurement system.

E. MEASUREMENT PROCEDURE

This study was approved by the Institutional Review Board (IRB) of Yonsei University, and the two adult subjects participated voluntarily. All methods were performed in accordance with the relevant guidelines and regulations (IRB No. 7001988-201907-HR-643-03).

Fig. 9 illustrates the measurement system. The frequency range of the FMCW radar (IVS-162, InnoSenT) is 24.00 GHz to 24.25 GHz, i.e., it has a 250 MHz bandwidth, which complies with the industrial, scientific, and medical band. The equivalent isotropic radiated power is 15 dBm, and the horizontal and vertical 3 dB beam widths are 45° and 38°, respectively. The horizontal and vertical side lobe suppression values are 15 dB and 20 dB, respectively. The modulation frequency was 100 Hz, and the sampling frequency was set to 6 400 samples/s.

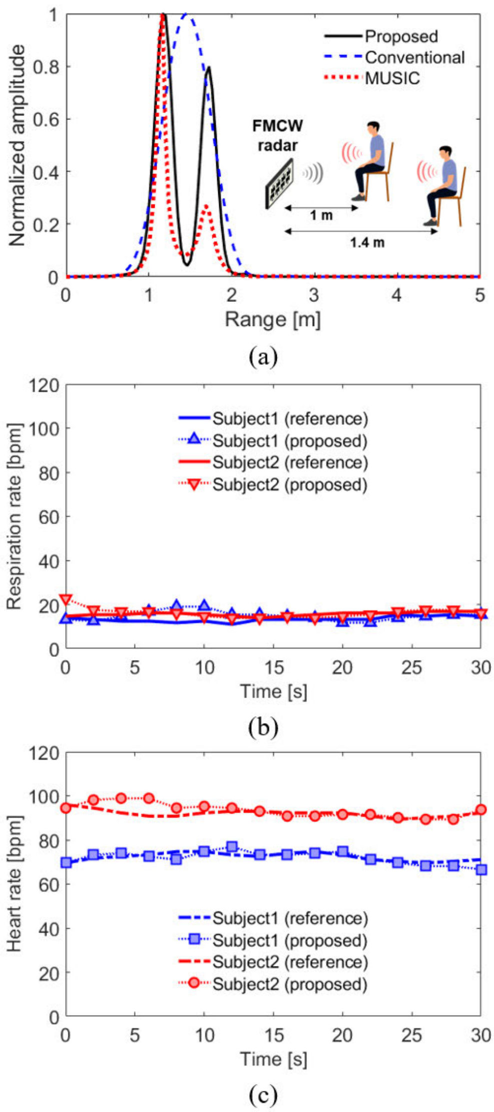
Measurements were performed for three main scenarios. The first experiment verified the range resolution limit of the proposed method. In a spacious indoor environment without strong clutter, measurements were conducted with two subjects sitting on chairs in a fixed position. The second experiment demonstrated clutter mitigation performance. In this experiment, one subject was sitting on a chair, and a metal plate with a size of 20 cm × 20 cm was employed to serve as a strong scatterer. Lastly, considering the real-world environment, the final experiment measured the vital signs of two subjects lying down on a bed.

In all three experiments, heartbeat and respiration signals were digitally band-pass filtered. The respiratory rate (RR) was filtered from 0.1 Hz to 1 Hz, i.e., 6-60 beats per minute (bpm), and the heart rate (HR) was filtered from 1 Hz to 2 Hz, i.e., 60-120 bpm. The detected vital signs were compared with measurements from commercial sensors. The sensors used were piezoelectric transducers for breathing (UFI-1132, UFI) and heartbeat (UFI-1010, UFI).

III. RESULTS AND DISCUSSION

A. RANGE RESOLUTION LIMIT

To verify the resolution limit of the proposed method, the position of the nearest subject (front subject) was fixed at 100 cm, while the position of the farther subject (rear subject) was changed from 180 cm to 140 cm in 10 cm increments. Fig. 10 shows the experimental results for the situation where the two subjects were located at 100 cm



(a)

(b)

(c)

FIGURE 10. Experimental results for two subjects at a distance of 100 cm and 140 cm: (a) range estimation, (b) comparison of the RR of the proposed method with that of the commercial sensor; and (c) comparison of the HR of the proposed method with that of the commercial sensor.

and 140 cm. With the conventional method, the subjects overlap and are recognized as a single subject, as shown in Fig. 10(a). However, the proposed method and the MUSIC algorithm can clearly distinguish the two subjects. This demonstrates that the proposed method can discriminate between subjects 40 cm apart, beyond the Rayleigh resolution of 60 cm. For real-time monitoring of vital signs, the short-time Fourier-transform (STFT) was performed at 2 s intervals with 10 s windows. The vital signs are in excellent agreement with those obtained using commercial sensors in real time, as shown in Fig. 10 (b) and (c). Table 1 summarizes the experimental errors for five different cases. The errors were evaluated as average absolute and relative errors, which are defined as follows:

TABLE 1. Error in vital signs detection based on range difference.

Case			1	2	3	4	5
Location	Front subject		100	100	100	100	100
	Rear subject		180	170	160	150	140
Average absolute error [bpm]	RR	Front	0.63	0.42	0.63	0.52	0.27
		Rear	1.46	2.51	0.21	0.52	2.00
	HR	Front	0.73	2.51	0.68	2.20	4.05
		Rear	0.84	1.26	3.32	2.99	2.95
Average relative error [%]	RR	Front	2.50	1.62	2.63	2.26	1.01
		Rear	5.40	8.61	0.69	2.16	7.46
	HR	Front	0.68	2.22	0.59	1.98	3.30
		Rear	0.52	0.82	2.41	2.18	1.92

$$\text{Average Absolute Error} = \frac{1}{P}\sum_{p=1}^{P} \mid v_{\text{proposed}}(p) - v_{\text{commercial}}(p) \mid \;\; [\text{bpm}], \tag{6}$$

$$\text{Average Relative Error} = \frac{1}{P}\sum_{p=1}^{P} \frac{\mid v_{\text{proposed}}(p) - v_{\text{commercial}}(p) \mid}{v_{\text{commercial}}(p)} \;\; [\%], \tag{7}$$

where v_{proposed} is the vital sign estimated by the proposed method, $v_{\text{commercial}}$ is the vital sign detected by the commercial sensor, and P is the total number of time windows. Overall, the absolute error is about 4 bpm. The relative error of the HR is about 2.5%, while the respiratory errors are around 9%. Because the frequency of the respiratory signal is low, the error seems relatively large. However, because the average absolute error in RR is not large, the error is insignificant.

B. CLUTTER MITIGATION

Fig. 11 illustrates the experimental results when a metal plate was placed at 100 cm and the subject was positioned at 220 cm. The metal plate is a dominant scatterer and is detected by the MUSIC algorithm, as shown in Fig. 11(a). However, the proposed method removed the metal plate as clutter and detected only the human subject. The range-Doppler map also showed only the desired subject and not the metal plate, as illustrated in Fig. 11(b).

C. TWO SUBJECTS LYING DOWN

Fig. 12 shows the experimental setup and results for two subjects lying side by side on a bed. The total measurement time was 150 s. The proposed method can clearly detect two subjects with effective elimination of stationary clutter, such as the surrounding walls and the bed, as shown in Fig. 13(a). It is clear that the conventional method cannot differentiate between two subjects within the resolution limit. STFT was performed at 5 s intervals with 10 s windows. There was a false detection in the vicinity of 70 s for the rear subject, as shown in Fig. 13(b) and (c), due to movement of the subject. The real-time HR and RR results agree very well with those of commercial sensors.

When two subjects lie side by side, there is no significant space between them. However, the proposed method can

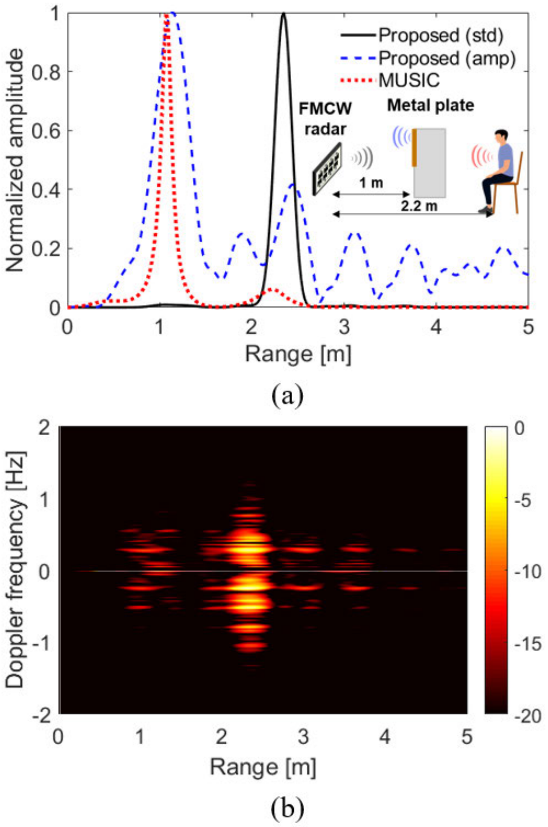


FIGURE 11. Experimental results for a subject with stationary clutter: (a) range estimation and (b) range-Doppler map.

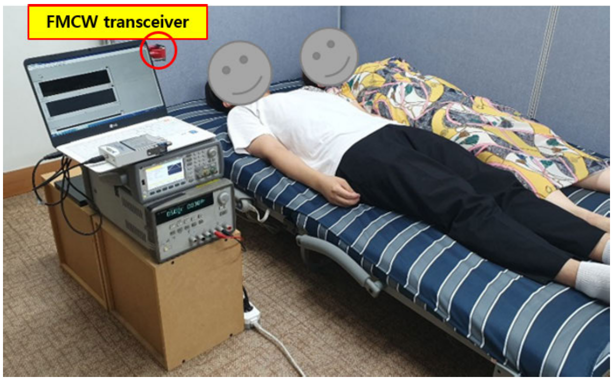


FIGURE 12. Experimental setup for two subjects lying on a bed.

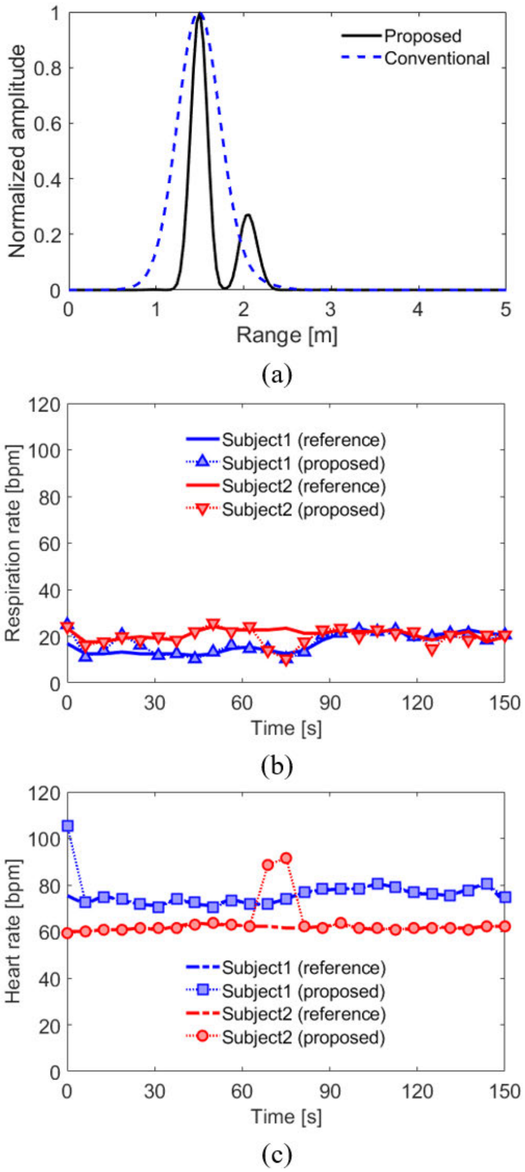
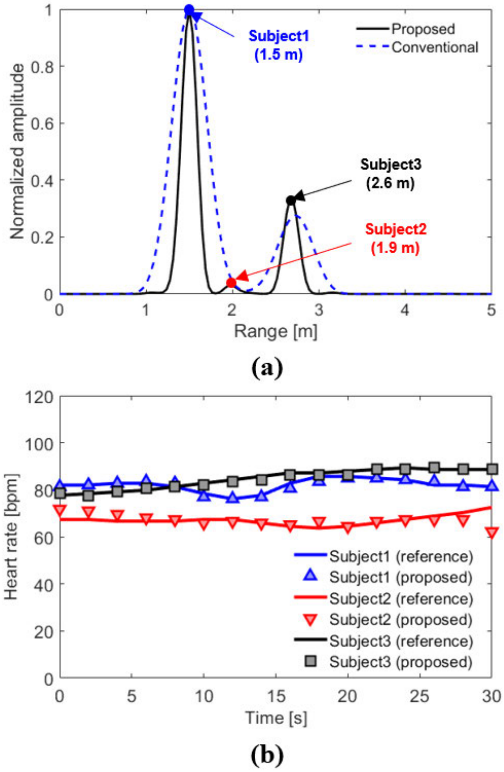


FIGURE 13. Experimental results for two subjects lying on a bed: (a) range estimation, (b) comparison of the RR obtained using the proposed method with that obtained by the commercial sensor, and (c) comparison of the HR obtained using the proposed method with that obtained by the commercial sensor.

successfully separate the vital signals of two subjects in such a position despite a theoretically insufficient resolution. The detection mechanism of the FMCW radar relies on the movement of body parts, such as the chest and abdomen. Thus, the proposed method can separate the position of the chest of each subject and not the overall position of the human body. Because the distance between the chests of the two subjects was about 45 cm, the two subjects were clearly distinguished.

D. DISCUSSION

Three scenarios were tested to verify the superiority and validity of the proposed method. For accurate vital signs detection for two subjects lying side by side in real time, it is necessary to consider: (1) resolution, (2) clutter rejection, and (3) computational burden. The experimental results of the three scenarios verify that there is resolution enhancement and a superior clutter mitigation performance. To evaluate computational complexity, MATLAB R2019a was used to compare the simulation time for the proposed method with that of the MUSIC algorithm. The simulations were performed on a personal computer with an Intel Core i5-7500 3.40 GHz CPU and 16.0 GB RAM. The total number of samples was 6 400, corresponding to 1 s of received signal, and the PRI was 0.01 s for 64 samples. Over ten simulations, the average simulation times for the MUSIC algorithm and the proposed method were 0.7859 s and



(a)

(b)

FIGURE 14. **Experimental results for three subjects sitting on a chair: (a) range estimation and (b) comparison of the HR obtained using the proposed method with that obtained by the commercial sensor.**

0.0043 s, respectively. It is clear that the MUSIC algorithm imposes a considerably large computational burden, while the proposed method exhibits very low computational complexity and provides real-time vital signals.

Furthermore, the proposed method can be utilized for three or more subjects. Fig. 14 shows the experimental results for three subjects positioned at 150, 190 and 260 cm. The proposed method clearly distinguished the locations of the subjects. The average absolute error for each HR is 0.73, 1.99, and 0.57 bpm, showing an excellent agreement with the reference sensor.

This study focused on situations with multiple subjects in the same direction, which is a much more challenging than when the subjects are positioned in different directions. The beam steering method can provide azimuth angle resolution for multiple subjects [22], [30]. Thus, the proposed method can be combined with the beam steering method to provide high-resolution two-dimensional position detection and vital sign measurement for multiple subjects. In real-world situations, subjects do not always remain at rest, and the movement generated by a physiological signal will be much weaker than the motion artifacts, making it difficult to detect the vital signs. This requires further investigation, such as considering the use of Kalman filtering [2], [31].

IV. CONCLUSION

This study proposes a novel method based on a 24-GHz FMCW Doppler radar for measuring the vital signs of multiple subjects separated by less than the theoretical resolution limit. The proposed method addresses three main issues: resolution, clutter, and computational load. To distinguish between multiple adjacent subjects and detect their vital signs, the proposed method utilizes phase information, resulting in resolution enhancement. Because the resolution is improved using a simple calculation, the computational load is low. Furthermore, interference caused by the presence of stationary clutter is easily mitigated using phase information. We envision contactless sensors using this novel method being advantageously employed in various practical applications, such as medical surveillance of infants and sleep apnea patients, as well as being incorporated into "smart homes" as a component of remote monitoring healthcare systems.

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