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Development of FM-CW Radar System for Detecting Closed Multiple Targets and Its Application in Actual Scenes

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Abstract

In this paper, detection method for 24 GHz band FM-CW radar system under closed multiple targets with small displacements environment was proposed, and its performances were analyzed by using computer simulation. The proposed detection method used a differential detection method for removing any signals from background objects, and also used a tunable FIR filtering in signal processing for detecting multiple targets. The proposed detection method enabled to detect both the distance and small displacement at the same time for each target correctly from the received signal including all of signals from the targets at the FM-CW radar. The basic performances for FM-CW radar were analyzed in computer simulation, and field experiments for detecting target under actual environments. The results showed that the proposed differential detection could only measure the desired targets, and the human breathing could also be detected in a hospital scene. Furthermore, under closed multiple targets environments, we showed the problems for detecting both distance and small displacements of multiple targets at the same time by using a single radar. Computer simulations were carried out for evaluating the proposed detection method with the tunable FIR filtering for FM-CW radar and analyzing the performance according to the parameters under closed multiple targets environment. The results in computer simulation showed that the proposed detection method could detect both the distance and small displacement correctly under closed multiple targets environment.

Type of Paper and Keywords

Regular research paper: *FM-CW radar, distance measuring, small displacement measuring, multiple targets detection, tunable FIR filtering*

1 Introduction

Recently, rapidly evolving wireless communication technologies provides us to communicate various information from a lot of manufactures in widely technologies field. IoT (Internet of Things) is popularly known as a key topic for developing system and services, and it enables various physical devices to collect various things such as sensor information. As one of sensing applications, radar has been employed to detect in widely areas such as on the ground, on the sea, in the air, in space. The radar systems can detect various information according to application areas by transmitted and received through radio wave.

Radar systems with 24 GHz band is based on ARIB

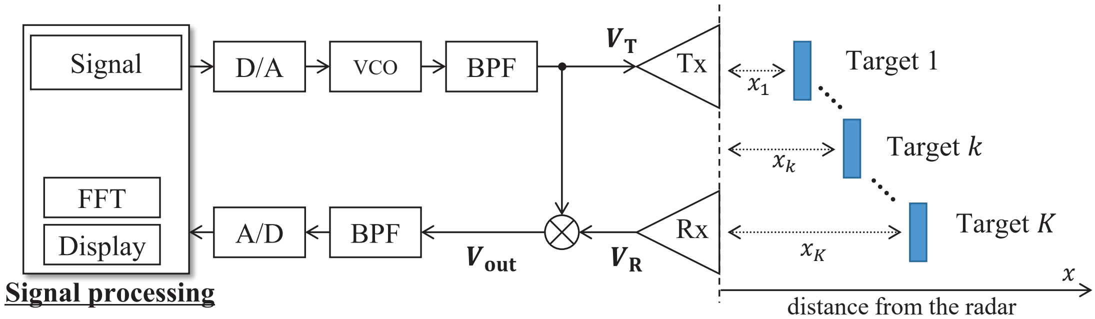


Figure 1: Block diagram of a FM-CW radar system

standard T73 [1] in Japan as sensors for detecting or measuring mobile objects for specified low power radio station. And the 24 GHz band radar system could be applied in various field such as security, medical imaging and so on under indoor and outdoor environments. Various radar systems were reported [2, 3, 4, 5]. Pulsed radar systems can measure the period between the transmitted and received signals. The pulsed radar can detect the distance in far field; however, the target in near field can not be detected correctly. Doppler radar systems can measure the frequency difference between the reflected and transmitted signals. The Doppler radar can detect the moving velocity of the target; however, the distance of the target can not be detected. FM-CW (Frequency-Modulated Continuous-Wave) radar systems [6, 7] is the most widely used for detecting the distance of the target object in near field and the small displacement of the target.

As previous study, we reported the design, performance analysis, and applications with 24 GHz band radar system for detecting both the distance from the radar and the small displacement for human breathing [8]. The radar system could detect both the distance to the human from the radar and the small displacement of the human breathing correctly; however, it was difficult for detecting the distances and displacements for multiple humans at the same time. In order to detect the distances and displacements under closed multiple targets environment, we proposed a detection method for signal processing with a tunable FIR filter in the FM-CW radar system [9]. Furthermore, performance analysis for FM-CW radar system was shown in computer simulations. In this paper, the proposed detection method considering both the differential detection and the tunable FIR filtering for detecting both the distances and small displacements under single and closed multiple targets environment. Moreover, applications based on IoT for detecting the human movements in actual scenes were described.

This paper consists of the following sections. In Section II, we describe the principle of a FM-CW radar system and its basic performance under single target environment. In Section III, we describe the proposed detection method under single target environment. In Section IV, we describe the proposed detection method under multiple targets environment. In Section V, we discuss the results of computer simulation and field experiments. Finally, Section VI concludes this paper.

2 FM-CW Radar System

2.1 Principle of FM-CW radar

Figure 1 shows the block diagram of a FM-CW radar system [10]. FM-CW (Frequency-Modulated Continuous-Wave) radar was one type of radar which was transmitting a continuous carrier modulated by a periodic function such as a sawtooth wave to provide range data shown in Figure 2.

In the FM-CW radar system, frequency modulated signal at the VCO is transmitted from the transmitter Tx; then, signals reflected from the targets are received at the receiver Rx. Transmitted and received signals are multiplied by a mixer, and beat signals are generated as multiplying the two signals. The beat signal pass through a low pass filter; then, an output signal is obtained. In this process, the frequency of the input signal is varied with time at the VCO. The modulation waveform with a linear sawtooth pattern [11] as shown in Figure 2. This figure illustrates frequency-time relation in the FM-CW radar, and the red line denotes the transmitted signal and the blue line denotes the received signal. Here, f_0 denotes the center frequency, f_{w} denotes the frequency bandwidth for sweep, and t_w denotes the period for sweep.

We define that the transmitting signal $V_{\mathrm{T}}\left(f,x\right)$ is represented as

$$V_{\mathrm{T}}\left(f,x\right) = A\mathrm{e}^{j\frac{2\pi f}{c}x} \ , \tag{1}$$

where f denotes a frequency at a time, x denotes a distance between a target and the transmitter, A denotes an amplitude value, and c denotes the speed of light.

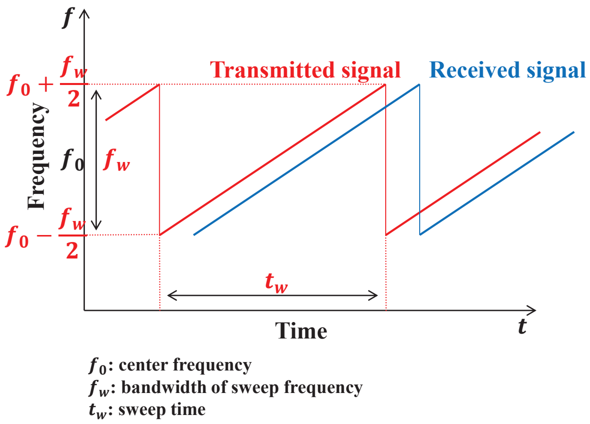


Figure 2: Sawtooth frequency modulation

The reflected signal $V_{\mathrm{R}}(f, x)$ is represented as

$$V_{\mathrm{R}}(f, x) = \sum_{k=1}^{K} A\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{2\pi f}{c}(2d_k - x)} \quad , \quad (2)$$

where γ_k and φ_k are the reflective coefficients for amplitude and phase on kth target, respectively. α_k denotes an amplitude coefficient for transmission loss from the kth target, and d_k is the distance between the transmitter and the kth target.

Here, at the receiver whose position is $x = 0$, Equation (2) is rewritten as

$$V_{\mathrm{R}}(f, 0) = \sum_{k=1}^{K} A\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{2\pi f}{c}(2d_k)} \quad . \quad (3)$$

The beat signal is generated as multiplying the transmitted signal in Equation (1) and the received signal in Equation (3) at the position $x = 0$. After through LPF, the output signal $V_{\mathrm{out}}(f, 0)$ is generated by

$$V_{\mathrm{out}}(f, 0) = \sum_{k=1}^{K} A^2\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{4\pi f d_k}{c}} \quad . \quad (4)$$

By using signal processing, a distance and a displacement for the target are given from the generated output signal in Equation (4). By using the Fourier transform, the distance spectrum of the output signal $P(x)$ is calculated as follow.

$$\begin{aligned} P(x) &= \int_{f_0-\frac{f_w}{2}}^{f_0+\frac{f_w}{2}} V_{\mathrm{out}} e^{-j\frac{4\pi f}{c}} df \\ &= \int_{f_0-\frac{f_w}{2}}^{f_0+\frac{f_w}{2}} \sum_{k=1}^{K} A^2\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{4\pi f d_k}{c}} e^{-j\frac{4\pi f x}{c}} df \\ &= A^2 \sum_{k=1}^{K} \alpha_k\gamma_k e^{j\varphi_k} \int_{f_0-\frac{f_w}{2}}^{f_0+\frac{f_w}{2}} e^{j\frac{4\pi f(d_k-x)}{c}} df \\ &= A^2 \sum_{k=1}^{K} \Bigg[\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{4\pi f_0(d_k-x)}{c}} \\ &\qquad \cdot f_w \mathrm{sinc}\left\{ \frac{2\pi f_w(d_k - x)}{c} \right\} \Bigg] \quad . \end{aligned} \quad (5)$$

In this equation, the function of sinc (x) denotes

$$\mathrm{sinc}(x) = \frac{\sin x}{x} \quad . \quad (6)$$

The amplitude value of the distance spectrum $|P(x)|$ in equation (5) is given as

$$\begin{aligned} |P(x)| &= A^2 \Bigg| \sum_{k=1}^{K} \alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{4\pi f_0(d_k-x)}{c}} \\ &\qquad \cdot f_w \mathrm{sinc}\left\{ \frac{2\pi f_w(d_k - x)}{c} \right\} \Bigg| \\ &\le A^2 f_w \sum_{k=1}^{K} \Bigg[\alpha_k\gamma_k \\ &\qquad \cdot \left| \mathrm{sinc}\left\{ \frac{2\pi f_w(d_k - x)}{c} \right\} \right| \Bigg] \quad , \end{aligned} \quad (7)$$

and we have equality if and only if the phase components $\phi_k + \frac{4\pi f_0(d_k-x)}{c}$ about all of k are equal.

Here, we assumed that the number of target is 1. The distance spectrum in equation (5) is rewritten as

$$\begin{aligned} P(x) = \Bigg[& A^2\alpha_1\gamma_1 e^{j\varphi_1} e^{j\frac{4\pi f_0(d_1-x)}{c}} \\ & \cdot f_w \mathrm{sinc}\left\{ \frac{2\pi f_w(d_1 - x)}{c} \right\} \Bigg] \quad , \end{aligned} \quad (8)$$

and the amplitude value of distance spectrum is given as

$$|P(x)| = A^2\alpha_1\gamma_1 f_w \left| \mathrm{sinc}\left\{ \frac{2\pi f_w(d_1 - x)}{c} \right\} \right| \quad . \quad (9)$$

This equation indicates that the distance for the target is generated by the amplitude value of distance spectrum.

Table 1: Parameters in computer simulations

Parameters	Values
Center frequency f_0	24.15 (GHz)
Bandwidth of sweep frequency f_w	50, 100, 200, 400 (MHz)
Sweep time t_w	1024 (μs)
Sampling time for sweep	0.1, 1, 10 (μs)
Number of FFT points	4096
Window function	hamming

The phase value of distance spectrum $\angle P(x)$ is represented as

$$\angle P(x) = \varphi_1 + \frac{4\pi f_0 (d_1 - x)}{c} = \theta_1(x) \quad . \tag{10}$$

Here, $\theta_1(x)$ satisfy $-\pi \le \theta_1(x) \le \pi$, then the displacement for the target is

$$-\frac{c(-\pi - \varphi_1)}{4\pi f_0} \le d_1 \le \frac{c(\pi - \varphi_1)}{4\pi f_0} \quad . \tag{11}$$

If the phase value satisfies $\phi_1 = 0$, equation (11) is rewritten as -3.11 [mm] $\le d_1 \le +3.11$ [mm] with $f_0 = 24.15$ [GHz]. That is, the small displacement of the target within ± 3.11 [mm] is generated by the phase value of distance spectrum.

On the other hands, the maximum distance for measuring $d_{\max}$ is

$$\Delta f = \frac{f_w}{t_w/t_s}[\mathrm{Hz}] \quad ,$$
$$d_{\max} = \frac{c}{4\Delta f}[\mathrm{m}] \quad , \tag{12}$$

where t_w denotes the sweep time, t_s denotes the interval time for sampling. For example, in the case with t_w = 1024 μs and t_s = 1 μs, the maximum distance is $d_{\max}$ = 384 [m].

2.2 Analysis of Basic Performances

At first, we describes the basic performance about the FM-CW radar with 24 GHz band. Parameters for computer simulation are listed in table 1, and the parameters were determined as ARIB standard T73[1]. Center frequency was 24.15 GHz, bandwidth are 50, 100, 200, and 400 MHz. Note that the 400 MHz bandwidth was only used for the computer simulation because of standards in the Radio Law in Japan. Sweep time was 1024 μs, sampling times for sweep were 0.1, 1, 10 μs, number of FFT points was 4096, and the hamming windows was adapted as the window function in signal processing.

We assumed that a static target is located at 10 m from the transmitter and receiver, and the distance spectrums are outputted with various parameters. Figure 3 shows the amplitude value for distance spectrum versus measured distance with various sweep bandwidth. The result shows that the sweep bandwidth influenced the distance resolutions and widely bandwidth could improve the resolution. In the case with t_s = 1 μs, the distance resolutions with f_{w} = 50, 100, 200, 400 MHz were $\pm$5, $\pm$1.5, $\pm$1, $\pm$0.5 m, respectively. Figure 4 shows the amplitude value for distance spectrum versus measured distance with various sampling time. The result shows that the sampling interval influenced the error about the measured distance and shortly sampling interval could reduce the error value for distance. In the case with f_w = 200 MHz, the error values about the measured distance with t_s = 10 μs was about 0.5 m.

Figure 5 shows the result for measuring a slowly moving target with f_w = 200 MHz and t_s = 1 μs. The target moved from 10 m to 20 m at intervals of 0.5 m on each time step. Figure 5(a) shows the amplitude value versus measured distance versus target distance with 3-dimensional viewing, and Figure 5(b) shows measured distance versus target distance with 2-dimensional view-

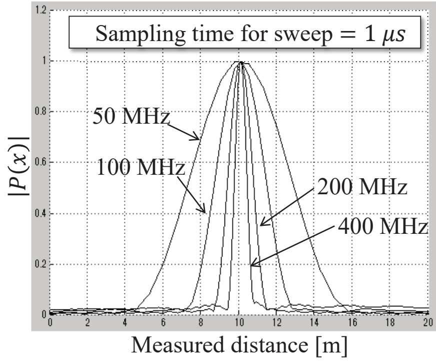


Figure 3: Resolution for distance spectrum according to bandwidth of sweep frequency f_w.

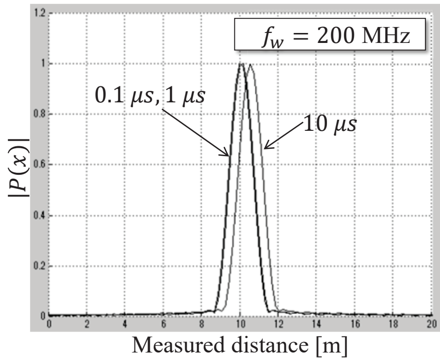
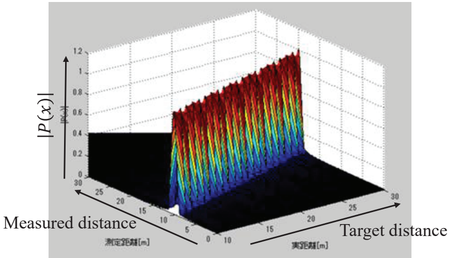
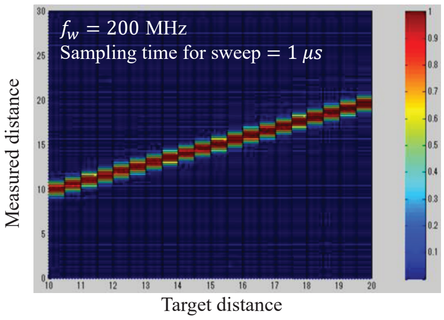


Figure 4: Error value for distance spectrum according to sampling time for sweep.



(a): 3D view.



(b): 2D view.

Figure 5: Distance spectrum for measuring moving target.

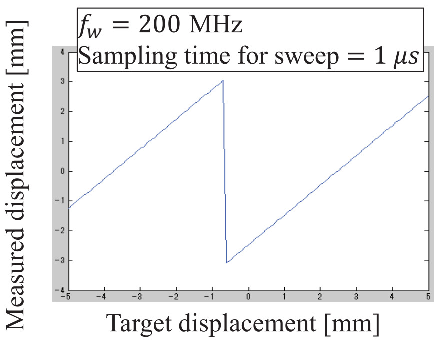
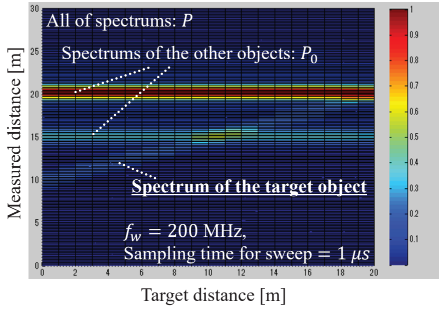


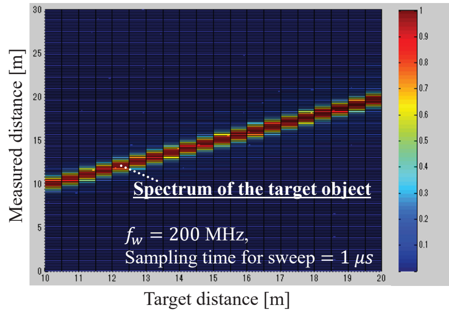
Figure 6: Measured displacement.

ing. The color in (b) is corresponding to the strength of the amplitude value in (a). From these figures, it was confirmed that the distance could be measured correctly according to the positions of the moving target.

Figure 6 shows the result for measuring a target with small displacement, and the measured displacement versus target displacement is outputted. The object was located at 10 m from the receiver, and the object moved from -5 mm to 5 mm at intervals of 0.1 mm. The small displacement could be measured by the phase value of distance spectrum, and the measured displacement was corresponding to the target displacement. Note that the measured displacement denotes the relative displacement and it is not corresponding to the absolute distance between the receiver and the target object. The small displacement within $\pm$ 3.11 mm was correctly measured with the parameters of the FM-CW radar system in this paper although the displacement more than $\pm$3.11 mm had uncertainty.



(a): without differential detection.



(b): with differential detection (Proposed).

Figure 7: Distance spectrum for measuring moving target distance with / without the differential detection under the environments which multiple objects are located.

3 Proposed Techniques for Single Target Detection

3.1 Detection for single target

As mentioned in the above section, the FM-CW radar system could measure the distance and the small displacement for single target at the same time. However, it was a special case that only the reflected signal on a target could be received at the receiver. In general, the receiver may receive the reflected signals from many objects. Therefore, when there was some objects for measuring the target distance, signal processing for detecting the distance spectrum from the only target would be required.

The proposed method removes the signals from the other objects by using the differential detection of distance spectrum. Figure 7 shows the distance spectrum

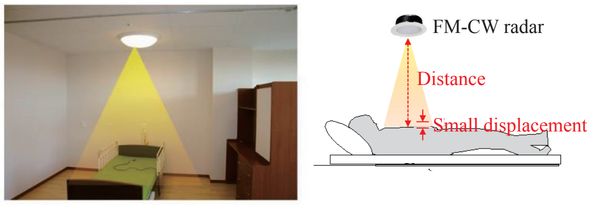


Figure 8: An setting example of FM-CW Radar for detecting human breathing

when the target object moves from 10 m to 20 m and the other objects are located at 15 m and 20 m. The transmitted signal is reflected on the target and the other objects, the receiver receives several reflected signals. Therefore, the distance spectrum of the other objects are also generated by the FM-CW radar system in Figure 7(a), and the distance spectrum of the target can not be detected clearly. In particular, when the reflection coefficient of the target is lower than that of the other objects, the distance spectrum of the other object has higher amplitude value than that of the target.

In the proposed differential detection, at first, the distance spectrum of the other objects P_0 is generated beforehand in Figure 7(a). Then, the distance spectrum of the target and the other object P is subtracted by P_0. By using the differential detection, distance spectrum removed the distance spectrum of the other targets is generated as $P - P_0$. Therefore, the distance spectrum of the desired target is only detected. Figure 7(b) shows the distance spectrum by using the proposed differential detection method, and the distance spectrum of the target is correctly measured. As compared with the measured distance spectrums in Figure 7(a) and (b), it is clearly confirmed that the proposed method can detect target distance by using the difference detection. The proposed differential detection can effectively detect the moving or static target distance from multiple reflections of the background static objects.

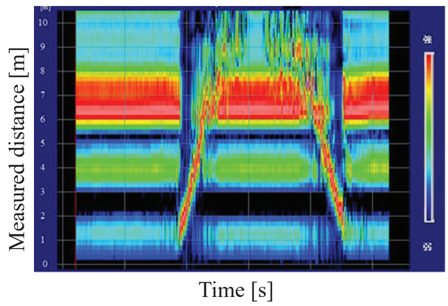
3.2 Field Experiments and Application

3.2.1 Setup condition for field experiments

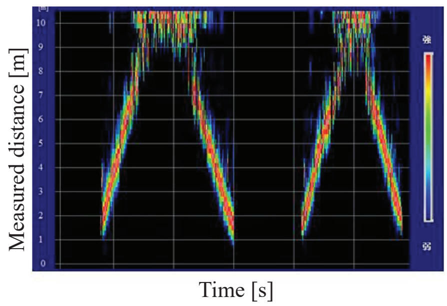
In order to evaluate the effectiveness of the proposed method for detecting the target distance and displacement, we developed a FM-CW radar system and carried out the experiments with the radar system in actual environment. Table 2 lists the parameters, and the developed FM-CW radar system got a certificate of conformity with technical regulations in Article 38-6 Paragraph 1 of the Radio Law in Japan, and developed FM-CW radar system was accommodate to ARIB standard T73 in Japan [1].

Table 2: Parameters in filed experiments

Parameters	Values
Center frequency f_0	24.15 (GHz)
Bandwidth of sweep frequency f_w	200 (MHz)
Sweep time t_w	1024 (μs)
Sampling time for sweep t_s	1 (μs)
Outputting power on Transmitting	7 (mW)
Antenna gain	11 (dBi)
Range of distance	0–100 (m)
Range of relative displacement	$\pm$3.11 (mm)



(a): without differential detection.



(b): with differential detection (Proposed).

Figure 9: Distance spectrum for measuring moving target distance with / without the differential detection.

3.2.2 Results in field experiments

Figure 9 shows the distance spectrum of a moving target. A person walked away from the FM-CW radar and then came close between 2 m to 10 m. In Figure 9(a), several distance spectrums of the person and the background objects were outputted. The distance spectrum of the moving person was not clearly detected in Figure 9(a) because of the reflected signals from background objects. In order to detect the distance spectrum of the moving

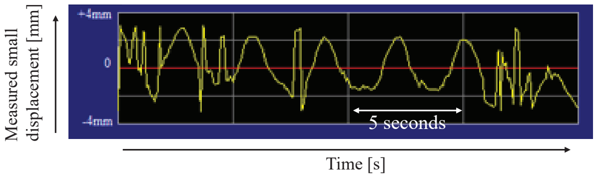
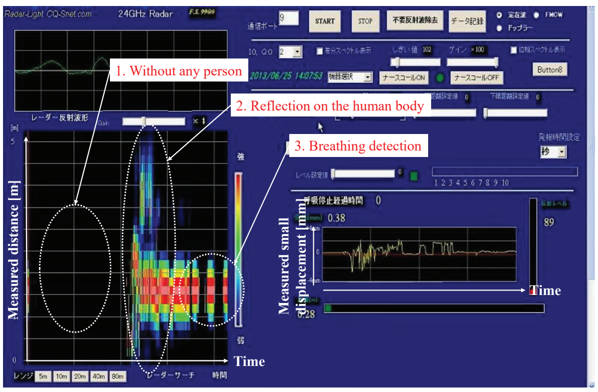


Figure 10: Displacement for measuring the movement of human breathing.



(a)

(b)

Figure 11: Example of application.

person with the differential detection method, the distance spectrum without the person was measured beforehand. By generating the distance spectrum of the background objects beforehand, the distance spectrum of the moving person was correctly detected in Figure 9(b) with the proposed differential detection. Therefore, the FM-CW radar system could measure movement of the target person effectively.

Figure 10 shows the result of measuring the small displacement for human breathing. The human's chest movement was measured within the range of relative small displacement. In Figure 10, it was detected that the period of breathing was about 4 s and the breathing movement was about within ± 2 mm.

3.2.3 Example of Application

In this section, we show an example of application with 24 GHz FM-CW radar system. Figure 8 shows a setup of the FM-CW radar system for detecting human breathing in actual scenes. The FM-CW radar satisfied the safety guideline, and the details of the safety guideline is described in Appendix.

Figure 11(a) shows the example of the results for detecting human breathing of single target in a room of a hospital. The distance spectrum in this example was measured as following flow.

1. Measuring distance spectrum without any person.
2. A person comes to the bed. The radar received signals from human's body.
3. The person lies asleep on the bed. The radar detects the person's breathing movement.

By generating the distance spectrum of the background objects without the person, the distance spectrum of the person was only detected. When the person comes within the range of radar, the radar system could detect reflected signals from the person, and the distance spectrums of the human's body were detected. After the person lied down on the bed, the radar system could detect the small displacement for the person's breathing movement. By using the differential detection method, the distance and small displacement of the moving object were clearly detected.

As connecting the developed FM-CW radars in several rooms in the hospital, detecting several targets could be realized. An example of monitoring several targets is shown in Figure 11(b). The developed FM-CW radars were connected the network system, and the information of detecting the distance and small displacement were sent to server in nurse station. In the nurse station, status of several targets could be monitored, and the alert information such as falling off the bed and stopping the human breathing could be monitored.

4 Proposed Techniques for Multiple Targets Detection

4.1 Problems for multiple targets detection

As mentioned in the above section, the FM-CW radar system could detect both the distance and displacement correctly under single target environments; however, the FM-CW radar could not detect both the distance and displacement correctly under closed multiple targets environments. In order to realize detection for closed multiple targets, we propose the detection method by using the signal processing with a tunable FIR filter.

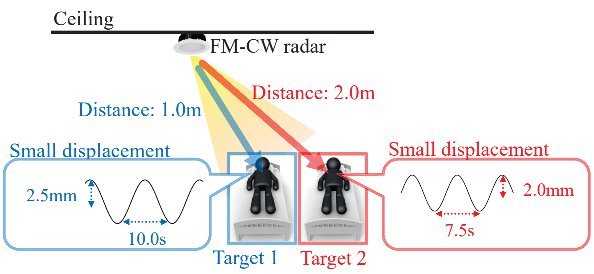


Figure 12: Setup conditions with 2 targets

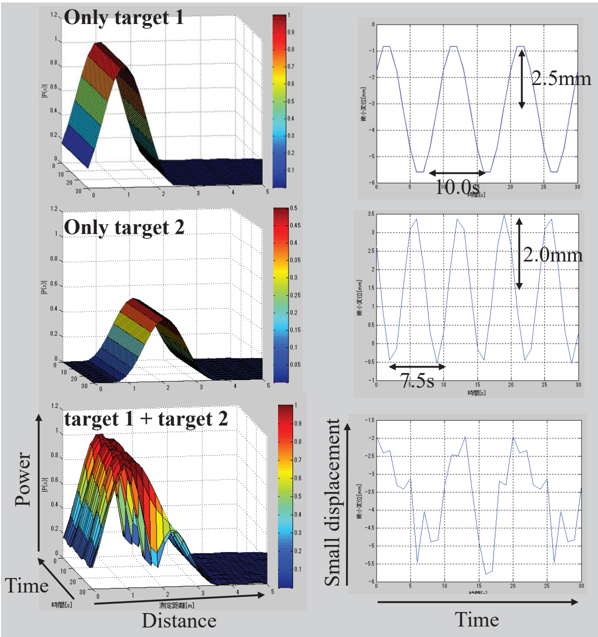


Figure 13: Simulated results of detection for closed multiple targets

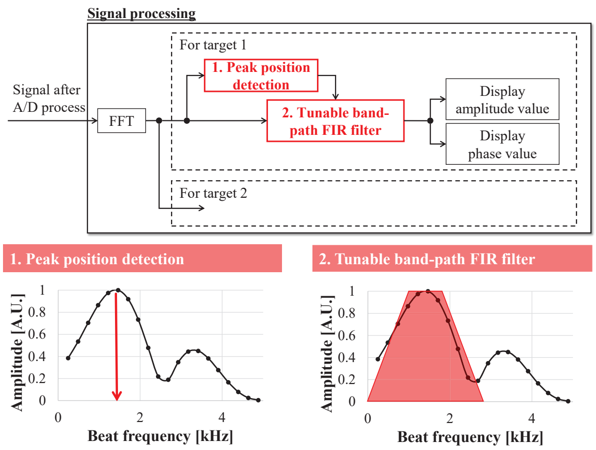


Figure 14: Block diagram of the proposed multiple targets detection in signal processing

Table 3: Parameters in computer simulations

Parameters	Values
Center frequency f_0	24.15 (GHz)
Bandwidth of sweep frequency f_w	100, 200, 400, 800 (MHz)
Sweep time t_w	256, 512, 1024, 2048 (μs)
Bandwidth for FIR filter B	200, 400, 800, 1600, 3200 (Hz)
Number of FFT points	4096
Window function	hamming

4.2 FIR filtering

The procedures of the proposed detection method for multiple closed targets is as follow. We assumed that the FM-CW radar is located a short distance from a bed as shown in Figure **??**. In this situation, the radio waves were radiated from the FM-CW radar, and 2 targets lied down on the bed. The distances from the radar to each target were different, so that the peaks of distance spectrum were detected at different frequency. In this case, the detected result shown in Figure 13 is sum of these 2 targets, and it is difficult for detecting both the distance and phase values for each user correctly.

In order to solve this problem, signal processing with the tunable FIR filter was used in the proposed detection method. Figure 14 shows the block diagram of the proposed detection method. At first, the A/D converted signal is carried out the FFT operation, and the distance spectrum is obtained. After processing the FFT operation, the peaks of amplitude value of the distance spectrum are calculated for each user. In the peak position detection processing, the two frequency value according to the targets is obtained; then, FIR filters are designed according to the peak positions of desired targets. The tunable FIR filter has the center frequency corresponding to the calculated frequency in the peak position detection, and the linear property for the phase value. By using the designed FIR filter, band-path filtering operation is carried out for the distance spectrum. After through band-path filter, the amplitude and phase value for each target are detected correctly.

4.3 Computer Simulations

4.3.1 Setup condition

In order to evaluate the performance for FM-CW radar system with the proposed method under multiple targets environment, we carried out computer simulations. Parameters for computer simulations are listed in Table 3, and the parameters are also based on ARIB standard T73

Table 4: Setup conditions for targets

Parameters	Target 1	Target 2
Distance	1.0 (m)	2.0 (m)
Amplitude of Displacement	2.5 (mm)	2.0 (mm)
Period of displacement	10.0 (s)	7.5 (s)

[1]. Center frequency was 24.15 GHz, and frequency bandwidths were 100, 200, 400, and 800 MHz. Note that the 400 and 800 MHz bandwidth were only used for the computer simulation because of standards in the Radio Law in Japan. Sweep times were 256, 512, 1024, and 2048 μs, sampling time of sweep was 0.1 μs, number of FFT points was 4096, and the hamming windows was adapted as the window function in signal processing. The bandwidths for FIR filter were 200, 400, 800, 1600, and 3200 Hz.

In the following sections, we describe the evaluation values for analyzing the results of multiple targets detection, and the performance analysis according to bandwidth for sweep frequency, sweep time, bandwidth for FIR filter, and position of target 2 are described.

4.3.2 Evaluation values for amplitude and phase values

Figure 15 shows the evaluation values for detecting the amplitude and phase values of the distance spectrum of multiple targets. As evaluation values, we defined the degree of amplitude separation for amplitude value and NMSE for phase value.

The degree of amplitude separation is represented by

$$S_k = 10 \log \frac{|P_{min}|}{|P_k|} = 10 \log \frac{|P(f_{min})|}{|P(f_k)|} \quad [\text{dB}] \quad , \tag{13}$$

where k denotes the number of target, S_k denotes the degree of amplitude separation, P_{min} denotes minimal value of amplitude whose frequency is f_{min}, and P_k denotes the peak value for k-th target with frequency of f_k.

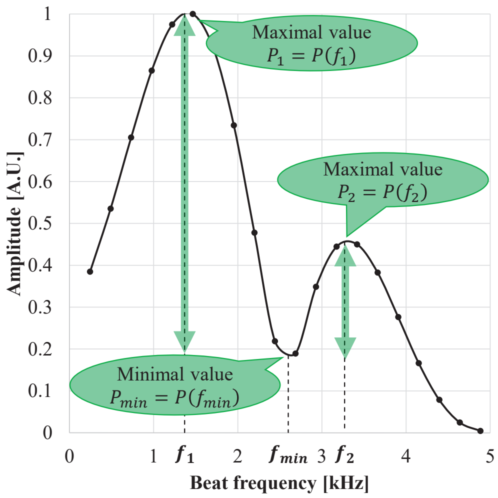
The NMSE for phase value is represented by

$$\text{NMSE} = \sum_{i=1}^{N} \frac{|d'_i - d_i|^2}{|d'_i|^2} \quad , \tag{14}$$

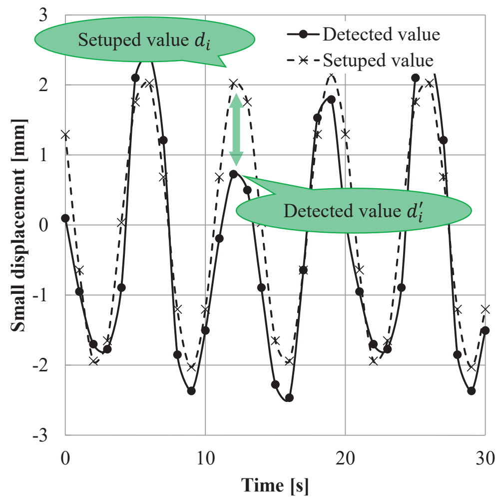
where N denotes the number of sampling points, d_i and d'_i denote the sampled signals of detected and setuped values for a target, respectively.

4.3.3 Performance for Bandwidth of sweep frequency

Figure 16 shows the evaluation values versus the bandwidth of sweep frequency f_w for amplitude value in (a)



(a): Amplitude

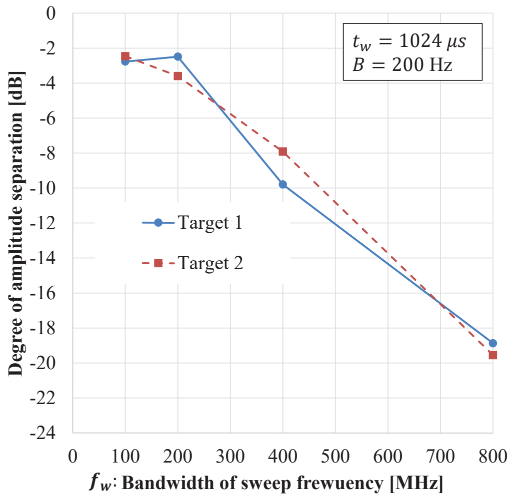


(b): Phase

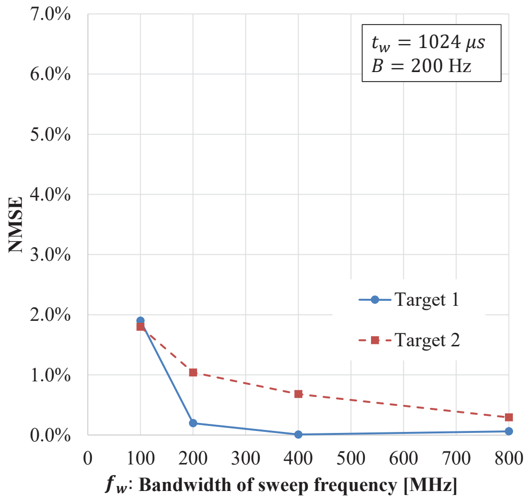
Figure 15: Definitions of evaluation values for computer simulation

and phase value in (b). As shown in (a), the degrees of amplitude separation were about -2.5 dB and -19 dB with $f_w = 100$ MHz and $f_w = 800$ MHz, respectively. Because the resolution of the distance spectrum was increased as an increasing the bandwidth of sweep frequency, the separation of targets for amplitude value become easily.

As shown in (b), NMSE was about 2 % with the bandwidth of sweep frequency $f_w = 100$ MHz, and NMSE was also improved as an increasing the bandwidth of sweep frequency. Although there was a few disadvantage for NMSE of target 2, the multiple targets detections could correctly achieved because the degree of amplitude separation with -1 dB and NMSE with 6 % were enough

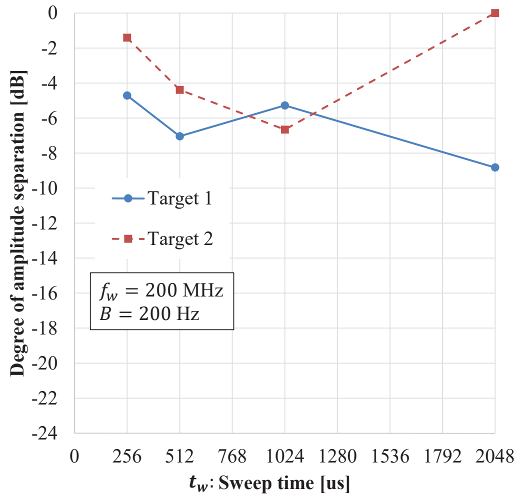


(a): Amplitude

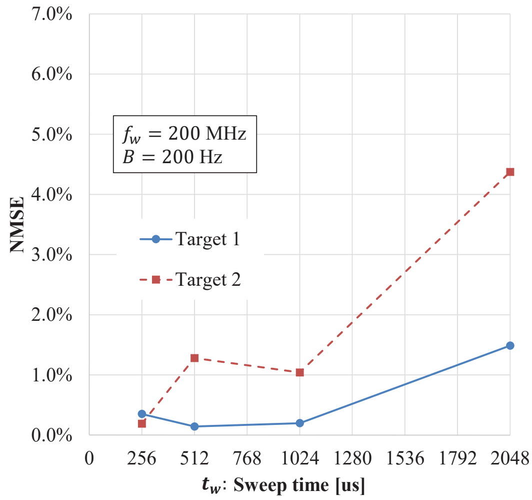


(b): Phase

Figure 16: Evaluation values versus bandwidth of sweep frequency



(a): Amplitude



(b): Phase

Figure 17: Evaluation values versus sweep time

values for detecting multiple targets in practical use.

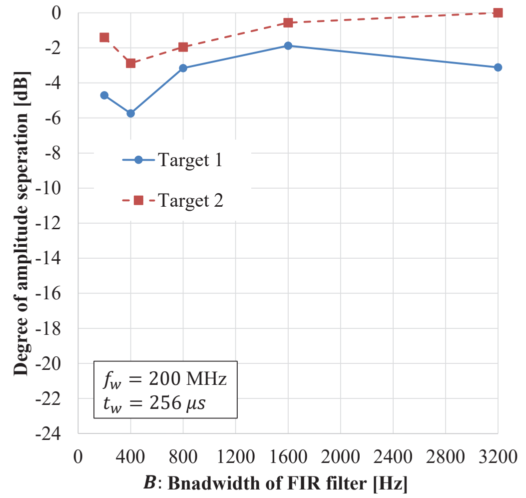
4.3.4 Performance for Sweep time

Figure 17 shows the evaluation values versus the sweep time t_w for amplitude value in (a) and phase value in (b). As shown in (a), the degree of amplitude separation for target 1 kept about -4 dB in accordance not to the sweep time. The degree of separation for target 2 had -1 dB during the sweep time $t_w = 256 \sim 1024\ \mu s$. In the case with $t_w = 2014 \mu s$, the degree of amplitude separation was almost 0 dB. That is, it was difficult to detect the peak value of amplitude for target 2. Moreover, compared to the result in (b), the worst NMSE for target 2 was about 4 % with $t_w = 2048\ \mu s$. Because the resolution for distance spectrum was decreased as an increasing the sweep time, the sweep time should be less than 1024 μs.

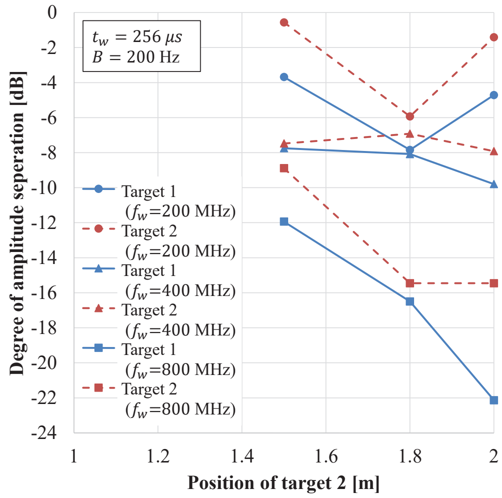
4.3.5 Performance for Bandwidth of FIR filter

Figure 18 shows the evaluation values versus the bandwidth of FIR filter B for amplitude value in (a) and phase value in (b). As shown in (a), the degree of amplitude separation for target 1 kept -2 dB in accordance not to the bandwidth of FIR filter B. When B was more than 1600 Hz, the degree was more than -1 dB, therefore, it was difficult to detect the peak value.

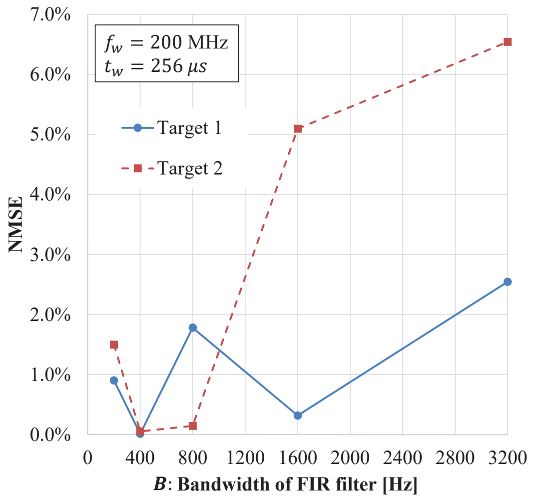
As shown in (b), NMSE for target 1 was less than 3



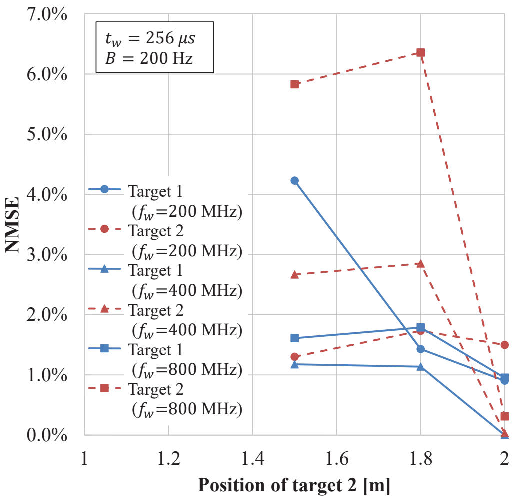
(a): Amplitude



(a): Amplitude



(b): Phase



(b): Phase

Figure 18: Evaluation values versus bandwidth of FIR filter

Figure 19: Evaluation values versus positions of target 2

%, but NMSE for target 2 was more than 5 % with $B =$ 1600 and 3200 Hz. Because the widely bandwidth of FIR filter was enough not to cut the signal of the other target completely, the bandwidth of FIR filter should be less than 1600 Hz.

4.3.6 Performance for distance between targets

Finally, we show the result for detecting multiple targets when the target 2 comes close to the target 1 from 2 m to 1.5 m. Figure 19 shows the evaluation values versus the position of target 2 from the radar for amplitude value in (a) and phase value in (b). The position of the target 1 was 1 m from the radar.

Compared to the results, the degree of amplitude separation and NMSE become depleted as the target 2 approaches to the target 1. As shown in (a), when the bandwidth of sweep frequency was more than 400 MHz, the degree of amplitude separation had good property which enough to detect the peaks. However, in the case with $f_w = 200$ MHz, the degree for target 2 was about -0.3 dB, and it was difficult to detect the peaks.

As shown in (b), when f_w was less than 400 MHz, NMSE could be kept about less than 5 %. However, in the case with $f_w = 800$ MHz, NMSE become depleted. It was difficult to detect peaks of amplitude for targets as decreasing distance between targets. Therefore, the center frequency of FIR filter was not enough to cut the other target's signal, and the imperfect FIR filter influenced NMSE values. Although there were a few difficulty for determining the parameters of the proposed detecting method for FM-CW radar, the proposed detecting method could be effective for detecting the distance and the small displacement at the same time under multiple targets environments.

5 Discussion

As related works, MIT group reported the radar system for detecting human breathing in [12]. The system could also detect the movement, and the human breathing in the room could be detected clearly. However, in Japan, the bandwidth for sweep frequency was strongly smaller than the MIT's radar system because of the ARIB standard T73. As shown in figure 3, the resolution was depending on the bandwidth; therefore, the smaller bandwidth influence the detected distance and small displacement. Moreover, under closed multiple targets environment, some distance between radars and each target must be required for separating the distance spectrum of each target. Therefore, in this paper, we used a tunable FIR filtering method in signal processing for detecting closed multiple targets at the same time.

6 Conclusion

In this paper, a FM-CW radar system with 24 GHz band with tunable FIR filter for detecting closed multiple moving targets with small displacements was described. The proposed detecting method generates tunable FIR filter whose center frequency is corresponding to the peak positions of distance spectrum of each target. The tunable FIR filtered signal can be detected the distance and displacement for each target correctly. In computer simulations, performances of FM-CW radar system under closed multiple moving targets environment was analyzed in accordance with the bandwidth of sweep frequency, sweep time, bandwidth of FIR filter, and the distance between targets. As the result, the 24 GHz FM-CW radar with the proposed detection method could effectively detect both the distance and the small displacement for each target under the multiple moving targets environments. And it was confirmed that the proposed detection method can detect both the distance and small displacement correctly when the distance between targets was 0.5 m.

As future works, we try to hardware implementation of the proposed FIR filtering and the field experiments.

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APPENDIX

In general, electromagnetic wave must be satisfied the guidelines on human exposure to electromagnetic fields, where it have been instituted in various organizations. IEEE C95.1 in USA [13] and ICNIRP in Europe [14] are the guidelines, and MIC also have instituted the guideline in Japan [15].

Developed 24 GHz FM-CW radar in this paper have the properties as follow. The power of the transmitter is 7 [mW], the transmitting antenna gain is 11 [dBi], the effective radiated power is 88 [mW], the radiation angle of the transmitting wave is about 50 [degree], and the distance between the transmitter and the human is 2.5 [m]. According to the radar equation, the electric field strength E and the power density P on the human body is calculated as

$$E = \sqrt{\frac{30 \times 0.088}{2.5}} = 0.65 \; [\mathrm{V/m}] \;,$$
$$P = \frac{E^2}{z_0} = \frac{0.65^2}{120\pi} = 1.12 \times 10^{-4} \; [\mathrm{mW/cm^2}] \;.$$

According to the guideline [15], these parameters must be satisfied as

$$E \leq 61.4 \; [\mathrm{V/m}] \;,$$
$$P \leq 1 \; [\mathrm{mW/cm^2}] \;.$$

Therefore, the developed 24 GHz FM-CW radar system in this paper sufficiently satisfies the conditions in the guideline.

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