NONCONTACT RESPIRATION MONITORING OF MULTIPLE CLOSELY POSITIONED PATIENTS USING ULTRA-WIDEBAND ARRAY RADAR WITH ADAPTIVE BEAMFORMING TECHNIQUE

M. Muragaki[⋆] *S. Okumura*[⋆] *K. Maehara*[⋆] *T. Sakamoto*[⋆†] *M. Yoshioka*[††]
K. Inoue[††] *T. Fukuda*[††] *H. Sakai*[††] *T. Sato*[⋆]

[⋆] Graduate School of Informatics, Kyoto University
[†] Graduate School of Engineering, University of Hyogo
[††] Advanced Research Division, Panasonic Corporation

ABSTRACT

Contactless respiration monitoring using Doppler radar is an important technology for healthcare applications. The radar measures small displacements of the body surface. In this study, we propose a new algorithm to separate multiple targets placed closely together at the same range but at different lateral positions using ultra-wideband array radar and the Capon method. The Capon method, which is an adaptive beamforming technique, assumes that arrival echoes are not correlated. However, echoes from the human body should be correlated and this reduces system performance. We improve the performance by introducing two different diagonal loading factor values for direction of arrival estimation and weight vector calculation. In an experimental study, the proposed method separates the echoes from two patients spaced at a lateral distance of approximately 70 mm. The estimated displacement error when using the proposed method is less than 0.13 mm, while that of the conventional method is 2.7 mm.

***Index Terms*—** Respiration, ultra-wideband radar, adaptive beamforming, Capon method, direction of arrival estimation

1. INTRODUCTION

Recently, contactless vital sign monitoring techniques using Doppler radar have attracted considerable research attention [1][2][3]. Doppler radar estimates the vital sign information, e.g., respiration and heart rate, by measuring the small displacements of the body surface that are caused by respiration and heartbeats. In this study, we focus on a technique for respiration estimation [4].

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When we use these techniques in realistic situations, e.g., in respiration monitoring at a hospital, simultaneous estimation of the vital signs of multiple patients is generally required. The use of ultra-wideband (UWB) radar, which offers high range resolution, allows the separation of multiple targets positioned at different ranges [3]. However, UWB radar cannot separate targets that are positioned at almost the same range and this situation occurs frequently.

Several techniques have been reported for estimation of the respiration rate of multiple targets using time-frequency analysis [5][6]. However, these methods cannot separate the received signals, i.e., they cannot estimate the body surface displacement of each individual target at each measurement time. Accurate displacement estimation is essential in measurement of the respiration phase at each measurement time and is the important information required for healthcare applications[7].

Therefore, in this study, we propose a new algorithm for displacement estimation of multiple closely positioned targets. We assume that we have two patients located at the same range but at different lateral positions and separate the echoes from multiple targets based on the difference in their directions of arrival (DOAs) using UWB array radar.

To estimate each displacement, estimation of the target positions and signal separations is required. The Capon method is an adaptive beamforming technique that optimizes the weight at each receiving antenna and provides high-resolution DOA estimation [8]. The optimized weight maintains the echo from the desired angle and eliminates echoes from undesired angles. Therefore, this method can also separate the echoes from different DOAs using an optimized weighting vector method at the desired angle.

To apply the Capon method to respiration measurement, we need to address the following problems. First, the Capon method assumes that the arrival echoes are not correlated [9]. However, the echoes from the body surface should be correlated for a short time.

To overcome this problem, we use and modify the diagonal loading technique, which adds quasi-noise and controls the trade-off between the resolution and the robustness of the Capon method [10]. In the conventional technique, the same diagonal loading value is used for both DOA estimation and signal separation [11][12]. However, the requirements for these two objectives are different. For DOA estimation, the resolution is more important than the robustness. In contrast, for signal separation, robustness has the higher priority. Thus, we change the value used depending on the objective.

The target intensities are time-dependent because respiration changes the scattering cross-section of each target. When the difference in the echo intensities from the different targets is too strong, the method fails to estimate the DOA of weak echoes. Therefore, we estimate the DOAs iteratively and produce a histogram of the estimated DOAs. Because the estimated DOAs should appear around the correct DOAs, the histograms value should thus increase around the correct DOAs.

The estimated DOAs contain correlation-related errors, and we thus select additional candidate DOAs around the estimated DOAs and separate the signals. Finally, we determine the most reliable candidates and then estimate the displacement. In this study, we conduct an experiment to evaluate the proposed method.

2. MATERIALS AND METHODS

We begin by explaining the principle of displacement estimation from radar signals. A small displacement causes a phase rotation at the center frequency [13]. This displacement, $l(t)$, is estimated using the following equation:

$$l(t) = \mathrm{unwrap}(\arg[s(t)])\lambda/4\pi, \tag{1}$$

where $s(t)$ is the received signal, λ is the wavelength at the center frequency, and unwrap is the phase unwrapping process required to connect a phase rotation of more than 2π smoothly. When multiple echoes from multiple targets are present, this method fails to estimate the displacement accurately.

2.1. DOA estimation using Capon method

In this study, we separate echoes reflected from multiple targets using the difference in their lateral target positions. We use an array radar that consists of M receiving antennas and apply an adaptive beamforming technique. Fig. 1 shows a schematic illustration of the measurement setup.

The Capon method is a well-known high-resolution adaptive beamforming technique [8]. The strategy of the Capon method is given as follows:

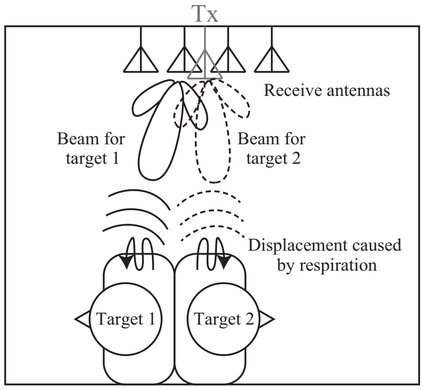

Fig. 1. Schematic illustration of the measurement setup.

$$\begin{aligned} \min P_{\mathrm{out}}(\theta, t) &= \frac{1}{2}\mathbf{w}^{\mathrm{H}}\mathbf{R}(t)\mathbf{w} \quad (2)\\ \text{subject to} \quad & \mathbf{a}^{\mathrm{T}}(\theta)\mathbf{w}^* = 1,\\ \mathbf{a}(\theta) = [1, \quad \cdots & \quad , \exp(\frac{-\jmath\omega d(M-1)\sin(\theta)}{c})], \quad (3)\end{aligned}$$

where P_{out} is the output power, $\mathbf{w}$ is the weighting vector, $\mathbf{R}(t)$ is the covariance matrix at the measurement time t, $\mathbf{a}$ is the steering vector, θ is the measurement angle, and c is the speed of light. The covariance matrix $\mathbf{R}(t)$ is given by

$$\begin{aligned} \mathbf{R}(t) &= \beta\mathbf{R}(t-\Delta t) + (1-\beta)\mathbf{R}_0(t), \quad (4)\\ \mathbf{R}_0(t) &= \mathbf{s}^{\mathrm{H}}(t)\mathbf{s}(t), \quad (5)\\ \mathbf{s}(t) &= [s_1(t)\cdots s_M(t)]^{\mathrm{T}}, \quad (6)\end{aligned}$$

where β is the forgetting factor. β determines the averaging time, and $s_m(t)$ is the received signal at the m-th receiving antenna.

The optimization problem shown in Eq.(2) is solved using the Lagrange multiplier method. The output power of the Capon method is given by

$$P_{\mathrm{out}}(\theta, t) = \frac{1}{\mathbf{a}^{\mathrm{H}}(\theta)(\mathbf{R}(t) + \eta_\theta\mathbf{I})^{-1}\mathbf{a}(\theta)}, \tag{7}$$

where η_θ is the diagonal loading factor for DOA estimation. Note that a small value for the diagonal loading factor increases the resolution while reducing the robustness of the process. A small diagonal loading value is suitable for DOA estimation because high performance DOA estimation is required.

When θ approaches the correct DOAs of the targets, the output power of the Capon method then increases. Therefore, the peaks in the output power may represent the DOAs of the targets.

2.2. Depiction of DOA using a histogram

As mentioned above, the signal intensity varies from time to time and the method cannot always estimate all DOAs. To overcome this problem, we iteratively detect the peaks of each $P_{\mathrm{out}}(\theta, t)$ during the period $t_1 \leq t \leq t_2$ and compose a histogram of the DOAs of the detected peaks.

Because these peaks should appear around the correct DOAs, the angles that have the maxima in the histogram should represent the DOAs of the targets. Here, we define θ_k as the DOAs determined using the histogram.

2.3. Signal separation and displacement estimation

While we can estimate the DOAs, the estimation accuracy is low because of the correlation of the arrival waves. To increase the robustness of the method, we select additional DOAs as candidates around θ_k. In this study, we select five candidates for each θ_k. These DOA candidates, designated $\theta_{k,i}$, are given by $\theta_{k,i} = \theta_k + (i-2)\Delta\theta$, where $\Delta\theta$ is the DOA estimation interval and $i = 1, \cdots, 5$ is the candidate number.

We then calculate the optimal weighting vector using each of these candidates. The optimal weighting vector for the measurement angle $\theta_{k,i}$ is calculated using

$$\mathbf{w}_{\mathrm{opt}}(\theta_{k,i}) = \frac{(\mathbf{R}(t) + \eta_{\mathrm{w}}\mathbf{I})^{-1}\mathbf{a}(\theta_{k,i})}{\mathbf{a}(\theta_{k,i})(\mathbf{R}(t) + \eta_{\mathrm{w}}\mathbf{I})^{-1}\mathbf{a}(\theta_{k,i})}, \quad (8)$$

where $\mathbf{w}_{\mathrm{opt}}(\theta_{k,i})$ is the optimized weighting vector, and η_{w} is the diagonal loading factor used to calculate the weighting vector. When a correlation exists, the Capon method can then eliminate all signals by cancelling them with each other. Because we estimate the displacement using the signal phase, we therefore need to maintain the echo with high stability. We thus use a large diagonal loading value for the weighting vector estimation.

The separated signal $s_{k,i}(t)$ for each $\theta_{k,i}$ and its displacement, $l_{k,i}(t)$, are given by

$$s_{k,i}(t) = \mathbf{w}_{\mathrm{opt}}^{\mathrm{H}}(\theta_{k,i})\mathbf{s}(t), \quad (9)$$

$$l_{k,i}(t) = \mathrm{unwrap}(\arg[s_{k,i}(t)])\lambda/4\pi, \quad (10)$$

When $\theta_{k,i}$ is close to the correct DOA, the estimated displacement is then almost equivalent to the true displacement. However, when $\theta_{k,i}$ is inaccurate, the estimated displacement then approaches a random signal because the Capon method tries to cancel all the signals.

Therefore, to estimate each DOA conclusively, we calculate the displacement differences between all combinations of the candidates. The difference between the i_1-th and i_2-th candidates is given by

$$d_k(i') = \sum_{t=t_1}^{t_2} |l_{k,i_1}(t) - l_{k,i_2}(t)|, \quad (11)$$

where $i' = (1 \cdots I')$ is the combination number. Because we have selected five candidates, the number of combinations, I', is ${}_5\mathrm{C}_2 = 10$. We then select the candidate combination that has the smallest difference, $d_k(i')$. Finally, the displacement that is estimated using the proposed method is given by

$$l_{\mathrm{e}}(t) = \mathrm{unwrap}(\arg[s_{k,i'_1}(t) + s_{k,i'_2}(t)])\lambda/4\pi, \quad (12)$$

where i'_1 and i'_2 are the selected candidate numbers.

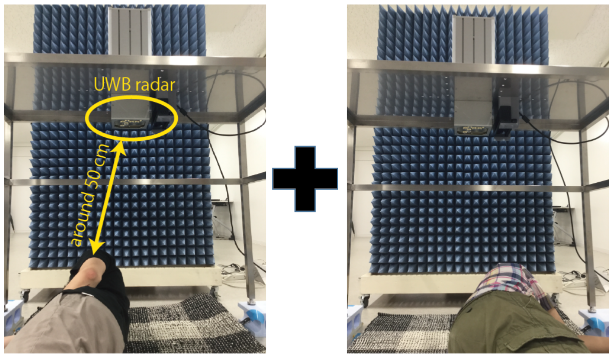

Fig. 2. Photographs of the experimental settings.

3. EXPERIMENTAL SETTINGS

Fig.2 shows photographs of the experimental settings used. We conducted two experiments using one of the two patients, and then linearly added the received signals acquired from the two experiments to emulate the situation when there are two closely spaced patients. The range for both targets is approximately 500 mm and the difference in their lateral positions is approximately 70 mm.

The center frequency of the transmitted signal is 60.5 GHz, and the bandwidth is 1.25 GHz. The pulse repetition interval is 7.3 ms. The range resolution is 12 cm. The pitch for each of the receiving antennas, d, is 3.3 mm. We used four receivers (i.e., $M = 4$).

We use two diagonal loading factors, η_θ and η_{w}, of -60 dB and -10 dB of the averaged received echo intensity in the proposed method. We estimate the displacement using $(t_1, t_2) = (0, 5)$ and $(5, 10)$ s. The histogram interval $\Delta\theta$ is 1 degree. β is 0.99, meaning that the averaging time is approximately 0.5 s.

4. RESULTS

Fig. 3 shows the output powers obtained using the proposed method, the conventional method, and the Capon method with a high diagonal loading value. For the conventional technique, we used a non-adaptive beamforming technique. The proposed method, which uses the appropriate diagonal loading value of $\eta_\theta = -60$ dB, successfully depicted the two DOAs. In contrast, both the conventional method and the Capon method with the high diagonal loading of $\eta_\theta = -10$ dB failed to separate the DOAs.

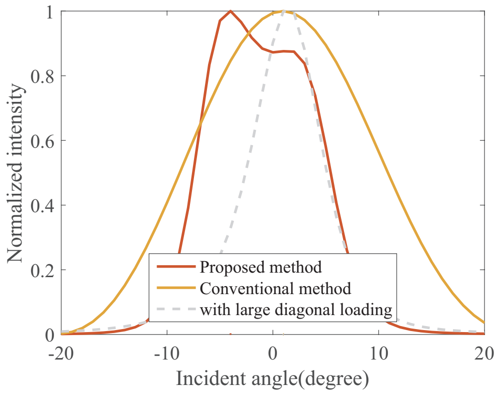

Fig. 3. Output powers of the proposed method (where $\eta_\theta = -60$ dB), the conventional method and the Capon method with high diagonal loading value ($\eta_\theta = -10$ dB).

Fig. 4 shows a histogram of the depicted DOAs. Because the pulse repetition time and the averaging time for the Capon method were 7.3 ms and 0.5 s, respectively, the independent data are acquired every 68 samples. We thus normalize the number of occurrences by 68. The proposed method clearly shows the positions of the two targets, while the conventional method and the Capon method with their inaccurate η_θ failed to estimate the targets.

Fig. 5 shows the estimated displacement. The proposed method succeeded in accurately estimating the displacement. The root-mean-square error of the proposed method and that of the conventional method for target 1 and target 2 are (target 1, target 2)= (0.11, 0.13) mm and (2.6, 2.7) mm, respectively. The proposed method used η_θ of -10 dB to provide a robust estimation, while the Capon method with the low diagonal loading value used η_θ of -60 dB. The true displacements of targets 1 and 2 are calculated using separately acquired data.

As indicated by the gray dotted lines in Figs. 3, 4 and 5, when we do not use an appropriate diagonal loading value, the method fails to estimate both the displacement and the DOA. These results show that the use of an appropriate diagonal loading value is important for respiration displacement estimation when using the Capon method.

5. CONCLUSION

In this study, we propose a technique to estimate the respirations of multiple targets simultaneously. We use the Capon method and modify the diagonal loading process. We use two different diagonal loading factor values for the DOA estimation and weight vector calculations. Additionally, we propose a method to improve the process robustness. In the experimental study, the root-mean-square error of the estimated displacement when using the proposed method was less than 0.13 mm, while that of the conventional method was 2.7 mm. We believe that the proposed method expands the range of application of noncontact respiration monitoring methods using the Doppler radar technique.

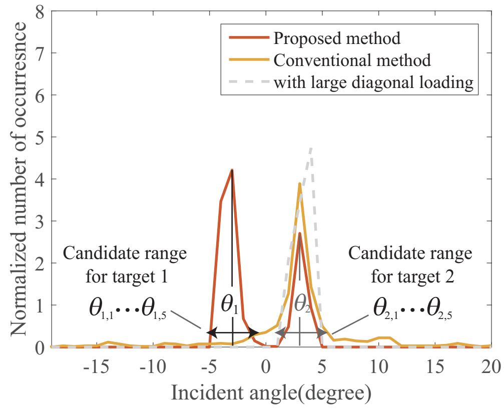

Fig. 4. Histogram of the estimated DOAs with $(t_1, t_2) = (0, 5)$ s. θ_1 and θ_2 are the DOAs depicted using the proposed method and the black arrows show the ranges of the DOA candidates.

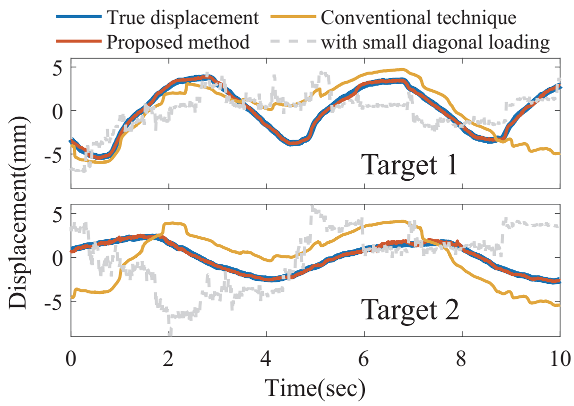

Fig. 5. True and estimated displacements of targets 1 (upper side) and 2 (lower side) when using the proposed method ($\eta_w = -10$ dB), the conventional method and the Capon method with low diagonal loading ($\eta_w = -60$ dB).

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