Non-Contact Respiration Measurement Using Ultra-wideband Array Radar with Adaptive Beamforming Technique for Cancer Radiotherapy

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Abstract – **Tumor position estimation is the key to effective radiation therapy. In clinical situations, tumor position is predicted from the breath phase. However, the accuracy of the prediction deteriorates when the breathing type is not known. To solve this problem, in this paper, we propose a new method to separate the signals from the chest and abdomen using ultra-wideband (UWB) radar based on an adaptive beamforming technique. First, we estimate the positions of the targets using the Capon method, and modify the method for near-field two-dimensional scanning. Next, we separate the signals using the directionally constrained minimization of power method that suppresses the off-axis signals by calculating the optimal weighting vector. We estimate the displacement at each scattering point using the separated signal, and evaluate the performance of the proposed method via realistic numerical simulation. The conventional non-adaptive beamforming technique failed to estimate the three scattering positions. However, the proposed method succeeded in estimating the scattering positions. The root mean squared errors of the displacement estimated using the proposed method at three scatters were 0.138 mm, 0.123 mm, and 0.259 mm.**

Index Terms —**Ultra-wideband radar, array processing, Capon method, respiration.**

1. Introduction

Radiation therapy is an effective treatment for lung cancer. In radiation therapy, an accurate real-time estimation of the tumor position is required because the position of the tumor varies over time with respiration. In clinical situations, tumor position is predicted using an X-ray fluoroscopic image of the body and the breath phase. However, the accuracy of the prediction decreases if it is not known whether the patient uses costal or abdominal breathing, or both simultaneously.

To solve this problem, we propose a new method to separate the costal and abdominal breath phases using a UWB array radar with an adaptive beamforming technique. First, we detect the position of the reflection points on the body surface using the Capon method. This method is a high resolution direction of arrival (DOA) estimation technique [1]. To image the body surface, we modify the Capon method to use 2-dimensional (2D) near-field scanning. Second, we separate the signal from each estimated reflection point using a directionally constrained minimization of power (DCMP) algorithm. The method calculates the optimized weighting vector for the array that suppresses the signal from undesired positions. Finally, we estimate the displacement of the targets by calculating the phase rotation of the separated signal. We evaluate the proposed method using numerical simulation, in which we use the optical Kinect sensor (Microsoft Corporation, Redmond, WA, USA) to construct the body surface model.

2. Materials and Method

(1) Scattering position estimation using Capon method

To estimate the position of the reflection points on the body surface, we conducted 2D near-field scanning at the target range-bin using 2D linear multiple-input and multiple-output (MIMO) radar. Fig. 1 shows the system model.

The Capon method estimates the DOAs by minimizing the output power, P_{out}, under the constraint condition that maintains the echo from the point of interest. The optimization problem is expressed by:

$$\min_{\mathbf{W}}\left(P_{\mathrm{out}} = \frac{1}{2}\mathbf{W}(t,x,y)^{\mathrm{H}}\mathbf{R}(t)\mathbf{W}(t,x,y)\right) \quad \text{subject to } \mathbf{a}^{\mathrm{T}}(x,y,z)\mathbf{W}(t,x,y)^{*} = 1, \tag{1}$$

$$\mathbf{a}(x,y,z) = [\mathrm{a}_{11},\cdots,\mathrm{a}_{M1},\mathrm{a}_{12},\cdots,\mathrm{a}_{MN}], \tag{2}$$

$$\mathrm{a}_{mn}(x,y,z) = \exp[-\mathrm{j}2\pi\{\sqrt{x^2+(y-y_n)^2+z^2} + \sqrt{(x-x_m)^2+y^2+z^2}\}/\lambda], \tag{3}$$

where t is the slow time, P_{out} is the output power of the Capon method, $\mathbf{W}$ is the weighting vector, $\mathbf{a}$ is the constraint vector, $\mathbf{R}$ is the covariance matrix, z is the target range-bin, M is the number of receivers, N is the number of transmitters, (x,y,z) is the position of the scanning point, the position of the m-th receiver is (x_m, 0, 0), the position of the n-th transmitter is (0 , y_n, 0), and $[]^{\mathrm{H}}$ and $[]^{\mathrm{T}}$ denote the Hermitian transpose and transpose, respectively.

The covariance matrix $\mathbf{R}$ is given by:

$$\mathbf{R}(t) = \beta\mathbf{R}(t-\Delta t) + (1-\beta)\mathbf{R}_0(t), \tag{4}$$

$$\mathbf{R}_0(t) = \mathbf{S}^{\mathbf{T}}(t)\mathbf{S}(t), \tag{5}$$

where β is the forgetting factor, and Δt is the pulse repetition interval. The output power is given by:

$$P_{\mathrm{out}}(t,x,y) = \frac{1}{2\mathbf{a}^{\mathrm{H}}(x,y,z)\mathbf{R}(t)\mathbf{a}(x,y,z)}. \quad (6)$$

In this study, we define the measurement point that has the local maximum power as the target position, (x_C, y_C, z).

(2) Displacement estimation using DCMP method

Next, we calculate the displacement of each target. We separate the signals using the DCMP method. The separated signal f is calculated as follows:

$$f(t,x_C,y_C) = \mathbf{W}_{\mathrm{opt}}^{\mathrm{H}}(t,x_C,y_C)\mathbf{S}(\mathrm{t}), \quad (4)$$

$$\mathbf{W}_{\mathrm{opt}}(t,x_C,y_C) = \frac{\mathbf{R}^{-1}(t)\mathbf{a}(x_C,y_C,\ z)}{\mathbf{a}^{\mathrm{H}}(x_C,y_C,\mathrm{z})\mathbf{R}^{-1}(t)\mathbf{a}(x_C,y_C,z)}. \quad (5)$$

The displacement L of each scatter is calculated from the phase rotation of the separated signal:

$$L(t,x_C,y_C) = \frac{\lambda \arg\big(f(t,x_C,y_C)\big)}{4\pi}. \quad (6)$$

(3) Simulation model

The center frequency of the transmitted signal is 60.5 GHz. The bandwidth is 1.25 GHz. The pulse repetition interval is 3.3 ms. The range resolution is 12 cm. The pitches of the transmitting antenna, d_1, and receiving antenna, d_2, are 4.0 mm and 4.6 mm, respectively. We used four transmitters and four receivers. The positions of the n-th transmitting and receiving antennas are $(0, (-2.5 + n)\,d_1, 0)$ and $((-2.5 + n)\,d_2, 0, 0)$, respectively.

To construct a human body simulation model, we used a Microsoft Kinect sensor, which can acquire three-dimensional target data using infrared light at 30 frames/s. We measured the motion of the human body for 7 s at a distance of 600 mm from the device. Under these conditions, the device has an error of less than 2 mm [2].

To make the model, we first extracted the scattering points. In this study, we first extracted the scattering points on the measured human body using the ray tracing method. Fig. 2 shows the density of the extracted scattering points. Because the reflection points were dense around the chest and abdomen, we used the three scatter points expressed by circle markers in Fig. 2. The signal was calculated using a ray tracing method. The scanning ranges were -90 mm $< x < 90$ mm, -280 mm $< y < 50$ mm, and $z = 600$ mm with an interval of 5 mm. We set the forgetting factor β to 0.995, which corresponds to 461 ms.

3. Results

We used a non-adaptive beamforming technique called the beamformer method as the conventional technique. The left and right panels in Fig. 3 show the result of the DOA estimation results acquired using the conventional and proposed methods, respectively. The beamformer method failed to depict the three scatter points. In contrast, the proposed method succeeded in estimating the target positions accurately.

Next, we estimated the displacement using the separated signals as shown in Fig. 4. The root-mean-square errors (RMSEs) of the proposed method for targets A, B, and C were 0.138 mm, 0.123 mm, and 0.259 mm, respectively. The proposed method succeeded in estimating the displacement accurately. This error is sufficiently small for use in radiotherapy.

4. Conclusion

In this paper, we proposed a new method to estimate the displacement of the body surface at different points simultaneously for use in radiation therapy. The proposed method succeeded in estimating the displacements of the three points with a RMSE of less than 0.26 mm. The results show that this method should be effective for use in radiotherapy.

References

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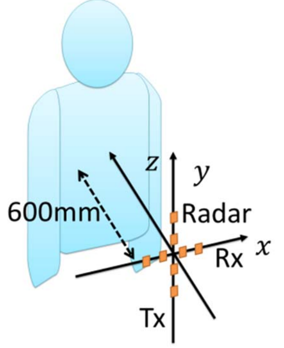

Fig. 1. System model.

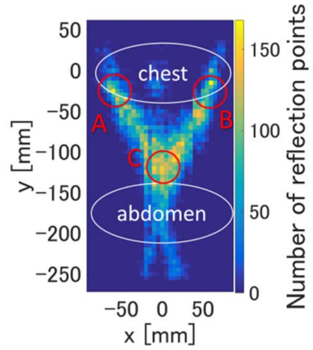

Fig. 2. Extracted scattering points.

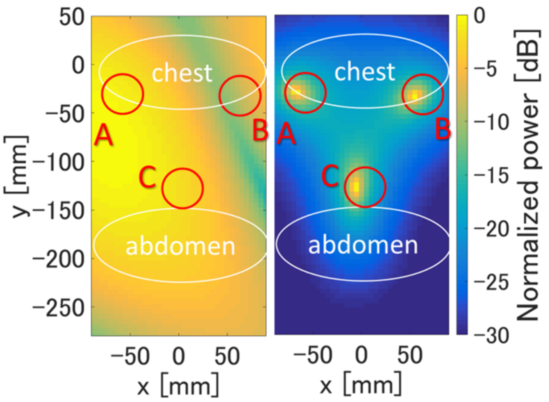

Fig. 3. Estimated power using beamformer and Capon methods.

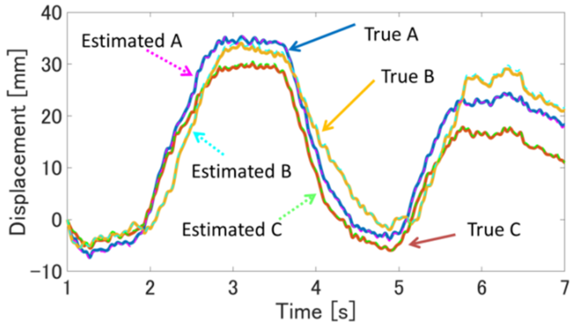

Fig. 4. Estimated displacement of chest and abdomen.