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Self-shape estimation algorithm for flexible ultrasonic transducer array probe by minimizing entropy of reconstructed image

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***Abstract*—Flexible ultrasonic transducer array probe can realize successive monitoring by pasting it to the body. Imaging with a flexible ultrasonic probe requires information of the elements' relative position. In this paper, we propose an algorithm to estimate the array shape from radio frequency data acquired by synthetic aperture. With this algorithm, the array shape is estimated based on the entropy of the reconstructed image using the assumed array shape. Entropy is used to evaluate the sharpness of an image. The real array shape can be estimated by searching for the shape which minimizes the entropy. Simulation experiments to verify the proposed algorithm were conducted. A 16 elements, 5 MHz, 1mm pitch flexible transducer array was used. The average position error of all elements of 4 trials between the real shape and the estimated shape was 0.037 mm. These results indicate that the proposed algorithm has a possibility to enable medical imaging with flexible ultrasonic transducer array probe.**

Keywords—ultrasound, flexible ultrasonic transducer array probe, shape estimation

I. Introduction

Ultrasound imaging is often used in medical diagnosis due to its low-invasiveness and compactness of device. Rigid probe is pressed against the patient's body during imaging to avoid air in between. Therefore, it is difficult to monitor the patient's body successively for hours because operators must keep pressing the rigid probe against the patient's body throughout monitoring.

By using flexible ultrasonic transducer array probe which is a probe whose transducer array shape can be deformed according to the surface shape of specimen, successive monitoring can be made possible. Thin flexible probe can be pasted on the patient's body, and there is no need to keep pressing it. Flexible probe is already used for non-destructive testing (NDT) of industrial products with complex surface shape. However, there are some barriers to use it for medical diagnosis.

The largest barrier in realizing medical diagnosis is that the information of elements' relative position in transducer array is unknown because the array shape is deformable and not constant. Information of elements' position is required for delay-and-sum beamforming in image reconstruction process. Precise information of elements' position is not necessary for NDT because it can detect defects only from the echo signals. However, human body cannot be diagnosed only by echo signals because internal structure of human body is complex and varies from person to person. Therefore, precise information of elements' position is required for medical diagnosis because diagnosis is performed using reconstructed images. To use flexible probe for medical diagnosis, a method to estimate the shape of transducer array is necessary.

Several methods have been proposed for examining the shape of flexible ultrasonic transducer array. A method using microwave and sensors was proposed by Mahaut *et.al.* [1]. A method using shape sensing fiber was proposed by Lane *et.al.* [2]. With these methods, external devices were used. A probe using external devices is large, complicated, and cannot be pasted on patient's body. Therefore, to enable successive monitoring with flexible probe, a shape estimation method without using external devices is required.

There is a shape estimation method for NDT using radio frequency (RF) data [3]. With this method, the shape was estimated using the contrast of the image. However, it cannot be used directly for medical imaging because internal structure of body is much more complicated than industrial products.

In this paper, we introduce a shape estimation method of flexible ultrasonic transducer array from RF data when the imaging object is human body.

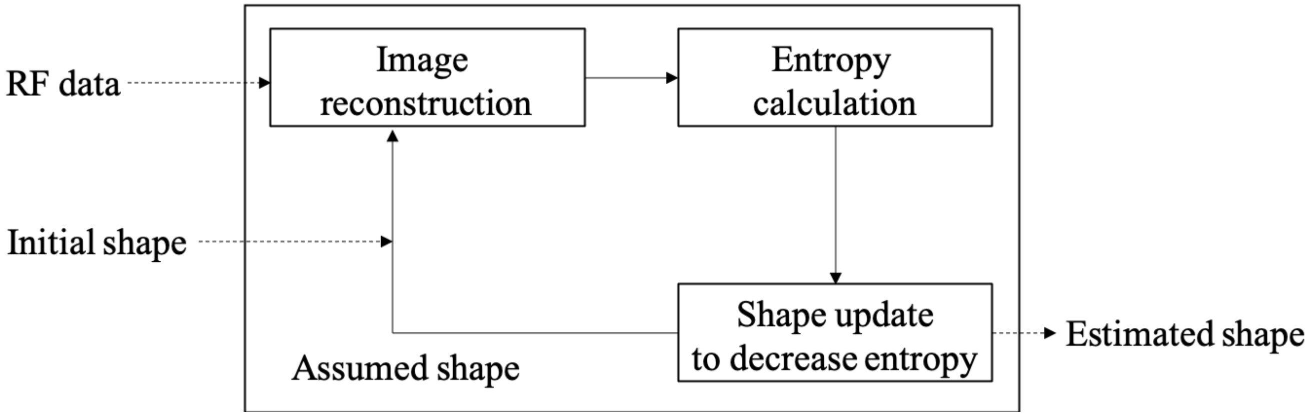

Fig. 1. Flowchart of the proposed method.

II. Proposed Method

In this proposed method, sharpness of reconstructed image with assumed array shape is used for shape estimation. If assumed shape is wrong, the reconstructed image is blurred, and if assumed shape is correct, the reconstructed image should be sharp. Therefore, by searching for an assumed array shape which maximize the sharpness of reconstructed image, the correct shape can be estimated. There are many indicators to evaluate the sharpness of an image. In this paper, we propose an evaluation method of sharpness of the reconstructed image using entropy. There is a correlation between the sharpness of the image and entropy. The sharper the image, the lower the entropy. Therefore, a correct shape can be estimated by searching for an assumed shape which minimizes entropy.

The proposed method is composed of several flows. The flowchart is shown in Fig.1. The input of this method are RF data and initial assumed shape. RF data is acquired by synthetic aperture (SA) [4]. At first, the image is reconstructed using RF data and assumed shape. After that, the entropy of reconstructed image is calculated and assumed shape is updated so that the entropy becomes lower. These processes are repeated until entropy is minimized. The assumed shape which minimizes the entropy is outputted as an estimated array shape.

Acquisition of RF data

RF data is acquired by SA. At each step in SA, ultrasonic pulse is transmitted from one element and echo signal is received by all elements. The basic idea of SA is that delay-and-sum beamforming is conducted computationally after acquisition of RF data. Since SA does not require the information of array shape at the time of data acquisition, it is only necessary to acquire RF data once, and not necessary for each assumed shape.

Definition of assumed array shape

Array shape is assumed based on sine expansion of $f(\boldsymbol{P})$:

$$f(\boldsymbol{P}) = P_1 \sin x + P_2 \sin 2x + \cdots + P_n \sin nx \qquad x \in [0\ \pi] \tag{1}$$

Where $\boldsymbol{P}$ is the shape parameter vector consisting of n parameters. Since sine functions are orthogonal functions, any array shape can be represented uniquely. The length of assumed array $f(\boldsymbol{P})$:

$$L(\boldsymbol{P}) = \int_0^{\pi} \sqrt{1+\{f'(\boldsymbol{P})\}^2}\, dx \tag{2}$$

depends on the shape parameter $\boldsymbol{P}$. On the other hand, actual length of array:

$$p(N-1) \tag{3}$$

is constant, where p is the pitch of elements, and N is the number of elements. Therefore, in order to make the length of assumed shape same as actual length, assumed shape is enlarged

$$p(N-1)/L(P) \tag{4}$$

times in both x and z directions.

Image reconstruction

The image is reconstructed using RF data and assumed array shape by delay-and-sum beamforming. In this method, the intensity of back scattering at each focal point is

$$I(x,z) = \sum_i \sum_j RF(i,j,t.t.) \tag{5}$$

Where x, z are the coordinate of focal point, i, j are the number of transmitters and receivers, RF is RF data, and $t.t.$ is traveling time. Traveling time is the time from when the ultrasonic wave is transmitted by the transmitting element to when it is received by the receiving element. If the speed of sound is constant,

$$t.t. = \frac{\sqrt{(x-X_i)^2+(y-Y_i)^2}+\sqrt{(x-X_j)^2+(y-Y_j)^2}}{c} \tag{6}$$

Where (X_i, Y_i), (X_j, Y_j) are the positions of transmitting element and receiving element, (x, y) is the position of focal point, and c is the sound speed.

Entropy calculation

At first, an image I is normalized to I_N so that the sum of intensity is 1.

$$I_N(x,z) = I(x,z) / \sum_i \sum_j I(i,j) \tag{7}$$

After normalization, entropy was calculated as following:

$$Entropy = \sum_i \sum_j \{-I_N(i,j) \times \log_2 I_N(i,j)\} \tag{8}$$

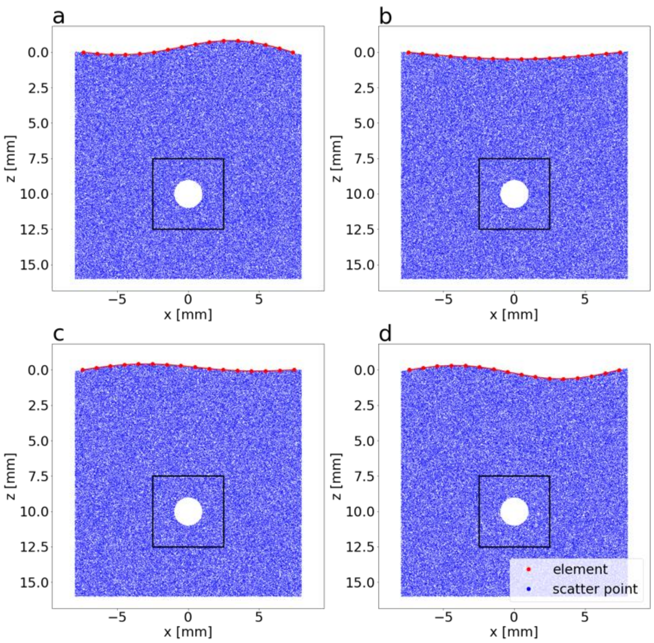

Fig. 2. Simulation setup: (a)array 1; (b)array 2; (c)array 3; (d)array 4. Scatter points were randomly distributed at a density of 1000 $points/mm^2$. There is a circular area with a diameter of 2 mm without scatter points at a depth of 10 mm. Flexible arrays consisting of 16 elements with 1 mm pitch were placed on the surface of scatter points. The regions surrounded by black frames are the ROIs.

Update of Assumed shape

The shape parameter vector which minimizes the entropy was searched by gradient descent method.

$$\widehat{\boldsymbol{P}} = argmin\{Entropy(\boldsymbol{P})\} \tag{9}$$

III. Simulation Setup

We conducted four simulation experiments to verify the effectiveness of the proposed method. The shape of array varies for each simulation. RF data was generated by simulation. In this simulation, the size of scatter points was 0, and diffraction, attenuation, and multiple scattering were not considered. Directivity of transmission was also not considered. Scatter points and flexible transducer arrays are shown in Fig. 2. Scatter points (blue points in Fig. 2) were randomly distributed at a density of $1000\ \mathrm{points/mm^2}$. Circular areas with a diameter of 2 mm without scatter points were drawn at a depth of 10 mm. The speed of sound was set to 1540 m/s. A 5 MHz, one cycle wave, 16 elements flexible transducer arrays (red points in Fig. 2) were placed on the surface of scatter points. The pitch of elements was 1 mm. RF data were acquired by SA method at a sampling frequency of 20 MHz. Region of interest (ROI) of reconstructed images used for the shape estimations (black frames in Fig. 2) were placed at a depth of 10 mm. The size of ROI was $5\,mm \times 5\,mm$, and the resolution of image was $25\,pixels \times 25\,pixels$.

Assumed shapes were defined by two parameters P_1 and P_2:

$$f = P_1 \sin x + P_2 \sin 2x \tag{10}$$

Initial assumed shape was linear shape and the two parameters P_1 and P_2 were set to 0. The update of assumed shape was repeated for 100 times. The optimizer used for gradient descent optimization was Adam optimizer [5]. The learning rate used for the update of assumed shape was 0.025.

IV. Results

Four array shapes were estimated by the proposed method. Transition of each shape parameters during shape estimations are shown in Fig. 3a. The shape parameters P_1 and P_2 close to the real values were estimated with an average error of 0.013 and 0.0043.

Real, linear, and estimated shape of each array are shown in Fig. 3b. The average position error of all elements of four arrays between real shapes and estimated shapes was 0.037 mm, the standard deviation was 0.028 mm, the maximum value was 0.101 mm.

The transition of entropy during estimation of array 1 is shown in Fig. 3c. Red dashed line shows the entropy of reconstructed image using the real shape as an assumed shape. It shows that entropy was almost converged after 50 iterations and the entropy after estimation was lower than the entropy using real shape as assumed shape. Entropies before and after the estimation were 9.219 and 9.133, and the entropy using real shape as assumed shape was 9.143.

Reconstructed images using real, linear, and estimated shape of array 1 are shown in Fig. 3d. Their ROIs are the same as that used for estimation, and the resolution were $100\,pixels \times 100\,pixels$. Images using real shape and estimated shape have clear outlines of circles, although the image using linear shape had blurred and distorted outline of circle.

V. Discussion and Conclusion

In this paper, we proposed a shape estimation algorithm for flexible ultrasonic transducer array. Array shape estimation was based on the entropy of the reconstructed image using an assumed array shape. Four simulation experiments using relatively simple array shapes were conducted to verify the proposed algorithm. Shapes close to real shapes were estimated for all arrays. The average position error of all elements of four arrays between real shapes and estimated shapes was 0.037 mm. It can be said that it is accurate enough to reconstruct images because it is much smaller than half the length of transmitted wave. Quality of the reconstructed images using assumed shape was significantly improved by the estimation of array shape estimation using the proposed algorithm.

On the other hand, real shape and estimated shape were not identical. Furthermore, entropies using estimated shape were lower than that using real shape for all four shapes. From these results, it can be seen that the reconstructed images were sharper using the estimated shape than using the real shape. One possible reason of such mismatch between correctness of assumed shape and sharpness of reconstructed image is the resolution of reconstructed images, because the distance between pixels may affect the sharpness of reconstructed images. Another possible

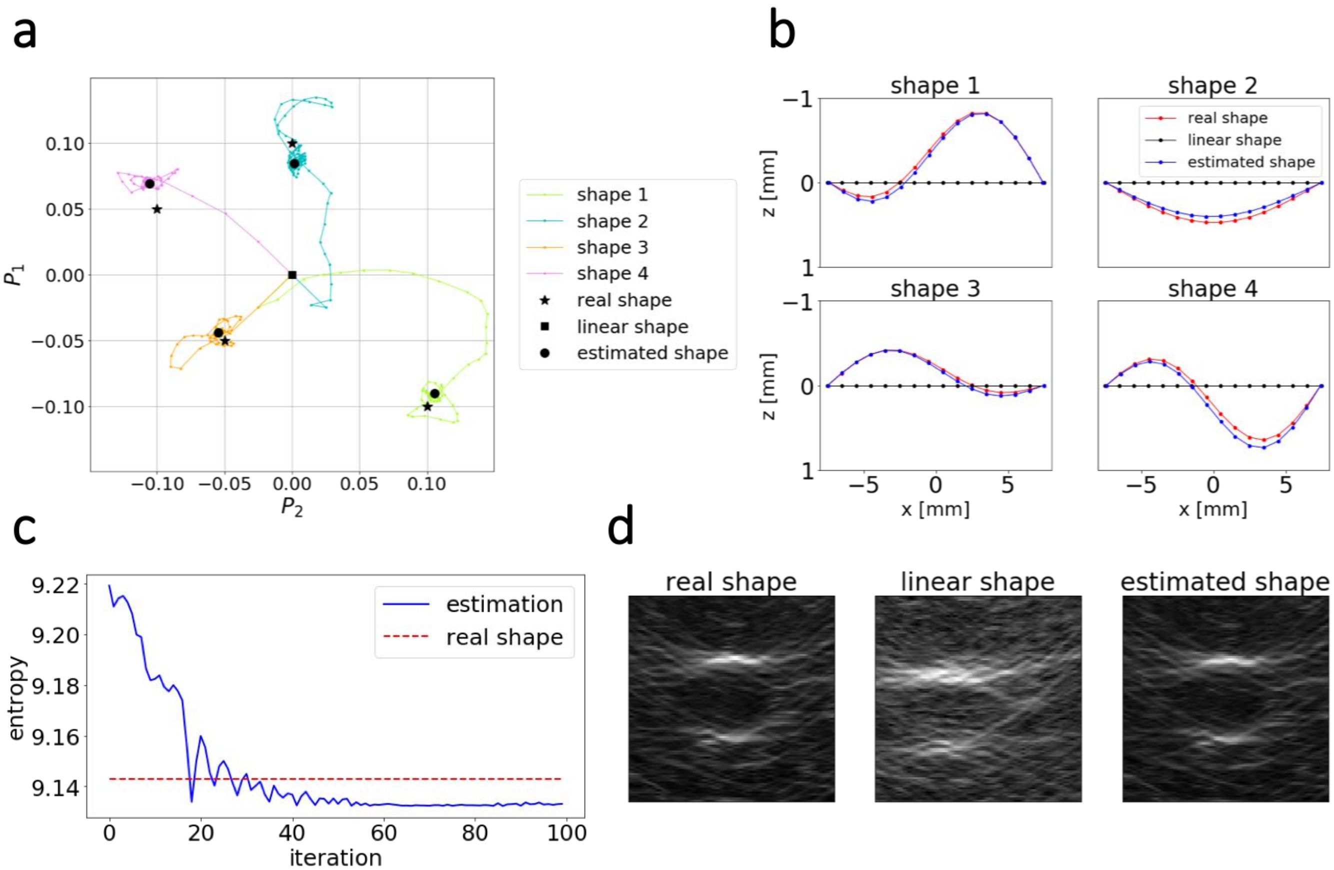

Fig. 3. Results of the simulation experiment: (a)Transition of shape parameters during estimations. Vertical axis: value of shape parameter P_1, Horizontal axis: value of shape parameter P_2;(b)The shape of real array, linear array, and estimated array for each shape estimation; (c)Transition of entropy of reconstructed image during the estimation of shape 1 (solid blue line) and entropy of reconstructed image with real shape 1 (dashed red line); (d)Reconstructed images using real shape, linear shape, and estimated shape as assumed shape.

reason is that point spread function (PSF) of ultrasonic images are not completely correlate with the correctness of array shape. In this case, the quality of ultrasonic images including images taken with a rigid probe can be improved by optimizing shape parameters and minimizing PSF with the proposed algorithm.

There are some limitations of the proposed algorithm. Firstly, the effectiveness was verified only by the simulations whose conditions are more simple than human body. To adapt the algorithm to the conditions of human body such as diffraction, attenuation, and multiple scattering, the algorithm needs to be improved.

Secondly, the array shapes used in the simulations were relatively simple. This time precise array shapes were estimated. However, more shape parameters would be needed to estimate a more complex array shape.

Finally, calculation speed is not enough for real-time monitoring. It takes about 30 seconds to estimate the shape of 16 elements array. To estimate the array shape of more elements in real-time, the algorithm needs to be improved. These limitations will be solved in future work.

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