A High-resolution Imaging Algorithm Based on Scattered Waveform Estimation for UWB Pulse Radar Systems

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Abstract— **Target estimation methods with UWB pulse signals are promising as imaging techniques for household or rescue robots. We have already proposed an efficient algorithm for shape estimation, SEABED(Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves), which is based on a reversible transform BST (Boundary Scattering Transform) between the time delay and the target shape. In this method, we determine quasi wavefronts from received signals with the matched filter of the transmitted waveform. However, the scattered waveform is in general different from the transmitted one depending on the shape of targets. These differences cause estimation errors in SEABED method. In this paper, we propose a high-resolution algorithm for general convex targets based on the scattered waveform estimation, and evaluate the method by numerical simulations.**

Keywords— **UWB pulse radar systems, SEABED, scattered waveform estimation, high-resolution, shape estimation**

I. Introduction

DEVELOPMENT of robot techniques is aiming at advanced robots that can measure surrounding environment. Many imaging methods using optical approach have been proposed. However, passive optical techniques suffer from an insufficient range resolution. On the other hand, radar imaging methods have a high range resolution. They can also estimate object shapes even in the case of a fire where optical methods cannot be used. In addition, radar systems can be applied to in-house human movement detection systems where optical methods are not suitable from the viewpoint of privacy. While many imaging algorithms for radar systems have been proposed [1]-[4], they require intensive computation for a target imaging. To solve this problem, we proposed SEABED [5], [6], and accomplished a fast and nonparametric target imaging. However, the accuracy of this method is limited because it assumes that the scattered waveform is the same as the transmitted one. The resolution of SEABED deteriorates especially around the target edge because of these waveform differences. To solve this problem we propose an estimation method of scattered waveforms from general convex targets. By utilizing scattered waveform estimation, we obtain a high-resolution imaging algorithm with SEABED method. Finally we evaluate the proposed method by numerical simulations.

II. System Model

We show the system model in Fig. 1. We deal with 2-dimensional problems and TE mode waves. We assume a non-dispersive and lossless medium and that a target has a uniform complex permittivity, and surrounded by a boundary which is composed of smooth curves concatenated at discrete edges. We also assume that the propagation speed of the radio wave is known. We utilize a mono-static radar system. An omni-directional antenna is scanned along a straight line. The current at the transmitting antenna is a mono-cycle pulse.

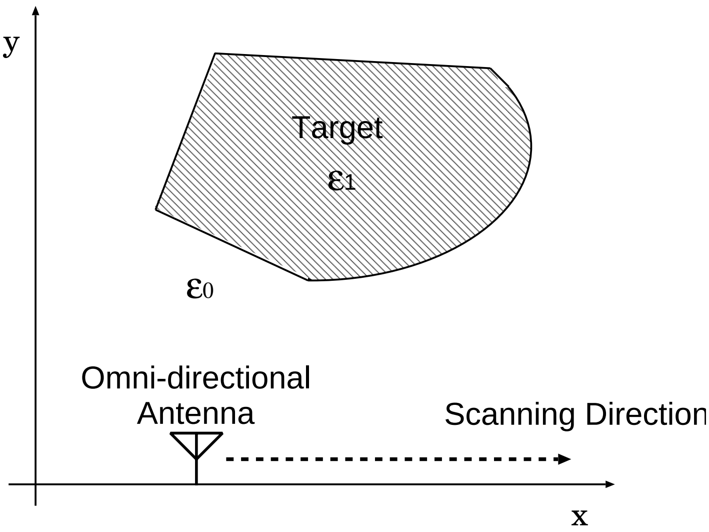

Fig. 1. System model.

We define r-space as the real space, where targets and the antenna are located. We express r-space with the parameter (x, y). Both x and y are normalized by λ, which is the center wavelength of the transmitted pulse in the air. We assume $y > 0$ for simplicity. The antenna is scanned along x-axis in r-space. We define $s'(X, Y)$ as the received electric field at the antenna location $(x, y) = (X, 0)$, where we define Y with time t and speed of the radio wave c as $Y = ct/(2\lambda)$. We apply a matched filter of transmitted or estimated waveform for $s'(X, Y)$. We define $s(X, Y)$ as the output of the filter. We define d-space as the space expressed by (X, Y). The transform from d-space to r-space corresponds to imaging which we deal with in this paper.

III. Conventional method

We have already developed a non-parametric shape estimation algorithm based on BST (Boundary Scattering Transform) [5]. We call the algorithm SEABED (Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves). The algorithm utilizes the existence of a reversible transform BST between target shapes and pulse delays. We have clarified that SEABED has an advantage of direct estimation of target boundaries using inverse transform, which is a mathematically complete solution for the inverse problem.

Inverse Boundary Scattering Transform (IBST) is expressed as

$$x = X - Y\mathrm{d}Y/\mathrm{d}X, \quad (1)$$

$$y = Y\sqrt{1-(\mathrm{d}Y/\mathrm{d}X)^2}, \quad (2)$$

where (X, Y) is a point on a quasi wavefront. (x, y) is a point on a target boundary, and we assume $y > 0$, $Y > 0$ and $|\mathrm{d}Y/\mathrm{d}X| \leq 1$ [5].

The procedures of SEABED is as follows. First, we extract quasi wavefronts from $s(X, Y)$ which is the output of the matched filter with the transmitted waveform. Second, we select the points of quasi wavefronts (X, Y) from the peak of $s(X, Y)$. Finally, we apply IBST to the extracted quasi wavefronts and estimate the target shape.

We show the examples of SEABED. We assume a noiseless environment. The antenna receives the signal at 39 locations with intervals of 0.125λ. Fig. 2 shows the output of the matched filter for the transmitted waveform. We select the points of quasi wavefronts (X, Y) from $s(X, Y)$ as shown in Fig. 3. Then, we transform (X, Y) to (x, y) with IBST and obtain the target boundary in Fig. 4, which is made of 39 estimated points. In this figure, we can recognize estimation errors around the edges of the target. This is because the errors of (x, y) is directly related to the errors of Y which are caused by the differences between the transmitted waveform and the scattered one. Therefore we need to estimate the scattered waveform in order to accomplish a high-resolution shape estimation.

IV. Proposed Method

In this section, we explain the proposed method. In this method, we iterate SEABED and a scattered waveform estimation alternately. First, we explain the fast waveform estimation for the shape estimation. Second, we explain the necessity of the stabilization of the quasi wavefronts and the method for the stabilization. Finally, we show the procedures of the proposed method.

A. Scattered Waveform Estimation

In order to estimate scattered waveforms, many algorithms have been proposed such as FDTD method and the moment method. However these methods require an intensive computation. It is indispensable to utilize a fast waveform estimation method not to spoil the advantage of the quick imaging by SEABED. We have already proposed the fast scattered waveform estimation from a finite plain boundary in 2-dimensional problems [7]. By utilizing this method, the computational time is reduced to within 0.1 second with a Xeon 2.8 GHz processor for each antenna location.

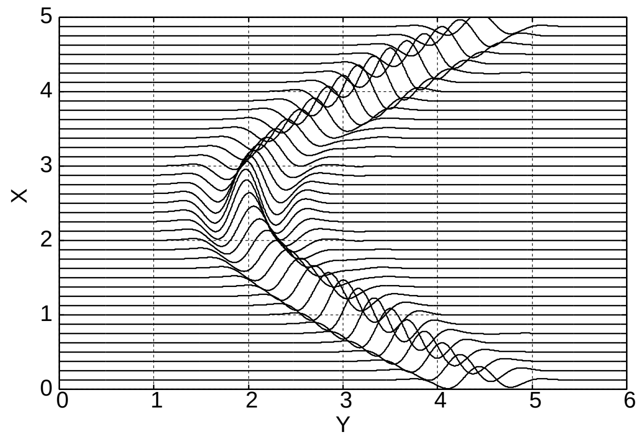

Fig. 2. Output of the matched filter for the transmitted waveform.

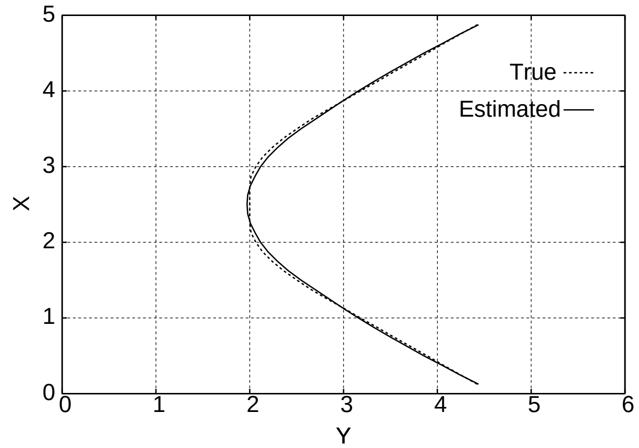

Fig. 3. Extracted wavefronts by the conventional method.

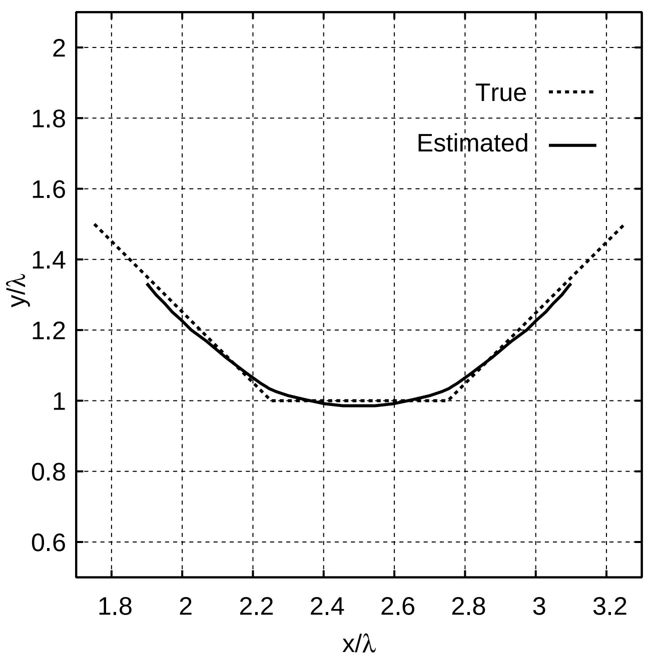

Fig. 4. Estimated boundary with the conventional method.

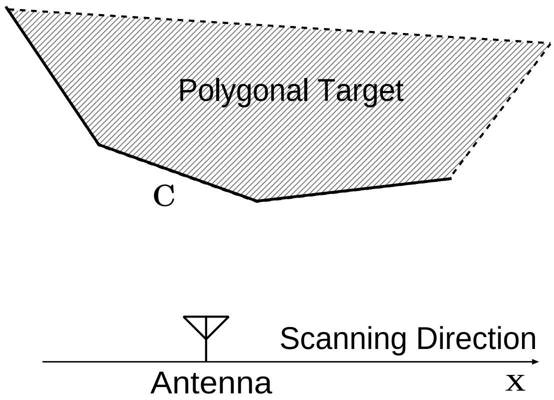

Fig. 5. Arrangement of the antenna and the polygonal target.

We propose the waveform estimation method for a polygonal target with this method. We calculate the transfer function by calculating the integral of the Green's function along the polygonal boundaries which contribute to the scattered wave. By applying this transfer function to the transmitted waveform, we calculate the scattered waveform $F(\omega)$ in the frequency domain approximately as

$$F(\omega) \quad = \quad \sqrt{\frac{\mathrm{j}k}{2\pi}} E_0(\omega) \int_C g \ \mathrm{d}s, \tag{3}$$

where C is the integration path of the plain boundaries of the polygon, k is the wavenumber, $E_0(\omega)$ is the transmitted waveform with the opposite sign in the frequency domain, and g is the 2-dimensional Green's function expressed as the 0th order Hankel's function of the 2nd kind. This method can deal with an arbitrary shape with a polygon approximation. Fig. 5 illustrates the locations of antenna and polygonal target.

In the proposed method, we approximate the estimated target as a polygon which is applicable for the scattered waveform estimation. We utilize the matched filter with the estimated waveform in each antenna location and update the quasi wavefronts.

B. Quasi Wavefronts Stabilization

In this section, we explain the quasi wavefronts stabilization. In the proposed method, we update Y and $\mathrm{d}Y/\mathrm{d}X$ from the updated quasi wavefronts for IBST. The shape estimation is sensitive to the errors of Y and $\mathrm{d}Y/\mathrm{d}X$ because they are directly related to (x, y) in IBST. We confirm that these errors degrade the estimated image. Therefore, we need to stabilize the updated quasi wavefronts to suppress these divergence. To stabilize the quasi wavefronts, we do not update the Y or $\mathrm{d}X/\mathrm{d}Y$ at X in the case that the difference from the previously estimated Y or $\mathrm{d}X/\mathrm{d}Y$ is larger than a threshold, respectively. This threshold is determined empirically.

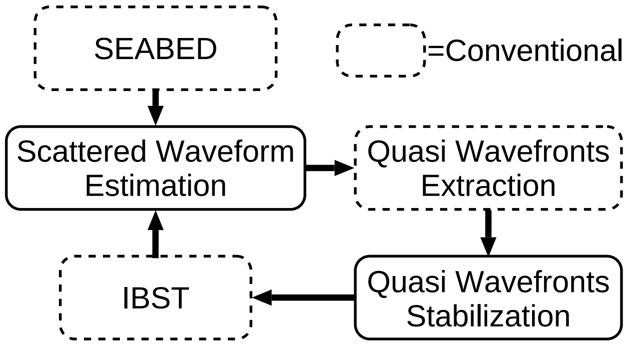

Fig. 6. Flowchart of the proposed method.

C. Procedures of The Proposed Method

Here we show the procedures of the proposed method.

Step 1). Estimate the target shape by SEABED with the matched filter for the transmitted waveform. Approximate the target shape as the polygon which is made by connecting the estimated points by straight lines.
Step 2). Estimate the scattered waveform from the estimated polygon and update the matched filter for the estimated waveform.
Step 3). Extract the quasi wavefronts from the output of the updated matched filter.
Step 4). Stabilize the updated quasi wavefronts.
Step 5). Apply IBST to the updated quasi wavefronts and update the target shape as polygon.
Step 6). Iterate Step 2) - 5) for M times.

By this procedure, the estimated waveform approaches to the true one. This improvement can enhance the accuracy and the resolution of the target shape. Fig. 6 shows the flowchart of the proposed method.

V. Performance Evaluation

In this section, we evaluate the performance of the proposed method. Fig. 7 shows the scattered waveform and the estimated one at $x = 2.0\lambda$ after 5 iterations, where the antenna mainly receives the edge diffraction wave. As shown in this figure, we confirm that the proposed method accomplish much higher accuracy in waveform estimations than the conventional SEABED, which assumes the transmitted waveform. Fig. 8 and 9 show the output of the matched filter with the estimated waveform and the extracted wavefronts from $s(X, Y)$ after 5 iterations, respectively. We accomplish the 5 times improvement in the estimation accuracy of the quasi wavefronts than the conventional method. Fig. 10 shows the estimated boundaries with the proposed method. In this figure, the estimated boundary can precisely express the true boundaries even at the edges. The estimated accuracy of the edge position is within 0.01λ, which is 10 times more accurate than the conventional method.

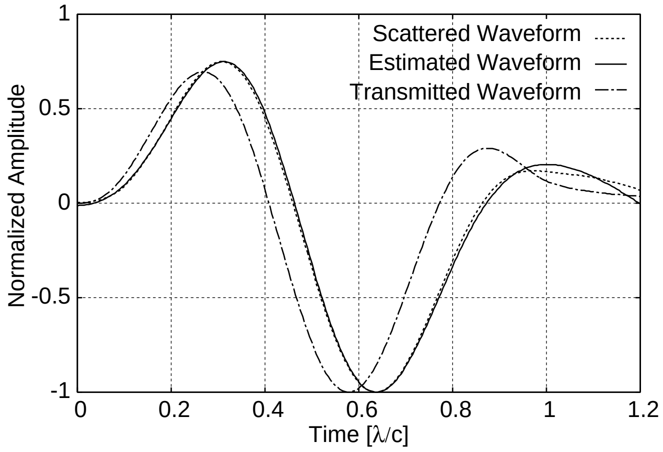

Fig. 7. Scattered waveform and estimated one.

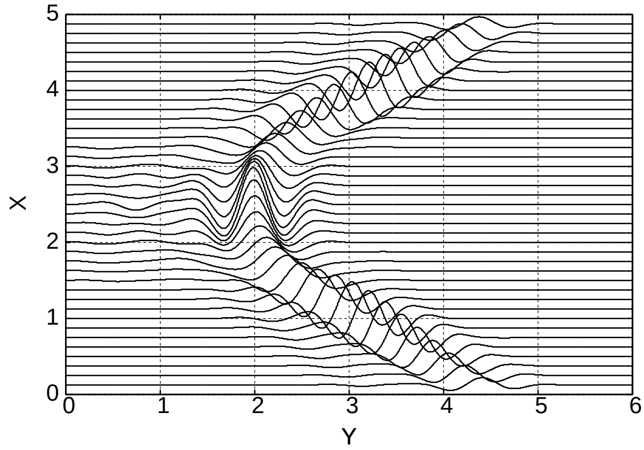

Fig. 8. Output of the matched filter for the estimated waveform.

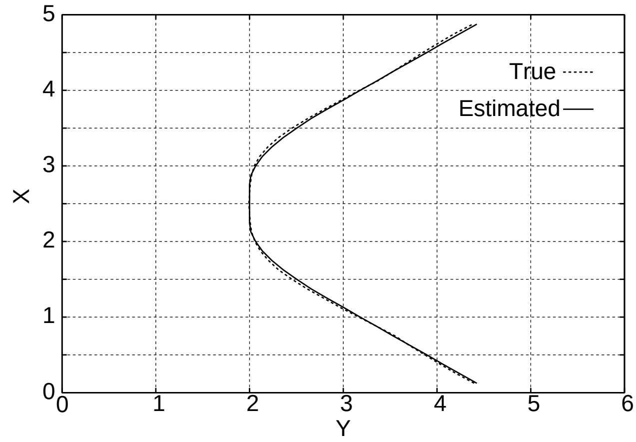

Fig. 9. Extracted wavefronts by the proposed method.

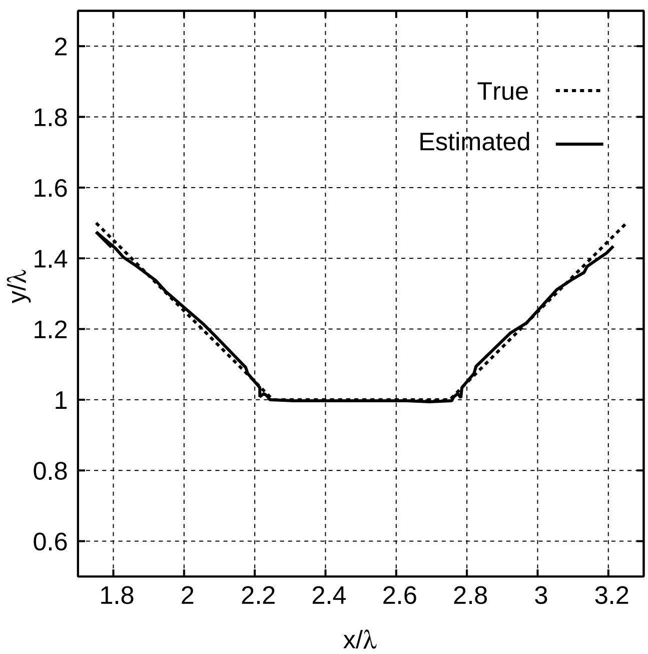

Fig. 10. Estimated boundary with the proposed method.

VI. Conclusion

We proposed a high-resolution imaging algorithm by iterating SEABED and the scattered waveform estimation alternately. We clarified the problem of SEABED in the estimation accuracy for the target boundary and the necessity of the scattered waveform estimation. We proposed the scattered waveform estimation for polygonal targets and the quasi wavefronts stabilization. We also showed the procedures of the proposed method. Finally we evaluated the performance of our proposed method. We accomplish the estimation accuracy for the edge position within 0.01λ. This is 10 times better than the conventional method.

We plan to expand the proposed method to an arbitrary target in a 3-dimensional problem.

Acknowledgment

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