High-Speed UWB Radar Imaging Algorithm for Complex Target Boundary without Wavefront Connections

Shouhei KIDERA[1], Takuya SAKAMOTO[1] and Toru SATO[1]
[1] Dept. of Commnucations Computer Engineering, Graduate School of Informatics,
Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto, 606-8501, Japan
Email:kidera@aso.cce.i.kyoto-u.ac.jp

Abstract

UWB radar is promising for near field measurements, such as non-contact measurement for reflector antennas. In our previous work, we developed stable imaging algorithm Envelope, that uses envelopes of circles. For complex targets, however, the image with Envelope becomes unstable, because it requires connections of peaks of the observed data. This connection is sometimes difficult due to multiple scatterings, that leads to non-negligible errors in imaging. This paper proposes a new imaging algorithm that utilizes fuzzy estimation for direction of arrival (DOA). It achieves direct boundary extractions with observed delays, and resolves the instability of the conventional method.

1 Introduction

UWB pulse radar has a great potential for high-range resolution imaging for near field sensing, such as target identification and self positioning for robots or vehicles. Although various kinds of radar algorithms have been proposed, these all require intensive computation [1]. Contrarily, the high-speed imaging algorithm, SEABED [2] achieves a direct and non-parametric imaging based on a reversible transform BST between the time delay and target boundary. However, the estimated image with SEABED is sensitive to random noises because BST utilizes the derivative of the received data. To enhance the stability, we have proposed a robust, fast imaging algorithm known as Envelope [3]. This method does not require derivative operations to create a stable image, but instead uses an envelope of circles that are determined with antenna locations and observed ranges. It accomplishes a stable imaging for simple boundary targets. However, for complex boundaries, the obtained image with Envelope is still unstable, because it requires a connecting procedure for the observed ranges for each antenna location. In general, a complex target has many scattering points on its surface, and it is quite difficult to extract an appropriate wavefront due to the multiple scatterings. In this paper, we propose a new imaging algorithm based on a direct mapping from the estimated ranges to the target boundary without the wavefront connection. This algorithm utilizes a fuzzy estimation for the angle of arrival with signal amplitudes, and realizes a stable imaging even for complex target boundaries. Finally, the results from numerical simulations prove that our proposed method has a clear advantage over the conventional algorithms.

2 System Model

The left hand side of Fig. 1 shows the system model. It assumes that the target has an arbitrary shape with a clear boundary, and that the propagation speed of the radio wave is a known constant. An omni-directional antenna is scanned along the x-axis. We utilize a UWB pulse as the transmitting current. R-space is defined as the real space where the target and antenna are located, and is expressed by the parameter (x, z). These parameters are normalized by λ, which is the center wavelength of the pulse. We assume $z > 0$ for simplicity. $s(X, Z')$ is defined as the output of the Wiener filter to the received electric field at the antenna location $(x, z) = (X, 0)$, where $Z' = ct/(2\lambda)$ is expressed by the time t and the speed of the radio wave c. We connect the significant peaks of $s(X, Z')$ as Z, and call this surface (X, Z) a quasi wavefront. D-space is defined as the space expressed by (X, Z). The transform from d-space to r-space corresponds to the imaging dealt with in this paper.

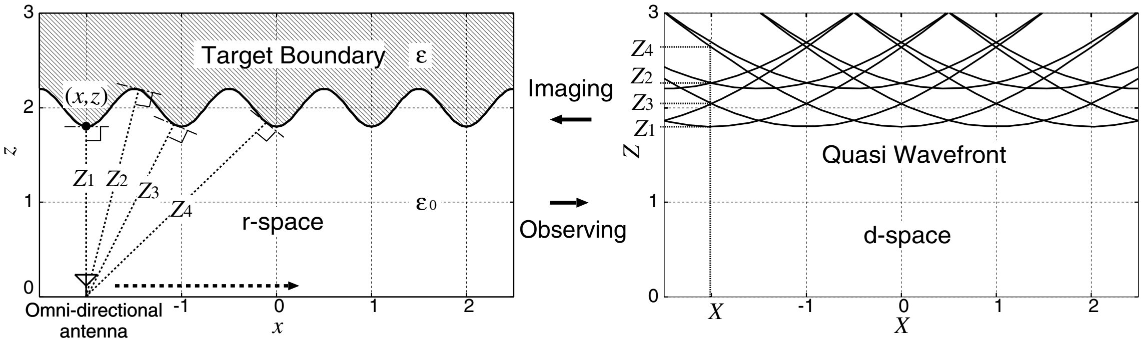

Figure 1: Target boundary in r-space (left) and quasi wavefront in d-space (right).

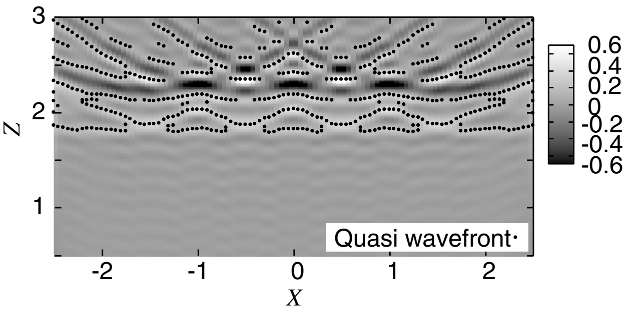

Figure 2: Output of the Wiener filter and extracted quasi wavefront.

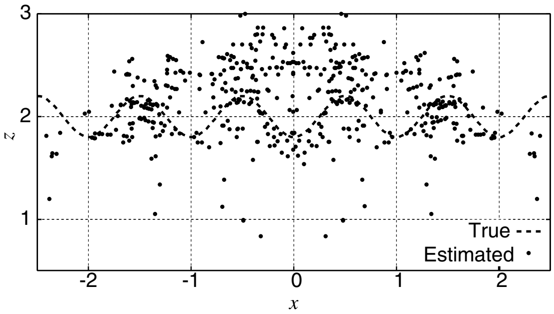

Figure 3: Estimated image with the conventional SEABED.

3 Conventional Algorithm

In our previous work, we proposed the high-speed imaging algorithm SEABED that utilizes a reversible transform BST between the target boundary (x, z) and the quasi wavefront (X, Z) [2]. Inverse BST is expressed as $x = X - Z\partial Z/\partial X,\ z = Z\sqrt{1-(\partial Z/\partial X)^2}$. This transform gives us a strict solution for the assumed inverse problem, and realizes a direct, non-parametric imaging. However, it produces large errors in targets with complex boundaries. Fig. 2 shows the output of the Wiener filter for the target boundary shown in Fig. 1. Fig. 3 shows the estimated image with SEABED. This image from SEABED is unstable, because BST utilizes the derivative of the quasi wavefront, and the fluctuation caused by multiple scattering can be enhanced with a derivative. Thus, for a complex target boundary, it is difficult to estimate a derivative for each quasi wavefront accurately.

To improve the stability of the estimated image, Envelope has been proposed as a stable and fast imaging algorithm without derivative operations. This algorithm utilizes the principle that the target boundary can be expressed as the envelope of circles, with a center point $(X, 0)$, and radius Z [3]. This principle introduces that these envelopes should circumscribe or inscribe to the target boundary. This method approximates the target region (x, z) for each (X, Z) as

$$\left.\begin{array}{c} \displaystyle\max_{\nu_X(X'-X)<0} x_{\rm p}(X') \le x \le \min_{\nu_X(X'-X)>0} x_{\rm p}(X') \\ z = \sqrt{Z^2-(x-X)^2} \end{array}\right\}, \tag{1}$$

where $\nu_X = {\rm s}gn(\partial x/\partial X)$, and X' is a searching variable, and $x_{\rm p}(X')$ is defined as the intersection point between the circles calculated with (X, Z) and (X', Z'). Eq. (1) determines an arbitrary target boundary without derivative operations. Thus, the instability caused by random noise is suppressed. However, for a complex boundary, the image with Envelope is still unstable as shown in Fig. 4. This is because Envelope requires an appropriate connection between the estimated range

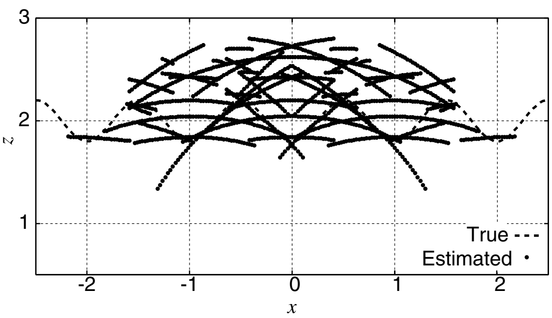

Figure 4: Estimated image with the conventional Envelope.

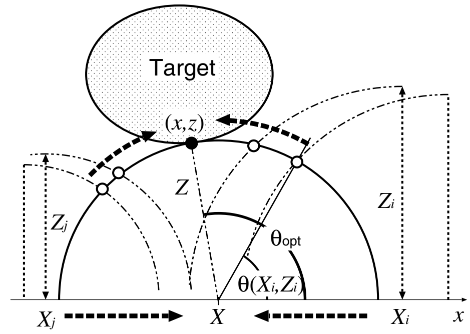

Figure 5: Angle of the arrival and convergence orbit of the intersection points.

points for a stable imaging. Complex targets, in general, have many scattering points on their surface, and each antenna observes many ranges. Thus, it is quite difficult to extract a correct quasi wavefront because each point on (X, Z) has multiple connecting candidates around itself. If this connection fails, the estimated image with Envelope includes non-negligible errors due to using the incorrect envelope of circles. Although the imaging algorithms with data synthesis or the Fourier transform do not require wavefront connections, we confirm that these all require intensive calculation.

4 Proposed Algorithm

This section describes a new imaging algorithm for complex target boundaries that resolves the previous problems. This algorithm is based on the simple principle that a target boundary point should exist on the circle with center $(X, 0)$ and radius Z. Thus, each target point (x, z) can be calculated from the angle of the arrival. For a stable angular estimation, this method utilizes the membership function $f(\theta, X_i, Z_i)$ as,

$$f(\theta, X_i, Z_i) = \mathrm{e}^{-\dfrac{\{\theta - \theta(X_i, Z_i)\}^2}{2\sigma_{\theta^2}}}, \tag{2}$$

where $\theta(X_i, Z_i)$ is defined as the angle of the intersection point between the circles with (X, Z) and (X_i, Z_i). Fig. 5 shows the relationship between the intersection point and $\theta(X_i, Z_i)$. Here, we utilize the principle that when (X_i, Z_i) moves along an appropriate quasi wavefront, $\theta(X_i, Z_i)$ converges to the true angle of arrival. The convergence orbit for the intersection points is shown in Fig. 5. This method calculates the optimum angle for each (X, Z) with signal amplitude $s(X_i, Z_i)$ as,

$$\theta_{\mathrm{opt}} = \arg\max_{\theta} \left\{ \sum_i s(X_i, Z_i) f(\theta, X_i, Z_i) \ \ \mathrm{e}^{-\frac{(X-X_i)^2}{2\sigma_X^2}} \right\}, \tag{3}$$

where σ_θ and σ_X are constants, that are empirically determined. The weight $s(X_i, Z_i)$ in Eq. (3) improves the noise tolerance. This method realizes the direct transform from the points of (X, Z) to the points of (x, z) without a wavefront connection. Thus, the instability caused by inappropriate connections can be suppressed with this method. For the target with a large curvature, such as point, each $s(X_i, Z_i)$ is smaller, however, $\sum_i f(\theta, X_i, Z_i)$ becomes larger because the intersection points converge into a small region. This algorithm can therefore obtain a stable image for complex target that have many boundaries with large curvatures.

The procedure for the proposed method is presented as follows.
Step 1). Extract quasi wavefront (X, Z), that satisfies $\partial s(X, Z')/\partial Z' = 0, s(X, Z') \geq \alpha \max_{Z'} s(X, Z')$. Parameter α is determined empirically.
Step 2). For each (X, Z), calculate $f(\theta, X_i, Z_i)$ with other points (X_i, Z_i) and determine θ_{opt} in

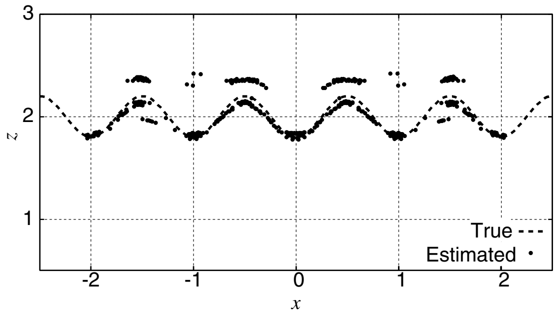

Figure 6: Estimated image with the proposed method.

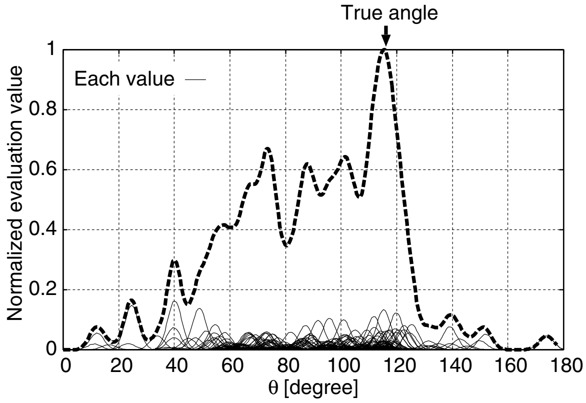

Figure 7: Example of the evaluation value in Eq. (3) at $(X, Z) = (-0.01, 2.025)$.

Eq. (3).
Step 3). Calculate each target point (x, z) as $x = X + Z\cos\theta_{\rm opt}, z = Z\sin\theta_{\rm opt}$
The proposed method achieves a direct mapping from the quasi wavefront (X, Z) to the target boundary (x, z) using this simple procedure.

5 Simulation Results and Conclusions

Fig. 6 shows the estimated image with the proposed method for the data in Fig. 2. A noiseless situation is assumed. $\sigma_X = 1.0\lambda$ and $\sigma_\theta = \pi/50$ are set. This result verifies that the proposed method enhances the stability of the estimated image significantly, even for a complex target boundary. Fig. 7 shows the example of the evaluation value in Eq. (3) at $(X, Z) = (-0.01, 2.025)$. We can recognize a maximum peak around the true angle, even for the situation that there are many connecting candidates around (X, Z). This is because it achieves a direct mapping from the quasi wavefront to the target boundary with the fuzzy function and signal amplitudes. Thus, it can suppress the errors for inappropriate connections. We confirm that the proposed method obtains a stable and correct target image for S/N $\geq$ 20 dB. The result also proves that the calculation time of the proposed method is within 0.2 sec with a Xeon 2.8 GHz, which is sufficient for real-time operation. We also confirm that this algorithm achieves a stable imaging, where multiple boundaries with large or small curvatures are intermingled, such as in plate and point targets. However, it is difficult for this method to achieve a stable imaging for more complex target boundaries, where multiple echoes cannot be resolved due to bandwidth limitations. Consequently, our future research is aimed at enhancing the application range of this method.

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