A High-Resolution Imaging Algorithm for Complex-Shaped Target Shapes by Optimizing Quasi-Wavefronts

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INTRODUCTION UWB(Ultra-Wide Band) radar is promising for sensors in robotics and security systems because of its high-resolution capability. Many algorithms have been proposed for UWB radar imaging [1, 2, 3, 4, 5], but they take too long time to apply to imaging for robotics. SEABED, a fast imaging method for UWB pulse radar, can obtain a target image within a short time by using a reversible transform between the target shape and the equi-phase curve of the received data [6, 7, 8, 9]. This equi-phase curve is called a quasi-wavefront, and the SEABED algorithm relies on accurate estimation of the quasi-wavefronts. For multiple targets and complex-shaped targets, however, scattered signals can interfere one anoother, making it difficult to estimate the quasi-wavefronts accurately. In this paper, we introduce an optimization for estimating quasi-wavefronts, and propose a high-resolution imaging algorithm that works even with multiple and complex-shaped targets.

SEABED ALGORITHM AND QUASI-WAVEFRONTS For simplicity, we make use of a 2-dimensional problem in this paper, where the objective is to estimate the target shapes. We assume a monostatic radar system, that uses an omni-directional antenna and where we measure the range between the scattering center and each antenna position. A fast IBST (Inverse Boundary Scattering Transform) based radar imaging algorithm has already been developed [6]. This algorithm is known as SEABED (Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves), and uses the existence of a reversible IBST between the target shapes and pulse delays. SEABED takes advantage of the direct estimation of target boundaries using an inverse transform, a mathematically complete solution for the inverse problem as shown in [9]. It is assumed that each target has a uniform complex permittivity, and is surrounded by a clear boundary. It is also assumed that the propagation speed is known. Here, for simplicity, we assume that the medium of the direct path is a vacuum.

The distance Y between the scattering center (x, y) and the antenna $(X, 0)$ is easily obtained from UWB radar. The curve of the relationship between X and Y is called a 'quasi wavefront'. As stated above the IBST is given by

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

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

In the SEABED algorithm, quasi-wavefronts are first extracted from the received signals $s(X, Y)$, and then the IBST is applied to these quasi wavefronts to obtain the final image. The conventional SEABED algorithm extracts the quasi-wavefronts (X, Y) by connecting the waveform peaks of the received signal $s(X, Y)$. For multiple and complex-shaped targets, however, scattered signals interfere with each other, making it difficult to estimate the quasi-wavefronts accurately.

PROPOSED ALGORITHM FOR INTERFERED SIGNALS Hantscher et al.[10]

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proposed an iterative subtraction method, that estimates the delay for the maximum peak of $s(X,Y)$ for each X, and subtracts an assumed waveform from $s(X,Y)$ with this estimated delay. This procedure is repeated with the residual signal after the subtraction. This method, however, does not work if the interference condition is severe because the estimated delay may be different to the true one.

To estimate quasi-wavefronts accurately, we assume a scattered waveform as did Hantscher et al., but introduce the optimization criteria of minimizing the evaluation function $e(V)$ as

$$e(V)=\int\!\!\int\left|s(X,Y)-\sum_{i=1}^{N}p(Y-q(X,\boldsymbol{v}_i))\right|^2 \mathrm{d}X\mathrm{d}Y, \tag{3}$$

where N is the assumed number of wavefronts, and $p(Y)$ the assumed scattered waveform. V is a parameter matrix that determines quasi wavefronts, and is defined as $V = [\boldsymbol{v}_1, \boldsymbol{v}_2, \cdots \boldsymbol{v}_N]$ with the vector $\boldsymbol{v}_i$ $(i = 1, 2, \cdots, N)$ that determines the i-th quasi-wavefront $q(X,\boldsymbol{v}_i)$. Here, points $(X_1, Y_{i,1}), (X_2, Y_{i,2}), \cdots, (X_M, Y_{i,M})$ are on a curve $q(X,\boldsymbol{v}_i)$ for $\boldsymbol{v}_i = [Y_{i,1}, Y_{i,2}, \cdots, Y_{i,M}]^{\mathrm{T}}$, which is calculated using B-spline interpolation of the 3rd order. $X_1, X_2, \cdots, X_M$ are fixed antenna positions located at equal intervals in an actual antenna scanning range $X_{\min} \le X \le X_{\max}$. This method decreases the dimension of variables for the optimization problem by expressing a general curve with M discrete points. This is because a quasi-wavefront for a convex target is naturally smooth regardless of the target shape.

A random search algorithm is adopted for the optimization in Eq. (3). Randomly selected $m(0 < m < M)$ elements in $\boldsymbol{v}_i$ are replaced by random numbers with a uniform distribution in $0 \le Y \le 3$, for randomly selected i with a probability of 25%, where m is also selected with a uniform distribution each time. Every element $Y_{i,j}$ of parameter matrix V is replaced by a random number with a uniform distribution for a probability of 2%. In addition, some elements of $\boldsymbol{v}_i$ and $\boldsymbol{v}_j$ are exchanged, which is called crossover, with probability of 2%. In this crossover, $Y_{i,l\le k}$ and $Y_{j,l\le k}$ are exchanged for uniformly selected random numbers $0 < i < N$, $0 < j < N$ and $0 < k < M$. This crossover operation is similar to a GA (Genetic Algorithm), which is critical to avoid a local minimum.

CONVENTIONAL IMAGING PERFORMANCE A true target shape, as in Fig. 1, is assumed, and the imaging capability of the conventional SEABED algorithm is tested with this assumed shape. Fig. 2 shows the received signals $s(X,Y)$ obtained by scanning the antenna along the x axis. Here, a scattered waveform is assumed to be a mono-cycle pulse, and geometrical optical scattering with Born approximation is also assumed. The signal-to-noise ratio (S/N) is 35dB. In this figure, a true quasi-wavefront is shown as a dashed line. The distance between quasi-wavefronts is shorter than the wavelength, making it difficult to distinguish peaks that corresponds to true quasi-wavefronts.

Circles in Fig. 3 show the estimated quasi-wavefronts for the conventional SEABED algorithm. This conventional SEABED algorithm simply connects the signal peaks to estimate a quasi-wavefront. This does not, however, work in this case because of the waveform interference. The estimated image from the conventional SEABED algorithm is shown in Fig. 4. Target shape estimation using the SEABED algorithm does not work at all as a result of an error in the extraction process of quasi-wavefronts as shown in this figure.

PROPOSED IMAGING PERFORMANCE We applied the proposed algorithm to the same signals as described in the previous section. Here, we assume the number of quasi-wavefronts is known and is $N = 4$. The number of iterations is 40000, and we confirm that the normalized evaluation value of the evaluation function is 0.2% at the 40,000-th iteration.

Here, the normalized evaluation value means normalizing the evaluation value by the initial evaluation value. Fig. 5 shows the estimated quasi-wavefronts using the proposed method, and these are almost correctly estimated using the proposed method. The estimated target shape using the proposed method is shown in Fig. 6. The proposed method can estimate multiple targets located closely, which means that super high-resolution is achieved. It remains as an important future study to decrease the number of iterations necessary to achieve both high-resolution and speed.

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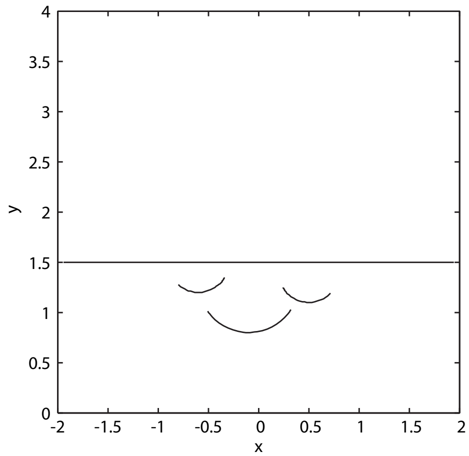

Figure 1: Assumed true target shape.

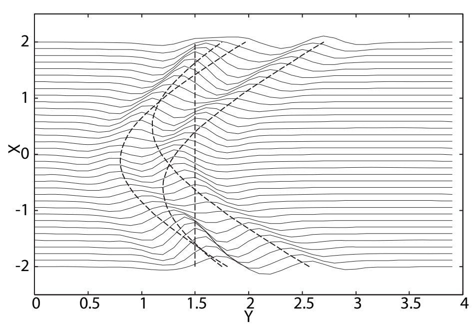

Figure 2: Received signals and true quasi-wavefronts.

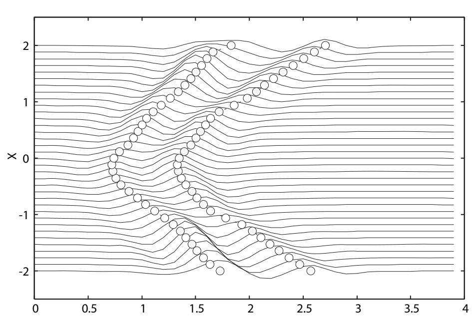

Figure 3: Estimated quasi-wavefronts with conventional method.

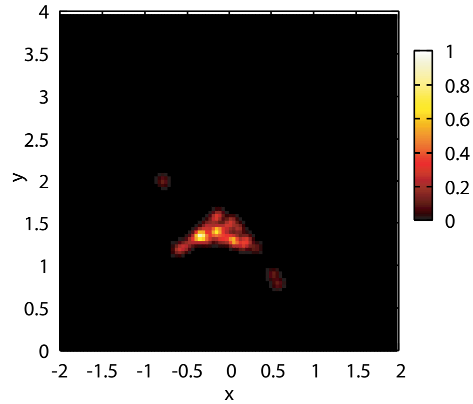

Figure 4: Estimated target shape with conventional method.

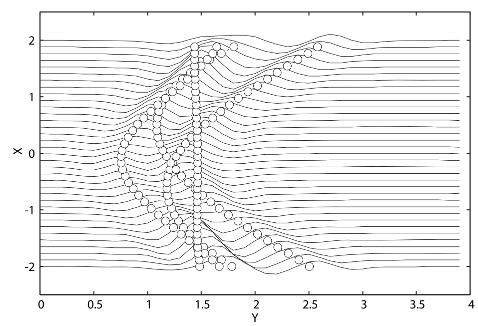

Figure 5: Estimated quasi-wavefronts with proposed method.

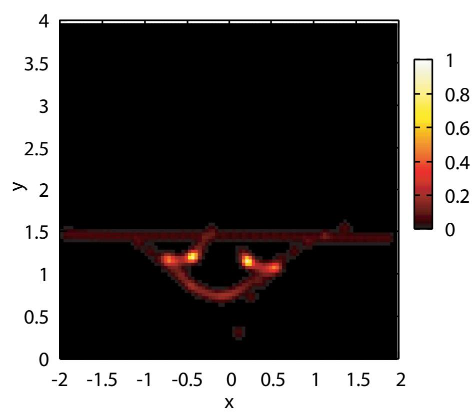

Figure 6: Estimated target shape with proposed method.