A high-resolution imaging algorithm without derivatives based on waveform estimation for UWB pulse radars

Shouhei KIDERA*, Takuya SAKAMOTO and Toru SATO
Graduate School of Informatics Kyoto University, Japan
Email:kidera@aso.cce.i.kyoto-u.ac.jp

1 Introduction

UWB pulse radars are promising as high-resolution imaging techniques, which are required for target positioning systems of rescue robots moving in a dark smoke. It can be also applied to a non-destructive measurement for industrial products (e.g. antennas and vehicles), in order to detect small surface defects. These applications require a fast, robust, and high-resolution imaging algorithm. We have already proposed a robust and fast imaging algorithm with an envelope of circles [1, 2]. This method utilizes the principle that the target boundaries are expressed as the envelopes of the circles with the radius of the time delays. Our method can realize robust imaging even in a noisy environment. However, the error of the estimated image is at least about 1/10 of the center wavelength of the pulse because the image is distorted especially around sharp edges. This is because we assume that the scattered waveform is the same as the transmitted one. In this paper, we utilize the shape estimation method together with a waveform estimation in order to enhance the resolution of the image. An imaging algorithm based on this idea has been published [3]. However, the earlier study utilizes a parametric approach and can be applied only to a simple polygon. In this paper, we extend this idea to general convex targets including smooth curves and edges. Numerical simulations and experiments show that the proposed method accomplishes a high-resolution imaging.

2 System Model

We deal with 2-dimensional problems and TE mode waves. We assume that the target has a convex shape, and surrounded by a clear boundary which is composed of smooth curves concatenated at discrete edges. We assume that the propagation speed of the radiowave is constant and known. We utilize a mono-static radar system. The left side of Fig.1 shows the system model. The r-space is expressed with the parameters (x, y). An omni-directional antenna is scanned along x axis in the r-space. Both x and y are normalized by λ, which is the center wavelength of the transmitted pulse. We define $s'(X, Y)$ as the electric field received at the antenna location $(x, y) = (X, 0)$, where Y is defined with the arrival time of the echo t and speed of the radio wave c as $Y = \mathrm{c}t/(2\lambda)$. The matched filter is applied with the transmitted or the estimated waveform to $s'(X, Y)$. We define $s(X, Y)$ as the output of the filter. We define the d-space as the space expressed by (X, Y), and call it a quasi wavefront. The transform from (X, Y) to (x, y) corresponds to imaging which we deal with in this paper.

3 Conventional method

We have already revealed that there is a reversible transform between a point on the target boundary (x, y) and a point on the quasi wavefront (X, Y) [1]. We call this transform BST (Boundary Scattering Transform). IBST (Inverse BST) is expressed as $\left.\begin{array}{rcl} x & = & X - Y\mathrm{d}Y/\mathrm{d}X \\ y & = & Y\sqrt{1-(\mathrm{d}Y/\mathrm{d}X)^2} \end{array}\right\}$. By utilizing BST, it has been proved that points on the target boundary should be expressed as points on the envelope of circles with the radius of Y and the center $(X, 0)$ for the quasi wavefront [2]. Fig. 1 shows the relationship between a quasi wavefront and an envelope of circles. This relationship enables us to estimate the convex targets including edges with the following procedure. We utilize the matched filter with the transmitted waveform, and obtain the output $s(X, Y)$. We extract a quasi wavefront as (X, Y) by connecting the peak of $s(X, Y)$. Then we calculate the estimated shape as $y = \max_X \sqrt{Y^2 - (x - X)^2}$ for each x. The left-hand side of Fig. 2 presents the applied example of this method. The estimated image is distorted, and target boundaries cannot be correctly identified. The error around the edges is approximately 0.07λ. This is because of the waveform distortion, which is not negligible around the edges.

4 Proposed Method

We propose an imaging algorithm with a scattered waveform estimation to enhance the resolution of the image. We calculate the transfer function with the integral of the Green's function along target boundaries which dominantly contribute to the scattering. The scattered waveform $F(\omega)$ in the frequency domain is approximated as $F(\omega) = \sqrt{\frac{\mathrm{j}k}{2\pi}} E_0(\omega) \int_C g(2\rho)\ \mathrm{d}s$, where C is the integration path, ρ is the distance between the antenna and the target boundary, $E_0(\omega)$ is the transmitted waveform in the frequency domain. Though this method is not a strict solution for the scattered waveforms, the accuracy is sufficient for our application. We explain the actual procedures of the proposed method as follows. We define $X_{\max}$ and $X_{\min}$ as maximum and minimum X, respectively

Step 1). Estimate an initial shape with the conventional method.

Step 2). Calculate the scattered waveform with the estimated image, and update the matched filter.

Step 3). Extract the quasi wavefronts with the output of the updated matched filter.

Step 4). Evaluate the updated quasi wavefront with the evaluation value as $\Delta Q_i = \int_{X_{\min}}^{X_{\max}} |Y_i(X) - Y_{i-1}(X)|\ \mathrm{d}X/(X_{\max} - X_{\min})$, where $Y_i(X)$ is defined as an estimated quasi wavefront for the i th iteration.

Step 5). The following equation is applied, $\Delta Q_i < \left\{\begin{array}{cc} \epsilon & (i = 1), \\ \Delta Q_{i-1} & (i \geq 2). \end{array}\right.$

If the equation holds true, we estimate the target shape with the updated quasi wavefronts, and return to the Step 2). Otherwise, we complete the shape estimation. We set ϵ empirically. The estimated waveform approaches to the true one by this procedure. This improvement can enhance the resolution of the target shape.

5 Performance evaluation

We show the applied examples with numerical simulations as follows. $\epsilon = 0.01\lambda$ is set empirically, and the number of the iteration is 4. The left-hand side of Fig. 2 shows the estimated image with the proposed method. The resolution of the target boundary, including the edges, is remarkably higher compared to the conventional method. In addition, the estimated error at the edge is within 0.01λ, which is 7 times improvement than the conventional method. Furthermore, we investigate the performance of our algorithm with the experiments. The target is made of stainless steel sheet. Fig. 3 shows the arrangement of the pair antennas and the target in the real environment. We utilize the UWB pulses with the center frequency of 3.3 GHz and the 10dB bandwidth of 2.0 GHz. The direction of the linear polarimetry axis of the antenna is along the z axis. We utilize two antennas whose separation in x-direction is 76 mm. The antenna pair are scanned for the range of -200 mm $\leq x \leq 200$ mm. In the bi-static model, the target boundary is estimated with the envelope of the ellipses which utilize the location of the transmitted and received antenna as the focus. We obtain the data for 2-dimensional problem with the same approach in [3]. Fig. 4 shows the observed signals with our experiment, where S/N is 35.0 dB. The left and right-hand side of Fig. 5 show the estimated images with the conventional and the proposed method, respectively. The number of iterations is 5, and the calculation time for this method is 2.0 sec with Xeon 3.2 GHz processor. The estimated image with the conventional method does not have sufficient resolution around the edges. In contrast, the proposed method obtains more higher-resolution image than the conventional method, especially around the edges. However, the image around the edges deteriorates compared with the right-hand side of Fig.2. This is because we cannot completely eliminate the direct wave and the undesirable echoes from other objects. To enhance the resolution of this region, data with higher S/N and S/I are needed.

6 Conclusion

We proposed a high-resolution imaging algorithm by simultaneously estimating the target shape and scattered waveform. We clarify that the proposed method achieves a high-resolution imaging with numrical simulations and experiments. The error of the estimated image is within 0.01λ, which cannot be obtained with the conventional algorithms.

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References

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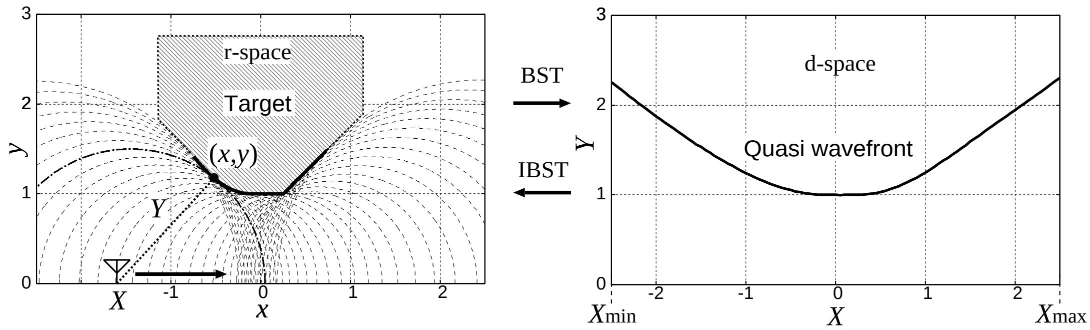

Figure 1: Target boundary and an envelope of circles in r-space (Left) and quasi wavefront in d-space (Right).

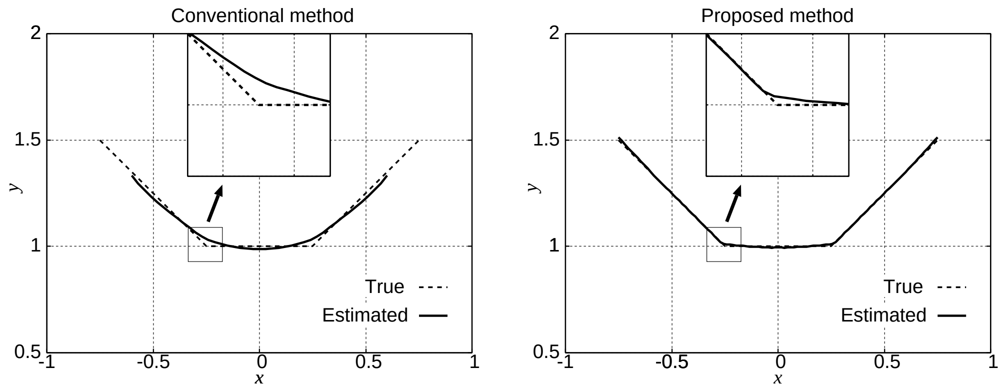

Figure 2: Estimated image with the conventional method (Left) and the proposed method (Right).

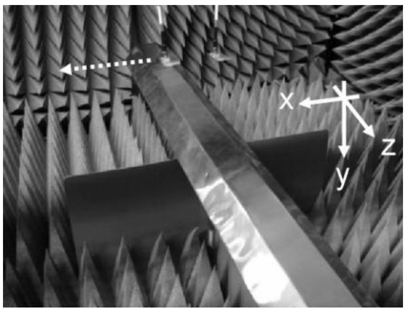

Figure 3: Arrangement in experiments.

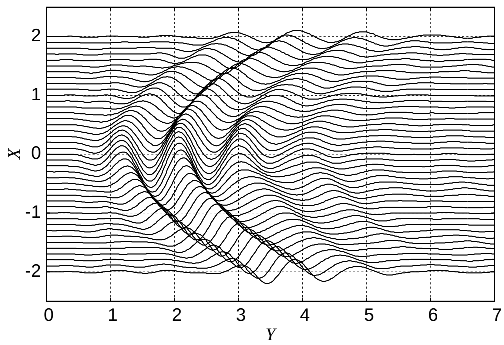

Figure 4: Scattered waveform in experiments.

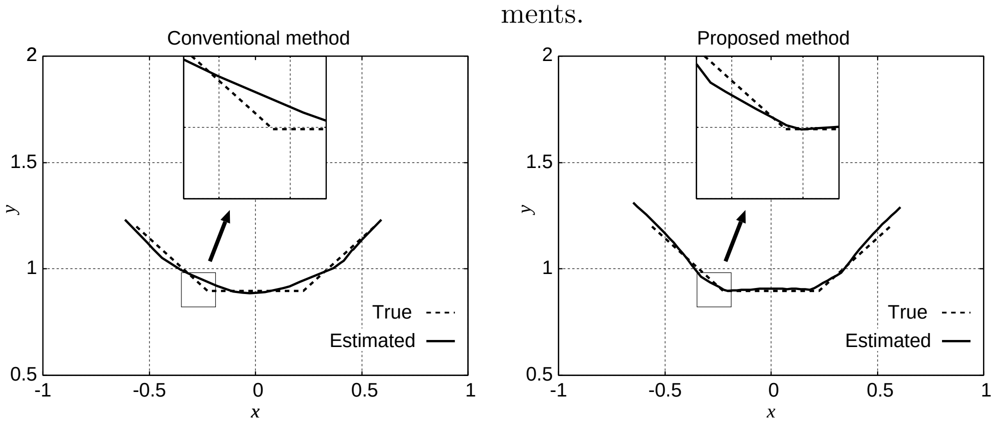

Figure 5: Estimated image with the conventional method (Left) and the proposed method (Right) in experiments.