Estimation Method of Quasi-wavefronts for UWB Radar Imaging with LMS Filter and Fractional Boundary Scattering Transform

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Abstract— UWB (Ultra Wide-Band) radar has a variety of applications including security surveillance systems. The SEABED algorithm is a fast imaging method for UWB radar, that uses a reversible transform between the real and data spaces [1]. We introduce an intermediate space between the real and data spaces [2]. Curves in the intermediate space can be smooth, and can be used to extract quasi-wavefronts (the equi-phase surface). In this paper, we use LMS (Least-Mean-Square) filters in the intermediate space for imaging arbitrary target shapes.

1. INTRODUCTION

UWB (ultra-wideband) pulse radar is a promising candidate as an environment measurement, or sensing, method for robots. Radar imaging for a nearby target is known as an ill-posed inverse problem: a problem that has been extensively studied [3, 4]. However, conventional algorithms require long computational time, that makes it difficult to apply UWB to real-time operations for robots. We have proposed a fast radar imaging algorithm, the SEABED algorithm, for UWB pulse radar [5, 6]. This algorithm is based on a reversible transform, IBST (Inverse Boundary Scattering Transform), between the target shape and observed data. This transform enables us to estimate target shapes quickly and accurately in a noiseless environment. The SEABED algorithm extracts equi-phase surfaces (also called quasi-wavefronts) first, and then applies an IBST to obtain the estimated image. However, in a noisy environment the image estimated by the SEABED algorithm is degraded because the quasiwavefronts cannot be accurately estimated. In this paper, we introduce an FIBST (Fractional IBST) [2] to the quasi-wavefront extraction process. This transform is obtained by expanding the conventional IBST, which enables us to deal with the intermediate space between real and data spaces, and propose a stable quasi-wavefronts extraction algorithm . We show some application examples with numerical simulations.

2. SYSTEM MODEL

We assume a mono-static radar system. An omni-directional antenna is scanned along a straight line. UWB pulses are transmitted at fixed intervals and received by the antenna. The received data is A/D converted and stored in memory. We estimate target shapes using the obtained data. We deal with a 2-dimensional problem. We define a real space in which targets and antenna are located. We express the real space with the parameters (x, y). Both x and y are normalized by λ, which is the center wavelength of the transmitted pulse in air. We assume $y > 0$ for simplicity. The antenna is scanned along the x-axis in r-space. We define $s(X, Y)$ as the received waveform after applying a matched filter at the antenna-location $(x, y) = (X, 0)$. Here, we define Y with time t and the speed of the radiowave c as $Y = ct/(2\lambda)$. We define a data space expressed by (X, Y).

3. SEABED ALGORITHM

In previous work we developed a fast radar imaging algorithm, 'SEABED', based on a BST (Boundary Scattering Transform) [5–8]. The algorithm uses a reversible transform, BST, between target shapes and pulse delays. The BST is expressed as

$$X = x + y\frac{\mathrm{d}y}{\mathrm{d}x}, \tag{1}$$

$$Y = y\sqrt{1 + \left(\frac{\mathrm{d}y}{\mathrm{d}x}\right)^2}, \tag{2}$$

where (X, Y) is a point on a quasi wavefront, and (x, y) is a point on the target boundary [1]. We have clarified that the inverse transform of the BST is given by

$$x = X - Y\mathrm{d}Y/\mathrm{d}X, \tag{3}$$

$$y = Y\sqrt{1 - (\mathrm{d}Y/\mathrm{d}X)^2}, \tag{4}$$

where we assume $|\mathrm{d}Y/\mathrm{d}X| \leq 1$. This condition is required because y should be a real number. First, quasi wavefronts are extracted from the received signals $s(X, Y)$ in the SEABED algorithm. Quasi wavefronts are extracted to satisfy the conditions $\mathrm{d}s(X, Y)/\mathrm{d}Y = 0$ and $|\mathrm{d}Y/\mathrm{d}X| \leq 1$. Finally, we apply the IBST to the quasi wavefronts, and obtain the final image. The extraction of quasi-wavefronts is critical to obtaining high-quality images with this algorithm. However, the quasi-wavefront cannot be accurately estimated for a noisy case. It is to solve this is the problem that we propose a new algorithm in this study.

4. FRACTIONAL BOUNDARY SCATTERING TRANSFORM

Here, we explain a fractional boundary scattering transform obtained by expanding the conventional boundary scattering transform [2]. We define the fractional boundary scattering transform, FBST (α) as

$$x^{(\alpha)} = x + \alpha y \frac{\mathrm{d}y}{\mathrm{d}x}, \tag{5}$$

$$y^{(\alpha)} = y\sqrt{1 + \alpha \left(\frac{\mathrm{d}y}{\mathrm{d}x}\right)^2}. \tag{6}$$

These equations contain a parameter $\alpha\,(0 \leq \alpha \leq 1)$, which is not included in the conventional boundary scattering transform. We call $(x^{(\alpha)}, y^{(\alpha)})$ a 'fractional transform quasi wavefront'. We call the space expressed by $(x^{(\alpha)}, y^{(\alpha)})$ a 'fractional transform space'. The fractional transform quasi-wavefront is equivalent to the conventional quasi-wavefront for $\alpha = 1$ and the fractional transform quasi-wavefront is equivalent to the target shape for $\alpha = 0$. The fractional inverse boundary scattering transform, FIBST (α) is defined in relation to the FBST similarly to the relationship between BST and IBST; by changing the sign of α.

Our study [2] clarified that data in the fractional transform space can be smooth regardless of the shape of targets. This characteristic can be used in the extraction of quasi-wavefronts. Additionally, data in any space can be transformed to arbitrary space as in Fig. 1, a fact that can be effectively used to develop our new algorithm. An example of data in 3 spaces (real, data, and fractional transform) is shown in Fig. 2. The data has an edge around $X = 1.5$, but the data in the fractional transform space is smooth, where we set $\alpha = 0.5$. In this way, we can avoid edges in the real and data space by applying an FBST to transform the data to the fractional transform space.

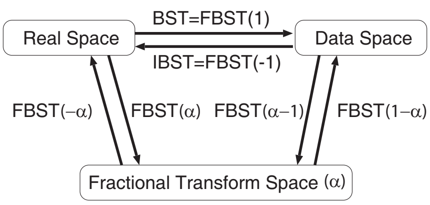

Figure 1: Relationships between spaces.

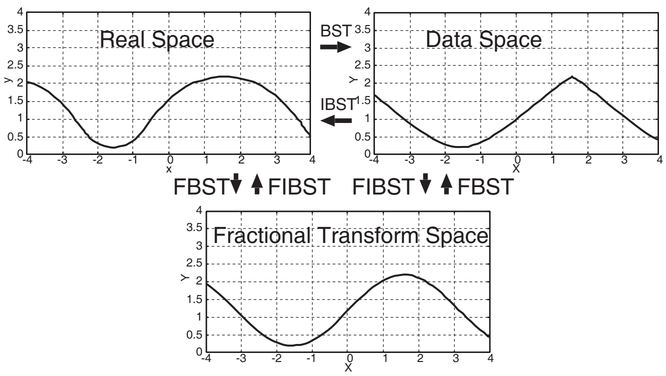

Figure 2: An example of data in real, data, and fractional transform spaces.

5. FRACTIONAL BOUNDARY SCATTERING TRANSFORM

A new extraction method for quasi-wavefronts is proposed here. 100 undesired interference points are assumed with the true quasi-wavefront points for each antenna position X. The first 10 true points are assumed and used as the initial value. We apply the FBST to the estimated quasi-wavefront to obtain the curve in the intermediate space, and apply a 5th-order LMS filter to estimate the entire curve. Then we apply the inverse FBST and obtain the predicted points. We adopt the nearest point to the prediction as the estimation in the next step. This procedure is repeated. This process is shown in Fig. 3 and contrasted with the conventional method as used in the original SEABED algorithm [1].

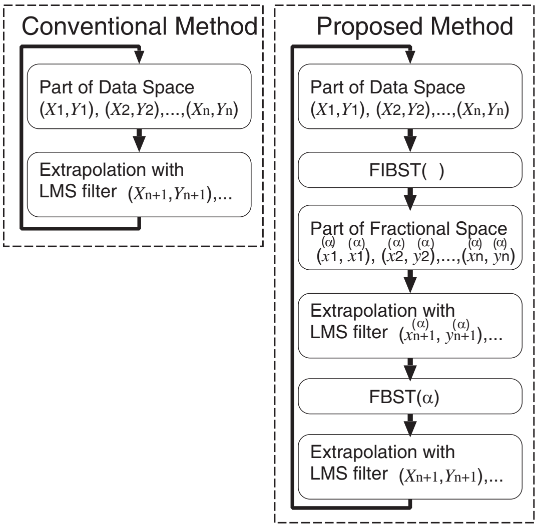

Figure 3: Procedures of the proposed and conventional quasi-wavefront extraction methods.

Figure 4 shows an example of the application of the proposed algorithm to the data shown in Fig. 2. The estimation of the quasi-wavefront until the 1st step in Fig. 4 is quite easy because of the smoothness in the data that means it does not depend on the method used. However, there is an edge around $X = 1.5$ in the data space. Simple LMS filtering fails to track the true quasi-wavefront here. The proposed algorithm applies FIBST to the data to obtain the fractional transform space data as black squares in step 2. Next, LMS filter prediction is applied to extrapolate the fractional transform space data in step 3. Finally, the FBST is applied to obtain the estimated quasi-wavefront in step 4. We adopt the nearest point to the prediction as the estimation in the next step. We repeat these procedures until the final point is estimated.

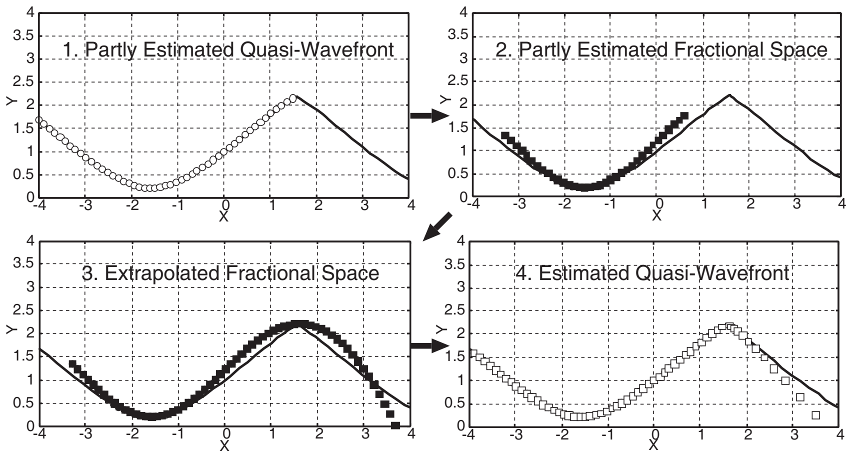

Figure 4: Application example of the proposed algorithm.

Figure 5 shows a comparison between the proposed method and the conventional method that applies the LMS filter in the data space rather than the intermediate space. The results show that the proposed method works while the conventional method produces a poor estimation. Fig. 6 shows the estimated image with the conventional method and the proposed method. For the conventional method, the shape for $x > 1.5$ is not estimated while our proposed method can correctly estimate the entire target shape.

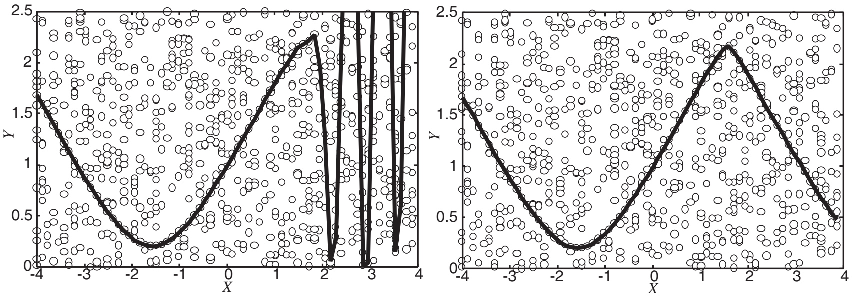

Figure 5: Quasi-wavefronts estimated with the conventional methods (left) and proposed methods (right).

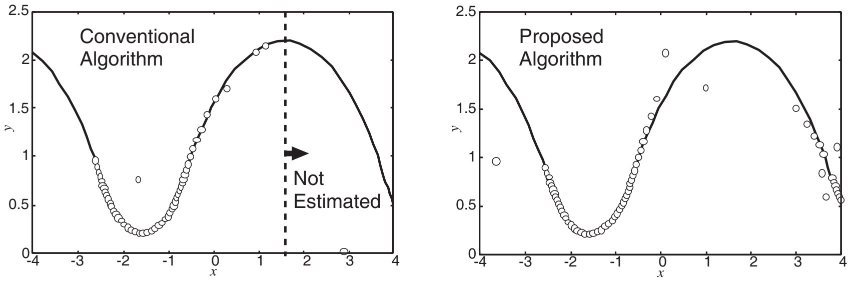

Figure 6: Images estimated with the conventional methods (left) and the proposed methods (right).

6. CONCLUSION

In this paper, we introduced a FIBST (Fractional IBST) to the quasi-wavefront extraction process, for the SEABED algorithm for UWB pulse radar imaging. This enables us to deal with the intermediate space between real and data spaces, and propose a stable quasi-wavefront extraction algorithm. The results of experimental application show that the proposed method maintains tracking data even in noisy environments. Additionally, the proposed method can estimate the entire target image while the conventional one cannot as it fails when multiple undesired points are caused by noise and interference.

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