A Stable and Fast 3-D Imaging Algorithm for UWB Pulse Radars with Fractional Boundary Scattering Transform

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Abstract

Radar imaging for a nearby target is known as an ill-posed inverse problem, on which various studies have been done. However, conventional algorithms require too long computational times. In order to resolve this difficulty, SEABED algorithm was developed. This algorithm is based on a reversible transform between the real and data spaces. In a noisy environment, the performance of the SEABED algorithm is severely degraded. In this paper, we newly introduce a fractional IBST, which is obtained by expanding the conventional IBST, which enables us to deal with the intermediate space between the real and data spaces, and propose a stable 3-D imaging algorithm by using the FIBST.

1 Introduction

The UWB (ultra-wideband) pulse radar is a promising candidate as an environment measurement method for robots. Radar imaging for a nearby target is known as an ill-posed inverse problem, on which various studies have been done. However, conventional algorithms require long computational time, which makes it difficult to apply them to real-time operations of robots. We have proposed a fast radar imaging algorithm, the SEABED algorithm, for UWB pulse radars [1, 2, 3]. This algorithm is based on a reversible transform, IBST (Inverse Boundary Scattering Transform), between the target shape and the observed data. This transform enables us to estimate target shapes quickly and accurately in a noiseless environment. However, in a noisy environment the image estimated by the SEABED algorithm is degraded because IBST utilizes differential operations. In this paper, we newly introduce a FIBST (Fractional IBST), which is obtained by expanding the conventional IBST, which enables us to deal with the intermediate space between a real and data spaces, and propose a stable 3-D imaging algorithm by using the FIBST. We investigate the estimation errors for the conventional algorithms and the proposed one with numerical simulations.

2 System Model

In our system model, UWB mono-cycle pulses are transmitted at a fixed interval and received by the same omni-directional antenna. We express a real space with the parameters (x, y, z). The antenna is scanned on the x-y plane in the real space. We define $s(X, Y, Z)$ as the electric field received at the antenna location $(x, y, z) = (X, Y, 0)$, where we define Z with time t and the speed of the radiowave c as $Z = ct/(2\lambda)$. It should be noted that the received data is expressed with (X, Y, Z), and the target shapes is expressed with (x, y, z). We define a data space as the space expressed by (X, Y, Z). The transform from the data space (X, Y, Z) to the real space (x, y, z) corresponds to the imaging we deal with in this paper. We normalize x, y, z, X, Y and Z by λ, the center wavelength.

3 Conventional SEABED Algorithm

In the SEABED algorithm, quasi-wavefronts (X, Y, Z) are easily extracted from the received data $s(X, Y, Z)$. We apply IBST to the quasi-wavefront to obtain the final image as

$$\left\{\begin{array}{lcc} x & = & X - Z\partial Z/\partial X, \\ y & = & Y - Z\partial Z/\partial Y, \\ z & = & Z\sqrt{1 - (\partial Z/\partial X)^2 - (\partial Z/\partial Y)^2}. \end{array}\right. \tag{1}$$

This technique is very simple, but it works well only for noiseless environments. Eq. (1) contains the derivative operations, which make the obtained image degraded with random components. Therefore, we have to utilize smoothing algorithm to stabilize the estimated image.

We utilized the following simple smoothing technique [4]. In the conventional smoothing technique, we apply smoothing to the quasi-wavefront to suppress the noise. Next, we apply the IBST to the smoothed quasi-wavefront to obtain the final stabilized image. We have clarified that this simple technique can stabilize the image to some extent. However, the smoothing process can distort the final image because the quasi wavefronts are not necessarily smooth even if the true target is smooth. On the other hand, the target shape itself is not guaranteed to be smooth, which implies that the smoothing of the final image is neither suitable. Consequently, the both of the smoothing processes in the data and real spaces are inappropriate, which is a fundamental problem for the stabilization.

In order to solve the problem, we have developed the new smoothing technique in the intermediate space between the real and data spaces for 2-dimensional imaging. The data in the intermediate space is guaranteed to be smooth regardless of the target shape. We need the transform FIBST in order to deal with the intermediate space. In the next section, we expand the 2-dimensional FIBST to the 3-dimensional one, to stabilize the 3-dimensional radar imaging.

4 Proposed Extended-SEABED Algorithm

The simple smoothing effectively works for convex targets because the quasi-wavefront is smooth for a convex shape. However, for general cases the quasi-wavefront is not necessarily smooth, so the image resolution can be degraded by unsuitable smoothing. To resolve this problem, we introduce FIBST by expanding the conventional IBST, and transform the data to an intermediate space between the real and data spaces, where the smoothing process hardly degrades the resolution. FIBST is expressed as

$$\left\{\begin{array}{lcc} \left[\begin{array}{c} x_{\theta,\alpha,\beta} \\ y_{\theta,\alpha,\beta} \end{array}\right] & = & \left[\begin{array}{c} X \\ Y \end{array}\right] - ZR(-\theta)\left[\begin{array}{cc} \alpha & 0 \\ 0 & \beta \end{array}\right] R(\theta) \left[\begin{array}{c} \partial Z/\partial X \\ \partial Z/\partial Y \end{array}\right], \\ z_{\theta,\alpha,\beta} & = & Z\sqrt{1 - \left[\begin{array}{cc} \partial Z/\partial X & \partial Z/\partial Y \end{array}\right] R(-\theta)\left[\begin{array}{cc} \alpha & 0 \\ 0 & \beta \end{array}\right] R(\theta) \left[\begin{array}{c} \partial Z/\partial X \\ \partial Z/\partial Y \end{array}\right]}. \end{array}\right. \tag{2}$$

In our proposed stable imaging algorithm, we select suitable parameters (θ, α, β) depending on the roughly estimated target shape, and apply the smoothing process to $(x_{\theta,\alpha,\beta}, y_{\theta,\alpha,\beta}, z_{\theta,\alpha,\beta})$ and finally apply FIBST again to obtain the final image. The procedure of the proposed algorithm is shown in Fig. 1 in contrast with the conventional one. First, the proposed algorithm estimates the rough image by utilizing the conventional algorithm. In this step, the image is severely distorted by the inappropriate smoothing process. Next, we calculate the Hesse matrix of the rough image for each point on that. Then, we obtain the eigenvalues and eigen vectors of the Hesse matrix. We determine the parameters α, β and θ based on the eigenvalues and the eigen vectors. We apply the FIBST with these parameters to the original quasi wavefront. Then, we apply a smoothing to the obtained FIBST. Finally, we apply the residue FIBST with $1 - \alpha, 1 - \beta$ and $-\theta$ to obtain the final image.

5 Numerical Simulations

We show some results of the numerical simulation to investigate the performance of the conventional and proposed algorithms. We assume the true targets shape in Fig. 2, which has saddle points. We adopt this

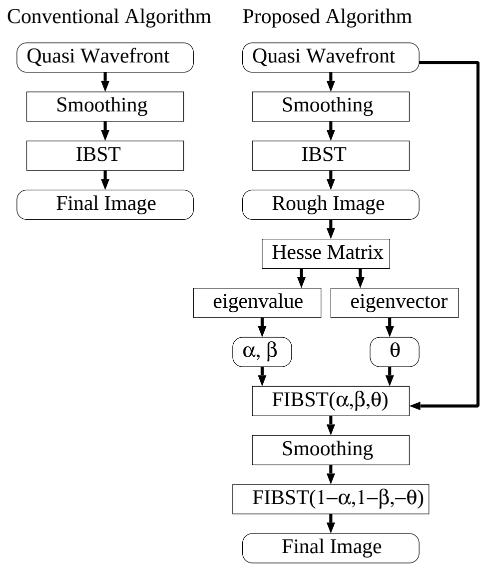

Figure 1: Procedures of the conventional and proposed algorithm

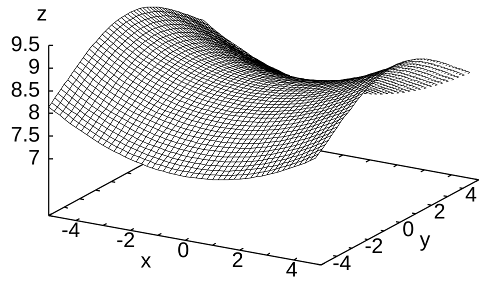

Figure 2: True target shape used in our numerical simulation.

shape because the saddle point is unique for 3-dimensional system compared to the 2-dimensional shape. The quasi-wavefront for a convex target is smooth, and the quasi-wavefront for a concave target is sharp and not smooth. The saddle point contains both of these effects, which is very difficult to adequately deal with.

The quasi-wavefront for the true target shape is shown in Fig. 3. We see that the quasi-wavefront is sharp in the direction of Y, which is caused by the concave target shape in the y direction. On the other hand, the quasi-wavefront is smooth in the direction of X, which corresponds to the convex target shape in the x direction. It is obvious that the conventional simple smoothing distorts the quasi-wavefront for Y direction.

In this paper, we omit the process of calculation of eigenvalues and eigen vectors for simplicity. We assume that the suitable parameters α, β and θ are chosen before the application of the FIBST. We adopt $\alpha = 0.1$, $\beta = 0.9$ and $\theta = 0$ here. We assume noiseless environment in order to evaluate the distortion of image without noise. The performance evaluation with noise is an important future task. We set the correlation length of the smoothing is equal to the center wavelength. The smoothing process of the conventional and proposed methods are displayed in the α-β diagram as in Fig. 4. Here, we assume $\theta = 0$ is fixed for simplicity. The parameters of FIBST α and β determine the space of the processed data. The point $(0, 0)$ is the data space, where the data is an original quasi-wavefront extracted with the received data. The point $(1, 1)$ is the real space, where the data directly express the real target shape. Other points (α, β) for $0 < \alpha < 1, 0 < \beta < 1$ correspond to the fractional data spaces. Especially, we apply the smoothing in the fractional data space $(\alpha, \beta) = (0.1, 0.9)$ as described above.

The estimated target shape by the proposed method is shown in Fig. 5. The estimation errors of the images with the conventional algorithm and the proposed algorithm are shown in Fig. 6 and Fig. 7. The estimation

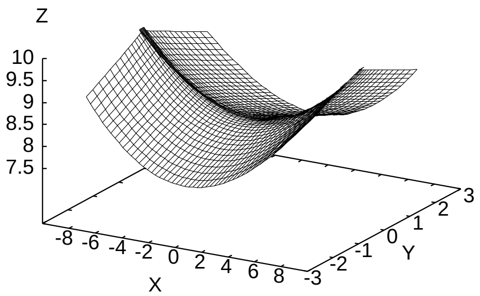

Figure 3: Quasi wavefront for the assumed target shape.

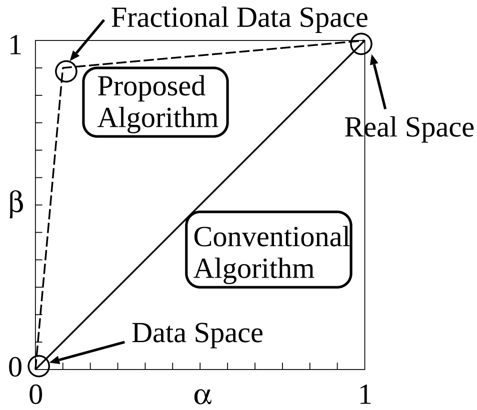

Figure 4: α-β diagram and three spaces.

accuracy for the proposed algorithm is higher than that of the conventional one by more than 2 times.

6 Conclusion

In this paper, we newly introduced the 3-dimensional fractional inverse boundary scattering transform (3-D FIBST), which enables us to deal with the intermediate space between the real and data spaces for 3-D problem. By utilizing the 3-D FIBST, we have clarified that we can apply a smoothing process with distortion suppressed.

References

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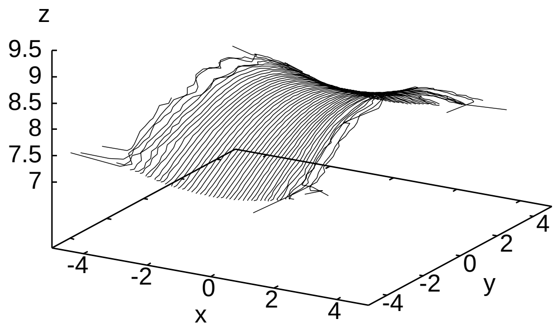

Figure 5: Estimated target image by the proposed algorithm.

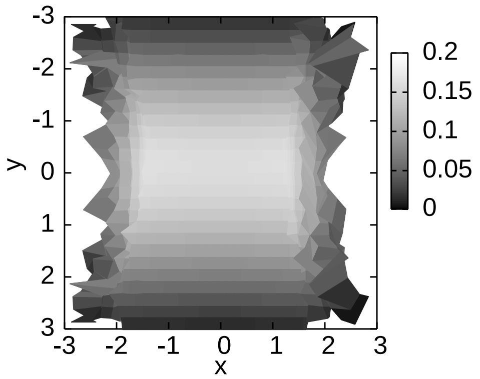

Figure 6: Estimation error for the smoothing in the data space (conventional).

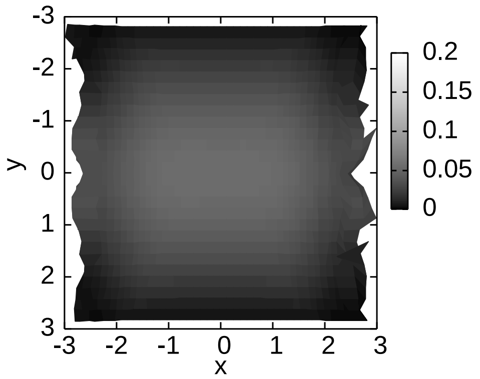

Figure 7: Estimation error for the smoothing in the fractional data space (proposed).