An Image Stabilization Algorithm for UWB Pulse Radars with Fractional Boundary Scattering Transform

Takuya SAKAMOTO* †, Toru SATO †
†Dept. of Commun. and Computer Eng., Kyoto Univ., Kyoto, Japan

INTRODUCTION A UWB pulse radar is a strong candidate for the environment measurement for robots. Radar imaging for targets close to the antennas is known as one of the ill-posed inverse problems, for which various studies have been done. Conventional algorithms require a long calculation time, which makes it difficult to apply them to a realtime operation required for robotics. We have proposed a fast imaging algorithm, SEABED algorithm, for UWB pulse radars [1–5]. This algorithm utilizes BST (Boundary Scattering Transform) which is a reversible transform between a target shape and the received data. SEABED can quickly estimate target images by this transform because it does not require iterative computations.

However, the estimated image of SEABED is degraded for noisy data because BST includes the derivative operation. In order to avoid this problem, we have derived the upper bound of the smoothness of data, which was effectively utilized to stably estimate target shapes with SEABED[6]. However, because this method works only for convex targets, the stable imaging for general targets cannot be achieved with the previous method. In this paper, we propose an image stabilization algorithm which can be used for any target shapes, based on a novel transform obtained by expanding BST.

BOUNDARY SCATTERING TRANSFORM We assume a mono-static radar system. An omni-directional antenna is scanned along a straight line. UWB pulses are transmitted at a fixed interval and received by the same antenna. The received data is A/D converted and stored in a memory. We estimate target shapes using the obtained data. We deal with a 2-dimensional problem for simplicity. We define a real space, where targets are located, and expressed with the parameters x and $y > 0$. Both x and y are normalized by λ, which is the center wavelength of the transmitted pulse in air. The antenna is scanned along x-axis in r-space. Fig. 1 shows the system model.

We define $s'(X, Y)$ as the received electric field at the antenna location $(x, y) = (X, 0)$, where we define Y with time t and the speed of radiowave c as $Y = ct/(2\lambda)$. We apply a matched filter of transmitted waveform for $s'(X, Y)$ and obtain the output $s(X, Y)$. We define a data space expressed by (X, Y). We define quasi wavefronts as the equi-phase curves in the data space. The transform from the data space to the real space corresponds to the radar imaging. Fig. 2 shows an example of a pair of target shape and its quasi wavefront. This quasi wavefront corresponds to the relationship of antenna position X and the distance Y between the antenna and the point P on the target, where a perpendicular condition is satisfied. The target is estimated by the following IBST (Inverse BST) as

$$x = X - Y\mathrm{d}Y/\mathrm{d}X, \tag{1}$$

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

where (X, Y) is a point on a quasi wavefront. SEABED algorithm obtains the target shapes by calculating the right-hand side of Eqs. (1) and (2). Because the IBST includes the derivative operation, additional stabilization technique is required to deal with noisy data. Smoothing of the estimated shape in the real space degrades the resolution because general target contains sharp edges, whose roughness $|\mathrm{d}^2 y/\mathrm{d}x^2|^2$ is locally large. We introduce a novel transform to solve this problem in the next section.

FRACTIONAL BOUNDARY SCATTERING TRANSFORM We expand the conventional transform IBST to define the novel transform, FIBST (Fractional IBST). FIBST(α) is defined with a parameter $0 \leq \alpha \leq 1$ as

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

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

which reduces to the conventional IBST in Eqs. (1) and (2) when $\alpha = 1$. The left-hand side of FIBST expresses the real space for $\alpha = 1$, the data space for $\alpha = 0$, and the intermediate space for $0 < \alpha < 1$. We call the output of FIBST a fractional transform quasi wavefront. We have proved that the sequential application of FIBST(α) and FIBST(β) is equivalent to FIBST($\alpha + \beta$), which enables us to divide an imaging operation into 2 steps as in Fig. 3.

The 2nd derivative of the fractional transform quasi wavefront is expressed as

$$\left|\frac{\mathrm{d}^2 y_\alpha}{\mathrm{d}x_\alpha^2}\right|^2 = \frac{\left|\mathrm{d}^2 y/\mathrm{d}x^2\right|^2}{\left\{1+(1-\alpha)\left(\frac{\mathrm{d}y}{\mathrm{d}x}\right)^2\right\}^3\left|1+(1-\alpha)\left(\frac{\mathrm{d}y}{\mathrm{d}x}\right)^2+(1-\alpha)y\frac{\mathrm{d}^2 y}{\mathrm{d}x^2}\right|^2}. \tag{5}$$

For $\alpha = 1$, the right-hand side of this equation is equivalent to the numerator, which is the 2nd derivative of the target shape. For $\alpha = 0$, the right-hand side of this equation is equivalent to the 2nd derivative of the conventional quasi wavefront [3]. We can obtain a smooth curves by using the FIBST(α) with a suitable parameter α, where smoothing operations hardly degrade the image resolution. Next, we apply the rest of transform FIBST($1-\alpha$) and obtain the final image. Fig. 4 shows the procedure of the proposed stabilization algorithm by contrast with the conventional smoothing algorithm in the data space [6].

We assume that the optimum parameter α_{opt} should minimize $\left|\mathrm{d}^2 y_\alpha/\mathrm{d}x_\alpha^2\right|^2$ in Eq. (5) for given y, $\mathrm{d}y/\mathrm{d}x$ and $\mathrm{d}^2 y/\mathrm{d}x^2$. We have analytically derived the optimum α, which is shown in Fig. 5, where $\alpha = 1$ (black) means that the smoothing in the real space is the best, and $\alpha = 0$ (white) means that the smoothing in the data space is the best. This figure shows that the conventional smoothing [6] works only in the white area, which includes concave targets with $\mathrm{d}^2 y/\mathrm{d}x^2 > 0$. The proposed algorithm adaptively selects the parameter α depending on the calculated optimum parameter α_{opt} as $\alpha = 0$ and $\alpha = 1$ for $\alpha_{\mathrm{opt}} > 0.5$ and $\alpha_{\mathrm{opt}} \leq 0.5$, respectively. Note that y, $\mathrm{d}y/\mathrm{d}x$ and $\mathrm{d}^2 y/\mathrm{d}x^2$ are directly calculated by the estimated quasi wavefront in the data space by the formulas in the reference [3]. Therefore, the proposed smoothing algorithm does not spoil the advantage of the quick imaging by SEABED algorithm.

APPLICATION OF THE PROPOSED METHOD We apply the proposed smoothing algorithm to numerically generated quasi wavefronts. The assumed target shape has both of a concave part and a convex part as shown in the upper figure in Fig. 6. We assume that the data is sampled at 1000 points along the x axis. We add Gaussian random error to the quasi wavefronts which is an approximation of the additive white Gaussian noise included in received signals. We assume that the quasi wavefront is obtained ideally from the received data. We add

Gaussian random sequences with the standard deviation of 1.0×10^{-2} wavelength to the ideal quasi wavefront Y for each X. We apply a preprocessing in which each quasi wavefront is smoothed with a short correlation length, which is set to 2.5×10^{-2} for X direction. Then, we apply the conventional smoothing method and the proposed smoothing method to obtain the target image with SEABED algorithm. The estimation accuracy of the conventional method is shown by the broken line in Fig. 6. The error of the conventional method is large in the right area around $x = 1.5$, where the target shape is concave. On the other hand, the error of the proposed method is shown by the solid line in this figure. The estimation accuracy for a concave surface is improved by 3 times, while the estimation accuracy for the convex surface remains unchanged as the conventional one.

CONCLUSIONS In this paper, we have proposed an image stabilization algorithm for the fast imaging algorithm SEABED with UWB pulse radars. Although SEABED algorithm can estimate target shapes in a remarkably short time, it has a weakness for noisy data. Therefore, a stabilization procedure is needed to utilize SEABED algorithm. A stabilization method has already been proposed, but it works only for convex targets and some kinds of concave targets. The proposed stabilization method in this paper is based on a novel transform FIBST which is obtained by expanding the conventional transform IBST. This new transform enables us to deal with the intermediate space between the real space and the data space. In the intermediate space with a suitable parameter, the smoothing hardly degrades the resolution of the estimated image. We analytically derived the optimum parameter for FIBST and developed the stabilization algorithm which can be applied to any target shape. Both of stabilization and high-resolution are achieved by the proposed algorithm. The application example showed that the estimation accuracy is improved by 3 times for some cases.

References

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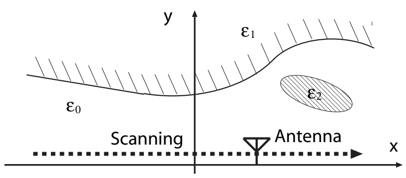

Figure 1: System model and antenna scanning.

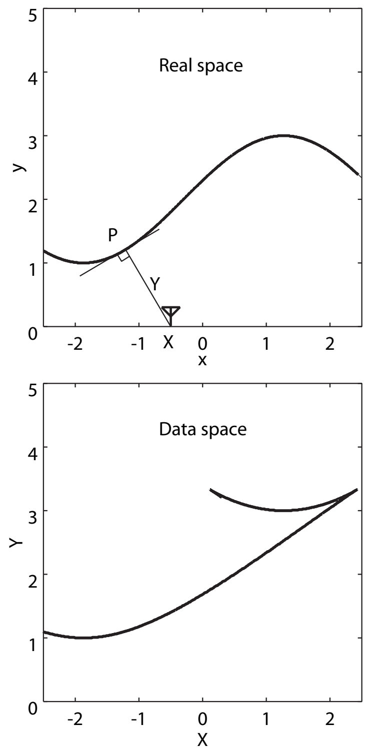

Figure 2: An example of a target shape and its quasi wavefront.

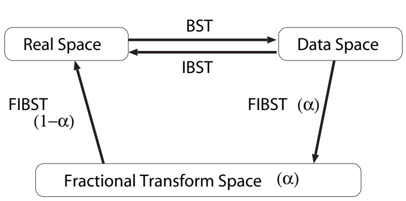

Figure 3: The relationship of the 3 spaces.

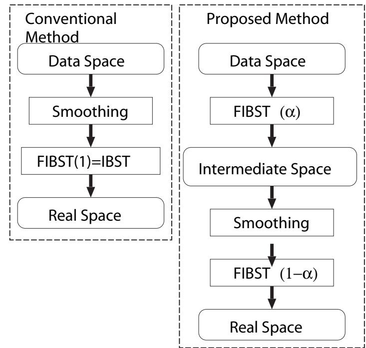

Figure 4: The procedure of the proposed algorithm.

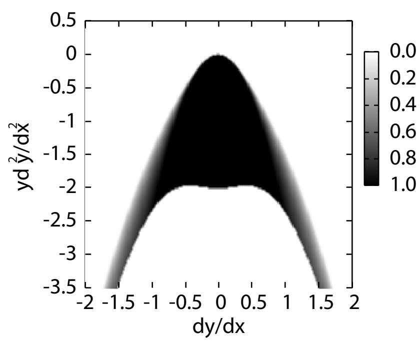

Figure 5: The optimum parameter α vs. the characteristic of a target shape.

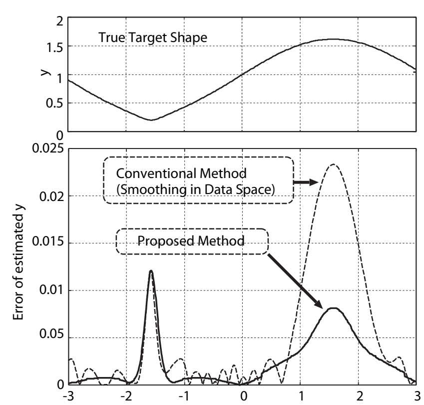

Figure 6: Estimation accuracy by SEABED algorithm with each stabilization method.