An Experimental Study on a Fast Imaging Algorithm for UWB Pulse Radar Systems

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INTRODUCTION Radar imaging is an important technique which has a variety of applications including rescue robots for disaster areas. It is known that radar imaging is one of ill-posed inverse problems. A large number of algorithms have already been proposed for this problem. However, the conventional algorithms require long calculation time. This problem causes a critical difficulty in applying radars to realtime operation which is needed for robots. In order to solve this problem, we have proposed a fast 3-dimensional imaging algorithm, SEABED [1]. This algorithm is based on a reversible transform between target shapes and observed signals under a certain condition. It has been clarified that SEABED algorithm can accurately estimate 3-dimensional target shapes in a considerably short time with numerical simulations [2]. In this paper, we apply SEABED algorithm to experimental data and investigate the performance of the algorithm. Additionally, we propose a smoothing algorithm which enable us to enhance the robustness of SEABED algorithm against noise.

SYSTEM MODEL Two omni-directional antennas are scanned on a plane as in Fig. 1. Pulses are transmitted at a fixed interval from an antenna and received by another antenna. The both antennas are located close to each other, which is approximately regarded as a monostatic radar system. The received data is A/D converted and stored in a memory. We estimate target shapes using the data. We assume that every target has a uniform complex permittivity, and surrounded by a clear boundary. The transmitted pulse is a UWB pulse which satisfies the criteria for UWB signals.

SEABED ALGORITHM We deal with 3-dimensional problems, and semi-linear polarization. We express real space with the parameter (x, y, z). All of x, y and z are normalized by λ, which is the center wavelength of the transmitted pulse in the air. We assume $z > 0$ for simplicity. The antenna is scanned on the plane spanned with x-axis and y-axis in r-space. We define $s'(X, Y, Z)$ as the received voltage at the antenna location $(x, y, z) = (X, Y, 0)$, where we define Z with time t and speed of the light c as $Z = ct/(2\lambda)$. We apply a matched filter of transmitted waveform to $s'(X, Y, Z)$. We define $s(X, Y, Z)$ as the output of the filter. We normalize X and Y by λ, and Z by the center period of transmitted waveform, respectively. SEABED algorithm utilizes a quasi-wavefront which is defined as extracted equiphase-surfaces from $s(X, Y, Z)$. It should be noted that the received data is expressed with (X, Y, Z) and target shapes are expressed with (x, y, z). The following equations hold for (x, y, z) and (X, Y, Z).

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

This equation is called Inverse Boundary Scattering Transform (IBST). SEABED algorithm obtains the target shapes by calculating the right hand side of Eq. (1). Fig. 2 shows the estimated target shape in a numerical simulation. Here we assume the true target shape as in Fig. 1.

APPLICATION TO EXPERIMENTAL DATA We show an application example of SEABED algorithm to an experimental data. In this paper, we set a metallic pipe with the radius of 92mm (1.2λ) and the length of 1m as a target object. Fig. 3 shows the experimental site, where we see the pair of antennas installed at a 2-D scanner over a metallic cylinder. The transmitted UWB pulse has the center frequency of 3.7GHz ($\lambda = 81$mm) and the bandwidth of 1.0GHz. The antenna transmits pulses at 23×23 positions with intervals of 10mm (0.12λ). Fig. 5 shows the extracted quasi-wavefront from the received signals. Fig. 6 shows the estimated target shape by applying IBST to the extracted quasi-wavefront. In general, quasi-wavefronts contain random components caused by noise and timing jitters. The random component degrades the image because IBST requires the 1st order derivative of a quasi-wavefront which is sensitive to random components. This problem is critical in applying SEABED algorithm to experimental data.

SMOOTHING OF SEABED ALGORITHM The reconstructed image is easily degraded by random components contained in quasi-wavefronts if we directly apply SEABED algorithm to experimental data. Smoothing of quasi-wavefronts is effective to solve this problem because SEABED algorithm can estimate the edge positions of a target and divide the target surface into multiple smooth surfaces. We can stabilize the image without sacrificing the resolution by smoothing each quasi-wavefront of a divided surface. If the abstract value of the 2nd order derivative of a quasi-wavefront is small, we can adopt a smoothing with a long correlation length because the quasi-wavefront can be locally regarded as a plane. We deal with an adaptive smoothing technique whose correlation length is changed based on the 2nd order derivative of the quasi-wavefront. For simplicity, we assume that the target shape is a convex one whose shape does not change with x. This means that the function $Z(X, Y)$ has a Hessian matrix whose non-diagonal components are equal to zero. We simply call the diagonal component of the Hessian matrix the 2nd order derivative.

First, we directly derive the 2nd order derivative of the quasi-wavefronts, and apply the smoothing with the corresponding correlation length. We adopt a 2-dimensional Gaussian filter with the determined corresponding correlation length. We determine the correlation length c as $c = \sqrt{12\delta/a}$, where δ is the acceptable distortion, and a is the coefficient of the 2nd order term of Taylor expansion. Here we set δ to 0.03λ. Fig. 7 shows the estimated image by using the smoothing algorithm described above. We see that the smoothing does not contribute to improvement of image because the 2nd order derivative is too sensitive to the random components.

PROPOSED SMOOTHING METHOD We propose a new smoothing method based on the characteristic of a quasi-wavefront. The 2nd order derivative of a quasi-wavefront satisfies

$$\frac{\partial^2 Z}{\partial Y^2} < \frac{1 - (\partial Z/\partial Y)^2}{Z}. \tag{2}$$

Eq. (2) enables us to evaluate the 2nd order derivative by using Z and its 1st order derivative. The 1st order derivative can be stably calculated compared to the 2nd order one. This proposed method utilizes the right hand side of Eq. (2)

instead of the left hand side. Fig. (8) shows the estimated image of the proposed method. We see the image is accurately estimated. The improvement of the image is equivalent to an increase of 5dB in S/N of a quasi-wavefront.

CONCLUSIONS In this paper, we have applied SEABED algorithm to experimental data. The random components in the received signal degrade the estimated image. We investigated two kinds of smoothing method to solve this problem. One of them directly utilizes the 2nd order derivative, which cannot improve the image accuracy. The proposed smoothing method utilizes the upper bound of the 2nd order derivative instead of the 2nd order derivative itself. We confirmed that the proposed smoothing method significantly improves the image, which corresponds to the gain of 5dB in S/N. In the future study, it is important to extend the proposed smoothing method in order to get rid of the required condition of target shape.

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References

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APPENDIX Here we show the derivation of Eq. (2). If the target shape z and the quasi-wavefront Z satisfy $\partial z/\partial x = 0$ and $\partial Z/\partial X = 0$ respectively, they are the functions of one variable, y and Y, respectively. Additionally, $z_{yy} > 0$ is satisfied if the target shape is a convex, where we use simple expressions such as $z_{yy} = \partial^2 z/\partial y^2$. It is known that $Z_{YY} > 0$ holds if $z > 0$ and $z_{yy} > 0$ [3]. The 2nd order derivative of z satisfies

$$z_{yy} = \frac{Z_{YY}}{(1 - Z_Y^2)^{3/2}(1 - Z_Y^2 - ZZ_{YY})}. \tag{3}$$

Considering $Z_{YY} > 0$ and $z_{yy} > 0$ we obtain the following equation, and thus Eq. (2).

$$0 < Z_{YY} < \frac{1 - Z_Y^2}{Z} \tag{4}$$

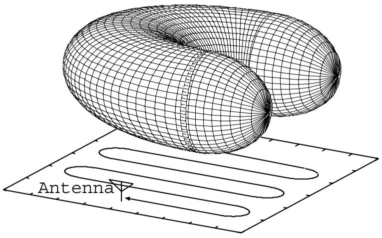

Figure 1: System model and antenna scanning.

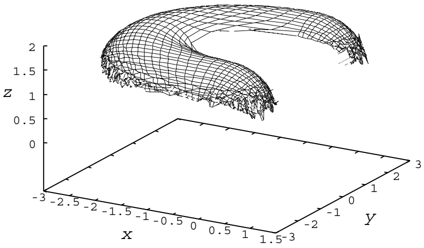

Figure 2: Estimated image in a numerical simulation. Computation time for the reconstruction is 0.1 sec.

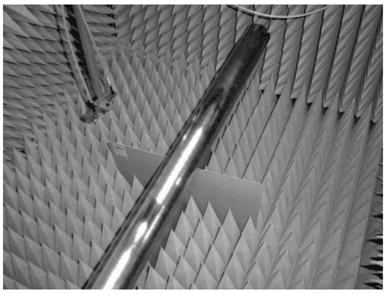

Figure 3: Experimental site of the UWB pulse radar system.

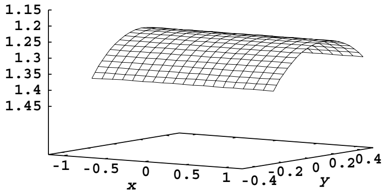

Figure 4: True target shape for experiment.

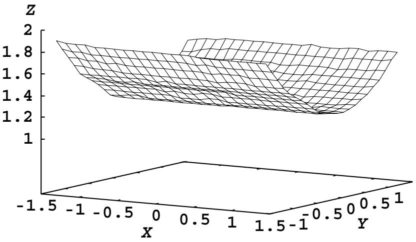

Figure 5: Quasi-wavefront extracted from experimental data.

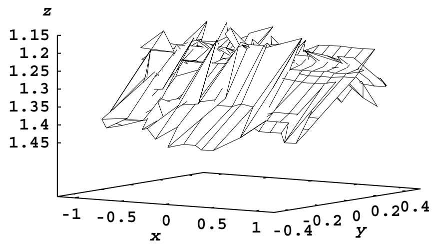

Figure 6: Estimated target shape using raw SEABED algorithm.

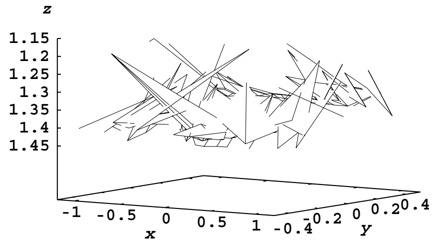

Figure 7: Estimated target shape with the smoothing based on the 2nd order derivative.

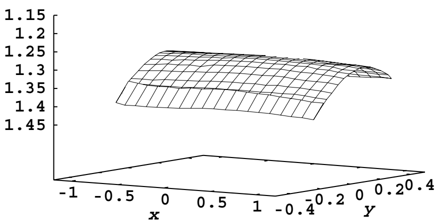

Figure 8: Estimated target shape with the proposed smoothing method.