A ROBUST AND FAST 3-D IMAGING ALGORITHM WITHOUT DERIVATIVE OPERATIONS FOR UWB RADARS

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Abstract: UWB pulse radars have a great potential for a high-resolution imaging, which is required for measuring techniques of rescue robots in dark smoke. Also they can be applied to a non-destructive measurement for surface details of the antennas and the aircraft. We have already proposed a fast 3-D imaging algorithm called SEABED based on a reversible transform BST (Boundary Scattering Transform) between the received data and the target boundary. However the target image estimated with SEABED is sensitive to a noise due to the derivative operations. To resolve this problem, we propose a robust imaging method without derivative operations for an arbitrary 3-D shape. We clarify that the proposed method can realize a robust and fast imaging with numerical simulations.

Introduction

UWB pulse radars are promising as a high-resolution imaging technique, which is applicable for a non-destructive measurement in order to detect small surface defects on reflector antennas and aircraft. Additionally, they are suitable for target locationing systems of rescue robots in dark smoke. These applications require a fast, robust, and high-resolution imaging algorithm. We have already proposed a fast 3-D imaging algorithm as SEABED, T. Sakamoto[1]. This method accomplishes a direct and non-parametric imaging by utilizing a reversible transform BST between the time delay and the target boundary. However, the estimated image with SEABED is unstable in a noisy environment because BST utilizes the derivative of the received data. To resolve this problem, we propose a robust and fast imaging algorithm with the envelope of spheres. We calculate spheres with the observed delays for each antenna location and utilize the principle that these spheres should circumscribe or inscribe the target boundary. This method does not utilize derivative operations, and enables us to realize a robust imaging for arbitrary shapes. The evaluations with numerical simulations show that our proposed method realizes a fast and robust imaging in a noisy situation.

System Model

Fig. 1 shows the system model. We assume that the target is surrounded by a clear boundary which is composed of smooth surfaces. We assume that the propagation speed of the radio wave is a known constant. An omni-directional antenna is scanned on a plane as $z = 0$. We utilize a mono-cycle pulse as the transmitting current and, assume the linear polarization in the direction of x axis. R-space is defined as the real space where targets and the antenna are located, and is expressed with the parameter (x, y, z). (x, y, z) is normalized by λ, which is the center wavelength of the pulse. We assume $z > 0$ for simplicity. We define $s'(X, Y, Z)$ as the received electric field at the antenna location $(x, y, z) = (X, Y, 0)$, where we define Z with time t and speed of the radio

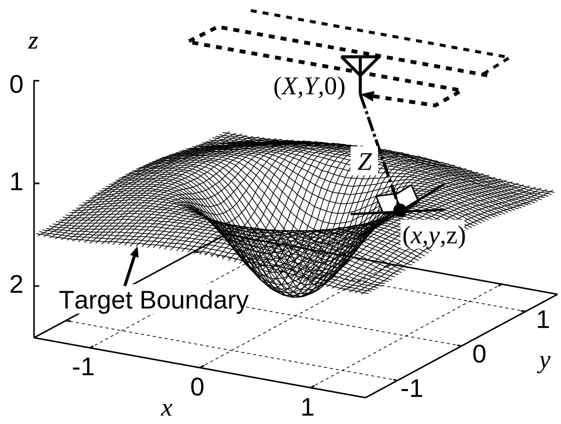

Figure 1: Assumed target shape and system model.

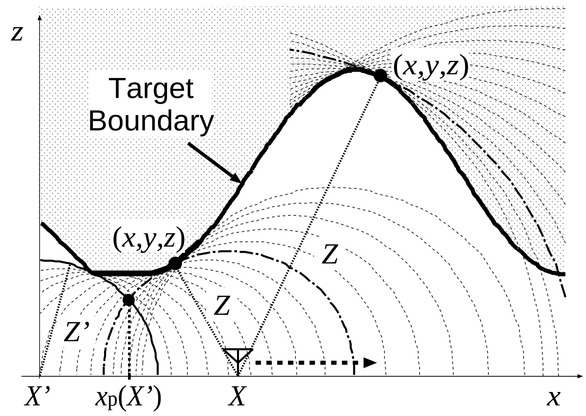

Figure 2: Relationship between a target boundary and an envelope of circles.

wave c as $Z = \mathrm{c}t/(2\lambda)$. We apply the matched filter with the transmitted waveform to $s'(X,Y,Z)$. We define $s(X,Y,Z)$ as the output of the filter. D-space is defined as the space expressed with (X,Y,Z), which is called quasi wavefront. The transform from D-space to R-space corresponds to the imaging which we deal with in this paper.

Proposed imaging algorithm

SEABED T.Sakamoto [1] utilizes the reversible transform BST between the target boundary (x,y,z) and the quasi wavefront (X,Y,Z). Inverse BST is expressed as $x = X - Z\partial Z/\partial X,\ y = Y - Z\partial Z/\partial Y,\ z = Z\sqrt{1-(\partial Z/\partial X)^2-(\partial Z/\partial Y)^2}$. This transform enables us to realize a direct 3-D imaging with the received data. However, the estimated image with SEABED is sensitive to a noise because BST utilizes the derivative operations. To resolve this problem, we propose a robust and fast imaging algorithm without derivative operations as follows. This algorithm utilizes the principle that the target boundary should be expressed as the envelope of the spheres, whose center point is $(X,Y,0)$, and radius is Z. Fig. 2 shows the relationship between the target boundary and an envelope of the circles in 2-D problems, for simplicity. As shown in Fig. 2, the envelope of the circles should circumscribe or inscribe to the target boundary. By extending this relationship to 3-D problems, we determine the region of the target boundary (x,y,z) for each (X,Y,Z) as

$$\left\{\begin{array}{c} \displaystyle\max_{s_X(X'-X)<0} x_{\mathrm{p}}(X') \leq x \leq \min_{s_X(X'-X)>0} x_{\mathrm{p}}(X') \\ \displaystyle\max_{s_Y(Y'-Y)<0} y_{\mathrm{p}}(Y') \leq y \leq \min_{s_Y(Y'-Y)>0} y_{\mathrm{p}}(Y') \\ z = \sqrt{Z^2-(x-X)^2-(y-Y)^2} \end{array}\right. , \quad (1)$$

where $s_X = \mathrm{sgn}(\partial x/\partial X)$, $s_Y = \mathrm{sgn}(\partial y/\partial Y)$, and X', Y' are searching variables. $x_{\mathrm{p}}(X')$ and $y_{\mathrm{p}}(Y')$ are the intersection points of the estimated circles on the plane $y = Y$ and $x = X$, respectively, as shown in Fig. 2. s_X and s_Y express the situation that the envelope of circles circumscribes or inscribes to the target boundary for each plain. This method does not spoil the information of the quasi wavefront as the similar approach in 2-D problems, S. Kidera et al.[2]. Thus, the instability caused by noise is suppressed. Eq. (1) determines the target boundary as the points on the envelope of spheres. We show the procedure of the proposed method as follows. We extract the quasi wavefront as (X,Y,Z) by connecting the significant peaks of $s(X,Y,Z)$, where Z is a

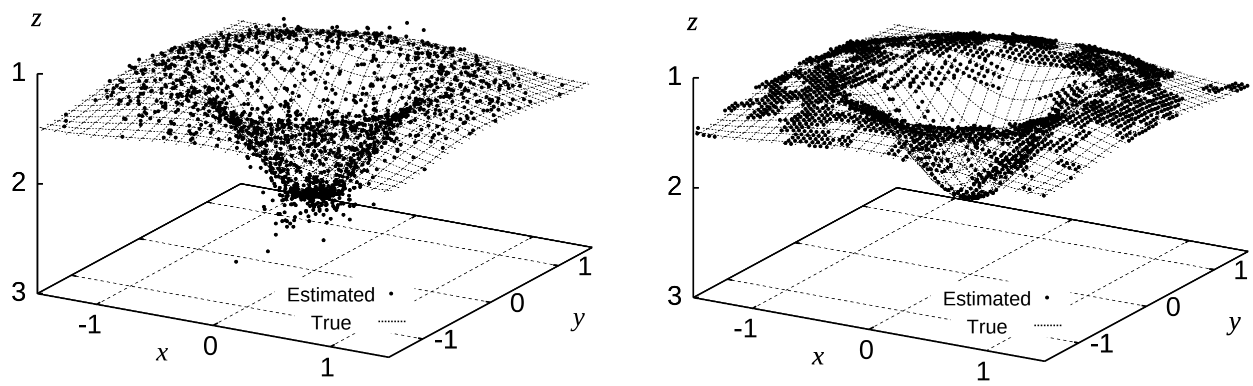

Figure 3: The estimated image with SEABED (left) and the proposed method (right).

single-valued function of X and Y. We determine the sign of $\partial x/\partial X$ and $\partial y/\partial Y$ by utilizing the characteristic of the quasi wavefront. The region of the target boundary is estimated in Eq. (1) for each (X, Y, Z). This method can determine the target boundary for arbitrary shapes without derivative operations.

Performance evaluation

The performance is evaluated as follows. We assume the target boundary as shown in Fig. 1. We give random error to the true quasi wavefront, whose standard deviation is $7.0\times10^{-3}\lambda$. The antenna is scanned for $-2.5\lambda \leq x \leq 2.5\lambda$, and $-2.5\lambda \leq y \leq 2.5\lambda$, which corresponds to S/N = 24 dB. The left and right-hand sides of Fig. 3 show the estimated images with SEABED and the proposed method, respectively. We confirm that the image with SEABED is instable, especially around the concave region due to the derivative of the quasi wavefront. Contrarily, the image with the proposed method is quite stable for all regions of the target boundary even in the noisy case. This is because the proposed method utilizes the inclinations of the spheres as those of the target boundary. The computational time of this method is within 0.2 sec for Xeon 3.2 GHz processor, which can realize the real-time operations.

Conclusion

We proposed a fast and robust imaging algorithm with the envelope of the spheres for an arbitrary target shape. In numerical simulations, we verified that the proposed method can realize a robust imaging even in a noisy environment without derivative operations. It is our future task to investigate the performance of the proposed method with experiments.
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References

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