A High-resolution 3-D Imaging Algorithm with Linear Array Antennas for UWB Pulse Radar Systems

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Introduction

UWB pulse radar systems have a great potential for a high-resolution imaging in indoor environments. While many imaging algorithms for radar systems have been proposed, they require intensive computation for a target imaging[1]. For a real-time imaging, we have already proposed a fast 3-dimensional imaging algorithm called SEABED based on a reversible transform BST(Boundary Scattering Transform) between the received signals and the target shape[2]. SEABED can be applied only to a mono-static radar system. Therefore, the resolution of the image is limited to the sampling number of the scanning. Moreover, we have to scan an antenna on a plane for 3-D imaging, which requires too long time. In order to avoid this difficulty, we utilize a linear antenna array system and propose a high-resolution imaging algorithm for this system based on a newly-developed reversible transform BST for a bi-static antenna. This method enables us to remarkably enhance the imaging resolution. By a numerical simulation, we clarify that the proposed method has a much higher resolution in the 3-dimensional imaging than the conventional SEABED method.

System Model

Fig. 1 shows the system model. We set a linear array composed of omni-directional antennas in x direction and scan it along y axis. We assume that the target has a uniform complex permittivity and a clear boundary. We define r-space as the real space, where targets and the antenna are located. We express r-space with the parameters (x, y, z). 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. We define $s'(X_{\rm T}, X_{\rm R}, Y, Z)$ as the received electric field when we set a transmitter and a receiver at $(X_{\rm T}, Y, 0)$ and $(X_{\rm R}, Y, 0)$ in r-space, respectively, where we define Z with time t and speed of the radiowave c as $Z = {\rm c}t/(2\lambda)$. We define $s(X_{\rm T}, X_{\rm R}, Y, Z)$ as the output of the matched filter. We extract $(X_{\rm T}, X_{\rm R}, Y, Z)$ as a quasi wavefront by connecting the peak points of $s(X_{\rm T}, X_{\rm R}, Y, Z)$. We also define d-space as the space expressed by $(X_{\rm T}, X_{\rm R}, Y, Z)$. The transform from d-space to r-space corresponds to imaging which we deal with in this paper.

Conventional Method

We have already developed a fast imaging algorithm called SEABED. This method assumes a mono-static antenna, and we define the antenna location as $(X, Y, 0)$ in r-space where $X = X_{\rm T} = X_{\rm R}$. We also define a point on the target boundary as (x, y, z). SEABED has an advantage of direct estimation of target boundaries using a reversible transform BST (Boundary Scattering Transform) between (x, y, z) and (X, Y, Z). The target shape (x, y, z) is expressed by IBST (Inverse BST) as

$$\left\{ \begin{array}{lll} x &=& X - ZZ_X \\ y &=& Y - ZZ_Y \\ z &=& Z\sqrt{1 - Z_X^2 - Z_Y^2}\ , \end{array} \right. \tag{1}$$

where $Z_X = \partial Z/\partial X, Z_Y = \partial Z/\partial Y$. SEABED achieves a fast imaging by applying IBST to estimated (X, Y, Z). However the resolution of this method is limited by the sampling number of scanning because it assumes a mono-static antenna. Also this method needs 2-dimensional scanning, which requires too long time.

Proposed Method

To solve these problems, we propose a high-resolution imaging algorithm with a linear antenna array based on BST for bi-static antennas. We define ΔX as the minimum distance of the array antennas. We select (X, Y, Z) which satisfies $X = X_{\rm T} + d = X_{\rm R} - d$ from $(X_{\rm T}, X_{\rm R}, Y, Z)$, where d is constant and satisfies $2d = k\Delta X, (k = 0, 1, ..., N_x - 1)$ as shown in Fig.1. Under this condition, a transform from (x, y, z) to (X, Y, Z) is expressed as

$$\left\{ \begin{array}{lll} X &=& x + \dfrac{2z_x(z^2 + z^2 z_x^2 + d^2)}{z(1 - z_x^2 + z_y^2) + \sqrt{z^2(1 + z_x^2 + z_y^2)^2 + 4d^2 z_x^2}} \\ Y &=& y + zz_y \\ Z &=& \sqrt{z^2(1 + z_y^2) + zz_x(X - x) + d^2}, \end{array} \right. \tag{2}$$

where $z_x = \partial z/\partial x, z_y = \partial z/\partial y$. We call this transform BBST (Bi-static BST). The inverse transform from (X, Y, Z) to (x, y, z) is expressed as

$$\left\{ \begin{array}{lll} x &=& X - \dfrac{2Z^3 Z_X}{Z^2 - d^2 + \sqrt{(Z^2 - d^2)^2 + 4d^2 Z^2 {Z_X}^2}} \\ y &=& Y + Z_Y\{d^2(x - X)^2 - Z^4\}/Z^3 \\ z &=& \sqrt{Z^2 - d^2 - (y - Y)^2 - (Z^2 - d^2)(x - X)^2/Z^2}. \end{array} \right. \tag{3}$$

We call this transform IBBST (Inverse BBST). These two transforms are inverse transforms of each other. IBBST is a mathematically complete solution for the inverse problem. Moreover it gives us a great advantage for the real-time imaging, because we can directly estimate the target shape for bi-static radar system. The procedures of the proposed method are as follows. We pick up a group of points

(X, Y, Z) from estimated $(X_{\mathrm{T}}, X_{\mathrm{R}}, Y, Z)$ under the condition $X = X_{\mathrm{T}} + d = X_{\mathrm{R}} - d$, and obtain the estimated points (x, y, z) with IBBST. By changing the distance d, we can increase the points of the image. The estimated points express different points on the target surface because the scattered waves propagate different paths. This is the reason why we can enhance the resolution of the target image.

Performance Evaluation

We set a target shape as shown in Fig. 2. We set a linear array at $-2.5 \leq x \leq 2.5$ whose number of antennas is $N_x = 16$. We scan it for $-2.5 \leq y \leq 2.5$, where we set the sampling number of the scanning as $N_y = 41$. We assume that the true quasi wavefront $(X_{\mathrm{T}}, X_{\mathrm{R}}, Y, Z)$ is obtained. Fig. 3 shows the estimated image with the original SEABED method. The total number of estimated points is 656. This figure shows that SEABED method has insufficient resolution to express the target surface for x direction, especially for the detail on the upper side of the target. This is because the number of the estimated points for x direction is limited to N_x. Fig. 4 shows the estimated image with the proposed method. The total number of estimated points is 4305. This figure shows that the proposed method obtains a remarkably higher resolution for x direction, and can express the target surface even on the small projection. This is because we can increase the number of the estimated points for x direction to $(N_x + 2)(N_x - 1)/2$. Also the calculation time of the imaging is within 0.03 sec at Xeon 3.2 GHz processor, which is quick enough for real-time operations.

Conclusion

We proposed an imaging algorithm with a linear antenna array based on a reversible transform BBST for a bi-static antenna. We showed that the proposed algorithm gives a high resolution image compared to the conventional SEABED.

Acknowledgment

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References

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[2] T. Sakamoto and T. Sato, "A fast algorithm of 3-dimensional imaging for pulse radar systems," 2004 IEEE AP-S International Symposium and USNC/URSI National Radio Science Meeting, Vol. 3, pp. 2099–2102, 2004.

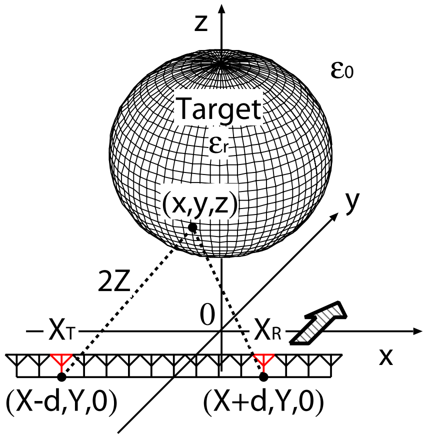

Figure 1: System model.

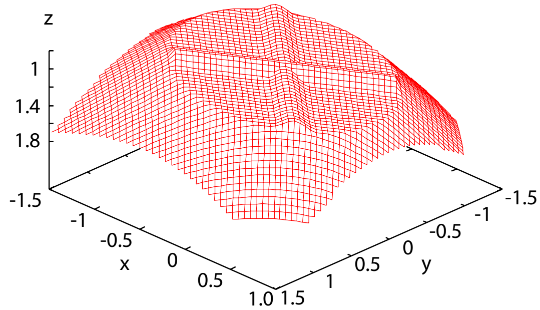

Figure 2: True boundary of the target.

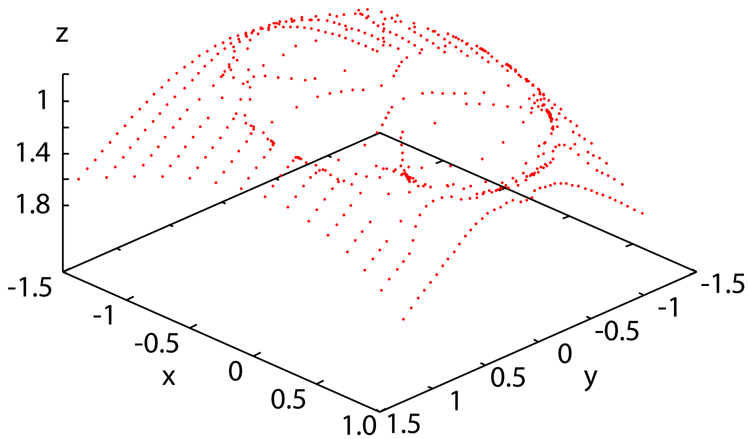

Figure 3: Estimated points with the conventional method ($N_x = 16, N_y = 41$, 656 points).

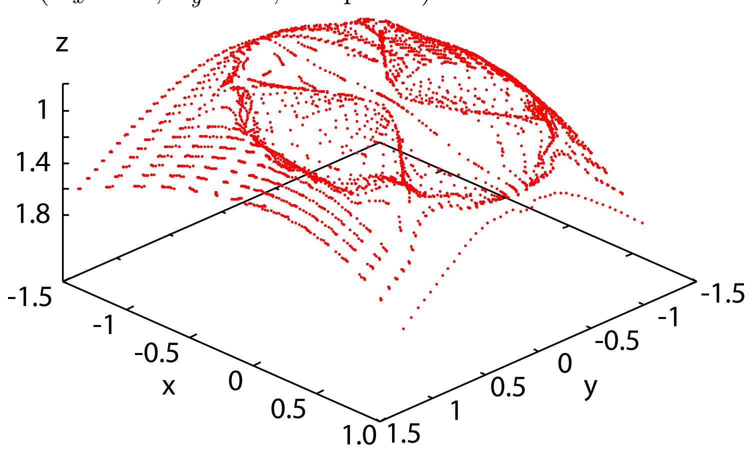

Figure 4: Estimated points with the proposed method ($N_x = 16, N_y = 41$, 4305 points).