High-Resolution 3-D Imaging Algorithm without Derivative Operations for UWB Through-the-Wall Radars

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1 Introduction

Recently, through-the-wall UWB radar has been extensively investigated for reliable human detection systems in disaster areas, in which survivors may be buried in collapsed walls or ruble. This technique requires quick, high-resolution imaging to avoid prolonging time in a dangerous situation for survivors and rescue operators. While various algorithms for through-the-wall radar have been proposed, all require intensive computation in data synthesis [1, 2]. Contrarily, the high-speed imaging algorithm, SEABED [3], which achieves direct and non-parametric imaging based on a reversible transform BST between the time delay and target boundary has been proposed. Application of SEABED for the through-the-wall imaging has been reported [4]. However, this work does not consider range errors, that depend on the thickness and electric permittivity of the wall. Thus, the image resolution becomes lower in the case of thick walls. Moreover, images obtained with SEABED is quite instable for random noises, because BST utilizes the derivative of the received data. In contrast, a fast 3-D (3-dimensional) imaging algorithm, Envelope, that does not require derivative operations to create a stable image has been proposed [5]. This algorithm uses the principle that an arbitrary target boundary can be expressed as the outer or inner envelopes of spheres, which are calculated from the observed ranges. However, for through-the-wall imaging, Envelope cannot reconstruct a correct image because it utilizes estimated ranges. To resolve this problem, we propose a high-resolution 3-D imaging algorithm by modifying Envelope. The target surface is calculated as the envelope of modified spheres, which are determined from the permittivity and thickness of the wall. In addition, this method can be combined with the direct range compensation method, SOC (Spectrum Offset Correction), which achieves high-resolution imaging, even for the edge of the target [5]. The results in numerical simulations verify that the proposed method achieves high-resolution 3-D imaging for targets behind a wall.

2 System Model

Fig. 1 shows the system model. It is assumed that the target has a convex shape with a clear boundary, and that the propagation speed is a known constant. An omni-directional antenna is scanned on a plane, $z = 0$. A rectangular wall with uniform permittivity $\epsilon_{\rm w}$ and thickness $d_{\rm w}$ is set parallel to the scanning plane. It is assumed that $\epsilon_{\rm w}$ and $d_{\rm w}$ are known constants. We utilize a mono-cycle pulse as the transmitting current, and assume linear polarization in the direction of the x-axis. R-space is defined as the real space where the target and antenna are located, and is expressed by the parameter (x, y, z). These parameters are normalized by λ, which is the center wavelength of the pulse. We assume $z > 0$ for simplicity. $s(X, Y, Z')$ is defined as the output of the matched filter to the received electric field at the antenna location $(x, y, z) = (X, Y, 0)$, where $Z' = \mathrm{c}t/(2\lambda)$ is expressed by the time t and the speed of the radio wave c. We connect the significant peaks of $s(X, Y, Z')$ as Z for each X and Y, and call this surface (X, Y, Z) a quasi wavefront. D-space is defined as the space expressed by (X, Y, Z). The transform from d-space to r-space corresponds to the imaging, dealt with in this paper.

3 Proposed Algorithm and Performance Evaluation

It has been reported that SEABED can be applied to the high-speed imaging for the through-the-wall application [4]. However, the image with SEABED is quite instable with random noises because the target direction is estimated based on differential range from adjacent antenna positions, which is sensitive to noise. To avoid instability, we utilize the stable and fast 3-D imaging algorithm without derivative operations as Envelope [5]. This algorithm utilizes the principle that the target surface can be expressed as the outer or inner envelope of the spheres with a center point $(X, Y, 0)$, and radius Z. Fig. 2 illustrates the relationship between the target boundary and the envelopes of the circles in a 2-D model, for simplicity. For convex targets, the z coordinates of the target boundary is calculated for given (x, y) as

$$z = \max_{X,Y} \sqrt{Z^2 - (x - X)^2 - (y - Y)^2}. \tag{1}$$

Eq. (1) determines the target boundary without derivative operations. Thus, the instability caused by random noise is suppressed. Application of this method to through-the-wall imaging is demonstrated here. A trapezoidal target is assumed and a rectangular wall is set $0.35\lambda \le z \le 0.49\lambda$. $\epsilon_{\mathrm{w}} = 5.0\ \epsilon_0$, and the conductivity of wall is 2.0×10^{-3} S/m. The signals are received for $-1.75\lambda \le x, y \le 1.75\lambda$ equal intervals 0.07λ. Fig. 3 shows that the estimated image with Envelope is considerably distorted, and cannot reconstruct the correct target boundary. This is because each scattering path is bent by the wall, and the estimated ranges have large offset errors. This image distortion is fatal for target identification, such as human detection.

To avoid this image distortion, we modify Envelope as follows. This method compensates for range shift due to wall penetration, and utilizes the envelope of modified spheres, that can be calculated from the permittivity and the thickness of wall. Fig. 4 shows the relationship between the target boundary and modified circles in a 2-D model. Each scattered path satisfies Snell's law. Here, the scattering path exists on the same plane because the rectangular wall is set parallel to the x-y plane. In these conditions, the target boundary can be expressed as the envelope of the following surfaces,

$$\left.\begin{array}{lcl} x &=& X + \left\{ Z - \frac{d_{\mathrm{w}}(\epsilon-1)}{\sqrt{\epsilon-\cos^2\phi}} \right\} \cos\phi\cos\theta \\ y &=& Y + \left\{ Z - \frac{d_{\mathrm{w}}(\epsilon-1)}{\sqrt{\epsilon-\cos^2\phi}} \right\} \cos\phi\sin\theta \\ z &=& d_{\mathrm{w}} + \left(Z - \frac{\epsilon d_{\mathrm{w}}}{\sqrt{\epsilon-\cos^2\phi}} \right) \sin\phi \end{array}\right\}, \tag{2}$$

where θ and ϕ are defined as $0 \leq \theta < 2\pi$ and $0 \leq \phi \leq \pi/2$, respectively. The z coordinates of the target boundary can be calculated for each (x, y),

$$z = \max_{X,Y} \left\{ d_{\mathrm{w}} + \left(Z - \frac{\epsilon d_{\mathrm{w}}}{\sqrt{\epsilon - \cos^2 \widehat{\phi}}} \right) \sin \widehat{\phi} \right\}, \qquad (3)$$

where $\widehat{\phi}$ can be numerically calculated with the first and second equations in Eq. (2) for given (x, y). We call this algorithm as modified Envelope.

The performance evaluations with this method are described as follows. It assumes that ϵ_{w} and d_{w} are known constant. Fig. 5 shows the estimated boundary obtained by the modified Envelope with the received signals used in Fig. 3. It remarkably enhances the accuracy for the estimated image. However, the image is slightly distorted especially around the target edges. This is because the scattered waveform deformations cause the errors of observed ranges in the waveform matching. We have proposed the direct range compensation with spectrum offset correction for the deformed waveform, which is termed SOC [5]. SOC approximates the range shift ΔZ as

$$\Delta Z = \left(f_{\mathrm{tr}}^{-1} - f_{\mathrm{sc}}^{-1} \right) f_0 / W, \qquad (4)$$

where $f_0 = \mathrm{c}/\lambda$, f_{tr} and f_{sc} are the center frequencies of the transmitted and scattered waveform, respectively. $W = 4$ is constant. Fig. 6 shows the estimated image after range compensation with SOC. This verifies that the resolution around the edge region is enhanced with the correctly estimated ranges. We also confirm that the proposed method is effective even in noisy situations, where S/N $\geq$ 25dB. The calculation time for imaging is around 4.0 sec for a Xeon 2.8 GHz processor.

4 Conclusion

We proposed a modified Envelope as high-resolution 3-D imaging algorithm for through-the-wall UWB radars. This algorithm utilizes the principle that the target boundary behind the wall can be expressed as an envelope of modified spheres, which are determined from the electric permittivity and thickness of the wall. In numerical simulation, we confirmed that the proposed method achieves higher-resolution 3-D imaging for advanced through-the-wall applications. It is our future task to develop the imaging algorithm with the wall permittivity and thickness estimation.

References

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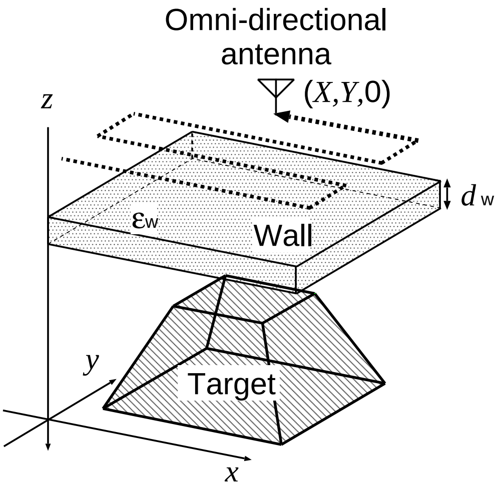

Figure 1: System model.

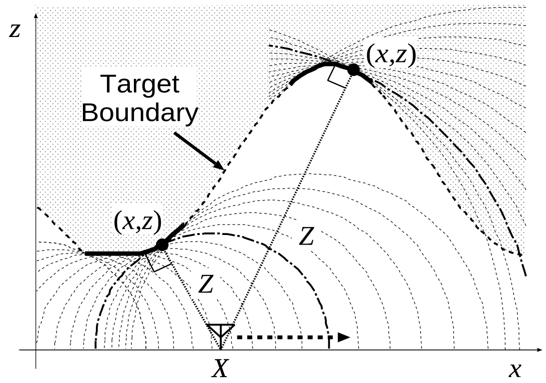

Figure 2: Relationship between target boundary and envelopes of circles.

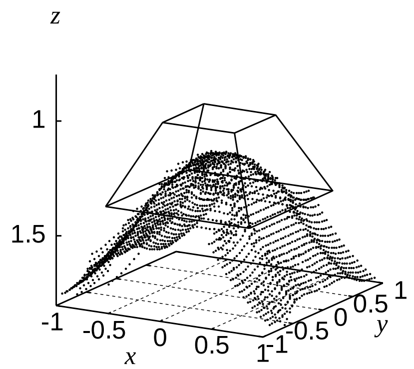

Figure 3: Estimated image with Envelope.

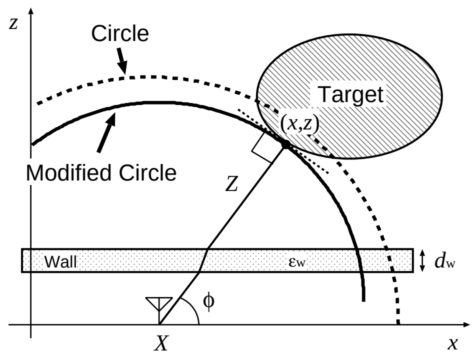

Figure 4: Relationship between modified circle and target boundary.

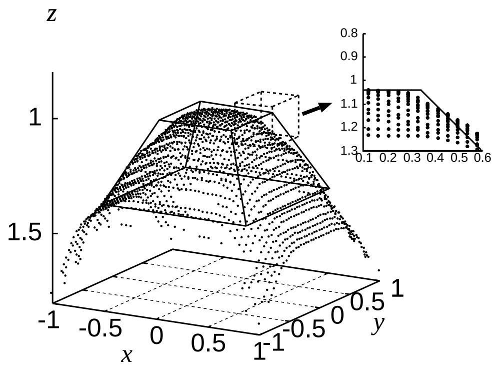

Figure 5: Estimated image with modified Envelope.

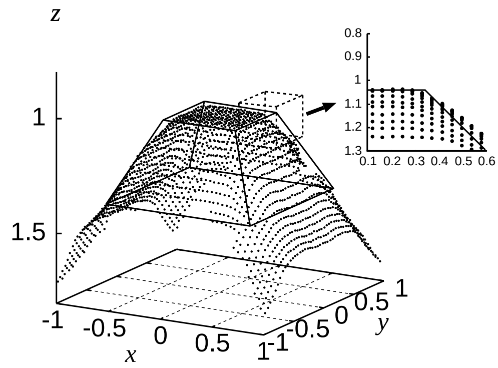

Figure 6: Estimated image with modified Envelope and SOC.