

An Experimental Study of High-Resolution 3-D Imaging Algorithm with Envelope of Modified Spheres for UWB Through-the-Wall Radars

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1 Introduction

Through-the-wall radar techniques have been highly developed for various applications, such as human detection buried under collapsed walls in disaster areas. These applications require a high-resolution imaging to detect the target shapes. While various through-the-wall radar algorithms have been proposed, they require intensive computation with SAR (Synthetic Aperture Radar) or other migration algorithms [1]. Contrarily, the real-time 3-D imaging algorithm, SEABED has been proposed [2]. This is a non-parametric 3-D imaging based on a reversible transform between time delay and target boundary. Furthermore, the extension study for SEABED to through-the-wall imaging has been reported [3]. However, these methods suffer from the distortions due to the range shifts of wall penetrations. In addition, SEABED is sensitive to small range errors, because it uses a derivative of the observed ranges. To obtain a stable image, the high-speed 3-D imaging algorithm, Envelope, has been developed, which does not use derivative operations [4]. For through-the-wall imaging, however, the observed range shift causes an error also for the Envelope imaging. As a solution to this problem, this paper proposes a high-resolution and high-speed 3-D imaging algorithm by modifying the original Envelope method, that considers the bent paths caused by the wall penetrations. In addition, this method can be combined with SOC (Spectrum Offset Correction) technique [4], that directly compensates the range shift due to scattered waveform deformation. The investigations with a numerical simulation and experiment verify that our algorithm produces a high-resolution 3-D image even for the through-the-wall imaging.

2 Modified Envelope for Through-the-Wall Radar

The left side of Fig. 1 shows the system model. A target with a convex boundary in the air is assumed. The current waveform at the transmitted antenna is mono-cycle pulse. An omni-directional antenna is scanned on the plane, $z = 0$. A planar wall with a uniform relative permittivity ϵ_w and thickness d_w is set parallel to x - y plane, where ϵ_w and d_w are known constants. R-space is defined as the real space, where the target and the antenna are located with the parameter (x, y, z) . $s(X, Y, Z')$ is defined as the output of the matched filter to the received electric field at the antenna location $(x, y, z) = (X, Y, 0)$. 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.

The original Envelope in 3-D model uses the principle that a target surface is expressed as an envelopes of spheres, with center $(X, Y, 0)$ and radius Z [4]. This

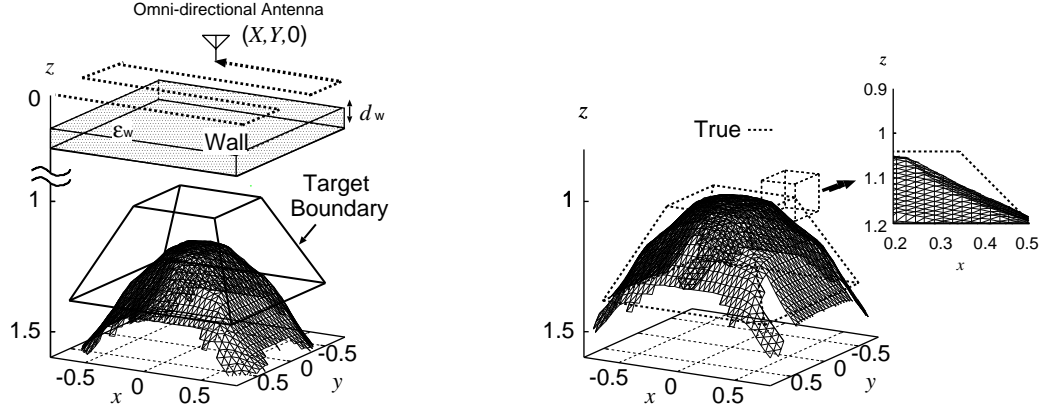


Figure 1: System model and images obtained by the original Envelope (left) and the modified Envelope with SOC (right).

method calculates the z coordinate of a convex target boundary for given (x, y) as,

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

Eq. (1) determines an arbitrary convex boundary without derivative operations, that removes the image fluctuation occurring in the SEABED. However, for through-the-wall imaging, the image obtained using this method is distorted by range shifts due to wall penetration. The left hand side of Fig. 1 shows the boundary obtained by the original Envelope. This is because this method does not consider the range shift due to the wall penetration. A trapezoidal target is assumed. $\epsilon_w = 5.0$, $d_w = 0.2\lambda$, and $\sigma = 2.0 \times 10^{-3}$ S/m. This figure shows that the image has a large error especially for z -direction, and the estimated shape is different from the actual one.

To resolve this problem, the original Envelope is extended to apply to the through-the-wall model. The simple 3-D Snell's law to a planar wall is considered. The modified Envelope expresses the target boundary as an envelope of the following surfaces,

$$\left. \begin{aligned} x &= X + \{Z(X, Y) + d_w(1 - \epsilon_w)\Psi(\phi)\} \cos \phi \cos \theta \\ y &= Y + \{Z(X, Y) + d_w(1 - \epsilon_w)\Psi(\phi)\} \cos \phi \sin \theta \\ z &= d_w + \{Z(X, Y) - \epsilon_w d_w \Psi(\phi)\} \sin \phi \end{aligned} \right\}, \quad (2)$$

where $0 \leq \theta \leq \pi$, $0 \leq \phi \leq \pi/2$, and $\Psi(\phi) = 1/\sqrt{\epsilon - \cos^2 \phi}$. This method is based on the principle that the convex target boundary behind a wall can be expressed as an outer envelope of the modified spheres. The z coordinates of target boundary is calculated for each (x, y) as,

$$z(x, y) = \max_{X, Y} \left[d_w + \left\{ Z(X, Y) - \epsilon_w d_w \Psi(\hat{\phi}(x, y, X, Y)) \right\} \sin \hat{\phi}(x, y, X, Y) \right], \quad (3)$$

where $\hat{\phi}(x, y, X, Y)$ can be solved from the 1st and 2nd equations in Eq. (2) for given (x, y) . Eq. (3) guarantees that an arbitrary convex boundary can be reconstructed with a correct Z . The right hand side of Fig. 1 shows the image obtained by the modified Envelope after the direct range compensations termed as SOC [4], which

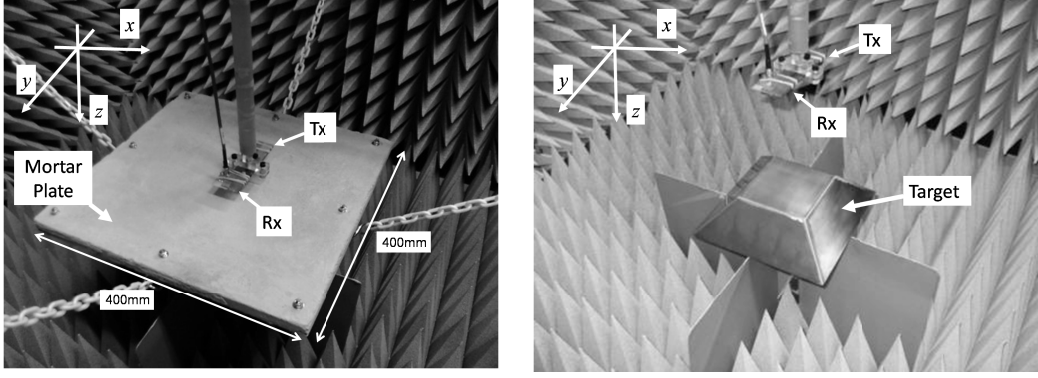


Figure 2: Experimental setups of mortar plate (left) and trapezoidal target (right).

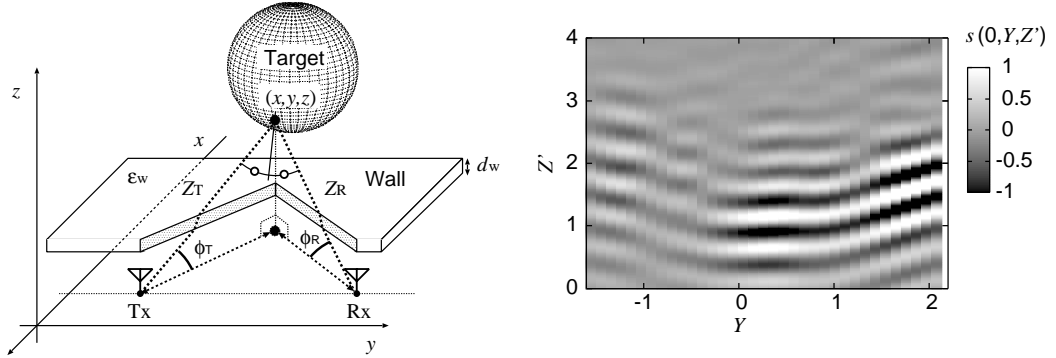


Figure 3: Scattering paths for bi-static model (left) and the output of the matched filter in experiment at $X=0$ (right).

compensates the range error due to waveform deformations. The estimated image with this method reconstructs a correct target boundary including the edge regions. This super-resolution imaging offers a reliable target recognition for the through-the-wall applications. The calculation time for imaging is about 4 sec with a single Xeon 3.2 GHz processor.

3 Performance Evaluation with Experiment

The experimental study of the proposed algorithm is investigated as follows. UWB pulse with a center frequency of 3.3 GHz and the 10dB-bandwidth of 2.0 GHz is used. The direction of the polarimetry axis of the antenna is along the y -axis. The target is a trapezoidal-shaped stainless steel object. A planar wall made of mortar is assumed. The thickness of wall is 17mm, and $\epsilon_w = 4.79$, which can be easily measured from the time delay of wall penetration. The left and right hand sides of Fig. 2 illustrate the arrangement of antennas with respect to the mortar plate and the trapezoidal target, respectively. The separation between the Tx and Rx antennas is 75 mm in the y -direction. The direct scattered signal from a trapezoidal target can be obtained by eliminating the reflection signal from only the mortar plate without a target.

For this experimental setup, the proposed method must be extended to bi-static

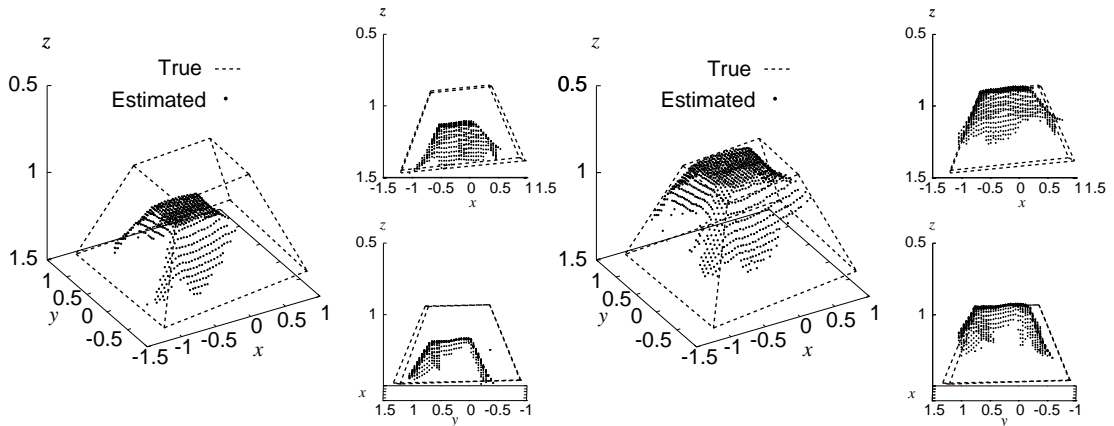


Figure 4: Estimated images with the original Envelope (left) and the modified Envelope+SOC (right) in the experiment.

model. The left hand side of Fig. 3 shows the bent scattering path for bi-static radar scanning. Applying Snell's law to each scattering plane, we confirm that the principle of the modified Envelope can be completely expanded to the bi-static radar model. The right hand side of Fig. 3 is the output of the matched filter for the scattered waveform at $X = 0$. The S/N is about 24 dB. The amplitudes of the received signals are not symmetrical for Y axis because of the asymmetry of the radiated antenna patterns. The left hand side of Fig. 4 shows the estimated image of the original Envelope. This figure offers that there is a non-negligible error for z axis due to wall penetrating. Contrarily, the right hand side of Fig. 4 shows the image obtained by the modified Envelope with the bi-static extension after range compensation SOC. This image has been correctly reconstructed including the target edges. There are some image distortions around the region for $y \simeq -0.5\lambda$ because the received signal from this region becomes small due to the asymmetry of the antenna pattern, as shown in the right side of Fig. 3. However, this distortion is not a substantial problem in the proposed method because it can be resolved by using another type of antenna with a symmetric pattern. Also the wall parameters ϵ_w and d_w can be estimated through other techniques [1]. This experimental verification shows that our algorithm offers a substantial improvement for high-resolution 3-D imaging, even for targets behind a thick wall.

References

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