Experimental Study of Shadow Region Imaging Algorithm with Multiple Scattered Waves for UWB Radars

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Abstract— Ultra-wide band (UWB) radar holds high range resolution in the near field sensing, and is thus applicable to security systems designed to identify a human body even in invisible situations. Although Synthetic Aperture Radar (SAR) creates a stable and accurate target image for such applications, it often suffers from increased shadow regions in the case of complex or multiple targets. On the contrarily, a multiple scattered wave has the potential to enlarge a visible range on target surfaces because it propagates a path which differs from that of a single scattered wave. While various algorithms based on time-reversal processing with multiple scattered waves have been developed, these require a priori information of surroundings or a target model. This paper proposes a shadow region imaging algorithm based on the aperture synthesis of multiple scattered waves. While the proposed algorithm only synthesizes a double scattered wave according to its propagation path, it can directly increase the visible area and is applicable to arbitrary target shapes. The results in the numerical simulation and experiment verify that the proposed algorithm directly makes a shadow region visible without a preliminary observation.

1. INTRODUCTION

UWB pulse radar is promising as a near field sensing technique with high range resolution, and is applicable to non-contact measurement for reflector antennas or aircraft bodies that have precision and specular surfaces. It is also applicable to a collision avoidance for automobile in the low visibility. For such applications, various imaging algorithms have been published, as the SEABED accomplishes a real-time imaging by using a reversible transform BST[1], and the Envelope+SOC reconstructs the target surface in the accuracy at the order of 1/100 wavelength [2]. The SAR algorithm is also promising, in terms of providing a stable and accurate image by using full information of received signals [3]. However, in the case of complex or multiple targets, any of algorithms suffers from increased shadow regions because it uses only the single scattered wave for imaging. On the contrarily, except for a edge diffraction wave, a multiple scattered wave propagates the path that is different from that of a single scattered wave, and this means that the multiple scattered echo has the potential to enhance the visible range. Although the time reversal algorithms with multiple scattered waves have been proposed when focusing on a reliable target detection or accurate positioning in cluttered situations [4, 5, 6], they require a target modeling or a priori information of the surrounding environment like walls. To expand the applicability of these methods, this paper proposes a direct imaging algorithm based on the aperture synthesis of multiple scattered signals. The results obtained from numerical simulation and an experiment verify the effectiveness of the proposed method that it is applicable to arbitrary target shapes, and directly enlarges the visible range on the target surface.

2. CONVENTIONAL ALGORITHM

Fig. 1 shows the system model. It assumes that the target has an arbitrary shape with a clear boundary, and high conductivity like metallic objects. The propagation speed of the radio wave c is assumed to be known constant. A mono-cycle pulse is used as the transmitting current, and the space is normalized by λ as the center wavelength of the pulse. The omni-directional antenna that is scanned on the plane $z = 0$. The real space in which the target and antenna are located is expressed by the parameter $\boldsymbol{r} = (x, y, z)$. $z > 0$ is assumed for simplicity. $s(X, Y, Z)$ is defined as the output of the Wiener filter at the antenna location $(x, y, z) = (X, Y, 0)$, where $Z = ct/(2\lambda)$ is expressed by the time t.

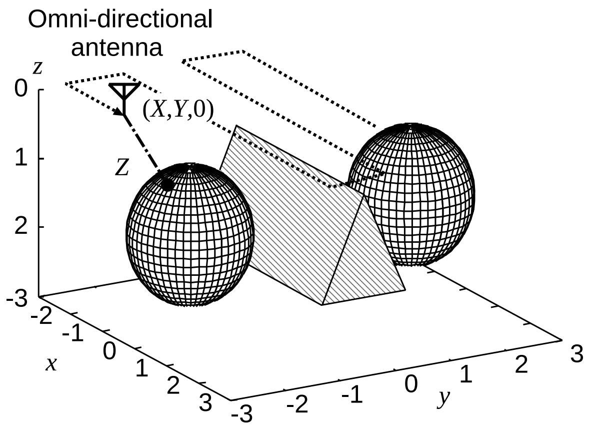

Figure 1: System model.

As the spatial measurement in the near field, the SAR algorithm has an ability to create a stable and accurate image by using UWB signal. The distribution image $I_1(\boldsymbol{r})$ obtained by the SAR is formulated as

$$I_1(\boldsymbol{r}) = \int_{\boldsymbol{q}\in\Gamma} s\left(\boldsymbol{q}, d_1(\boldsymbol{r}, \boldsymbol{q})/2\right) \mathrm{d}X\mathrm{d}Y \tag{1}$$

where $\boldsymbol{q} = (X, Y)$ and Γ is the scanning range of the antenna. $d_1(\boldsymbol{r}, \boldsymbol{q})$ is the round-trip distance between the point $\boldsymbol{r}$ and the antenna location as $(X, Y, 0)$. The target boundary can be extracted from its focused image $I_1(\boldsymbol{r})$. This algorithm has an advantage that it can produce a stable and accurate image for various target shapes The example of this method is presented as follows. The target shown in Fig. 1 is assumed. The received signals are observed for $-2.5 \leq X, Y \leq 2.5$ at 51 locations in each axis. The left hand side of Fig. 2 shows the image viewed at $x = 0$ with the conventional method. This figure shows that the image expresses only the bottom part of the target boundary, and the most part of the triangular boundary falls into shadow regions. This is because the distinguishable echo from this area cannot be observed at any antenna location, since the inclination of the triangle boundary is too large. This is an inherent problem in the conventional algorithms [1, 2] that only use single scattered echoes for a target reconstruction.

3. PROPOSED ALGORITHM

To overcome the previous problem, this paper proposes a shadow region imaging algorithm based on the aperture synthesis of double scattered signals. A double scattered wave propagates a different path from that of a single scattered one, except for an edge diffraction wave. Then, it often provides a significant information of two scattering centers on the target boundaries. The proposed method calculates the distribution image $I_2(\boldsymbol{r})$ synthesized by the double scattering waves as

$$I_2(\boldsymbol{r}) = -\int_{\boldsymbol{q}\in\Gamma} \int_{\boldsymbol{r'}\in R} I_1(\boldsymbol{r'}) s\left(\boldsymbol{q}, d_2(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{q})/2\right) F(\boldsymbol{r}, \boldsymbol{r'}\boldsymbol{q}) \ \ \mathrm{d}x'\mathrm{d}y'\mathrm{d}z'\mathrm{d}X\mathrm{d}Y$$

where $\boldsymbol{r'} = (x', y', z')$, R denotes the region of the real space. $d_2\left(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{q}\right)$ is the peripheral distance of the triangle whose apexes are located at $\boldsymbol{r}$, $\boldsymbol{r'}$ and the antenna location. The weight function $F(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{q})$ is defined as

$$F(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{q}) = 1 - \exp\left[-\frac{\{d_2(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{q}) - d_1(\boldsymbol{r}, \boldsymbol{q})\}^2}{2\sigma_{\mathrm{FZ}}^2}\right], \tag{2}$$

where σ_{FZ} is determined empirically. $F(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{q})$ suppress the weight for the region included in the Fresnel zone, which is determined by the initial image $I_1(\boldsymbol{r})$. The minus sign in Eq. (2) creates a positive image focused by double scattered waves, that have an inverse phase relationship from that of single scattered wave. Eq.(2) expresses the aperture synthesis of the received signals by only considering a double scattered path.

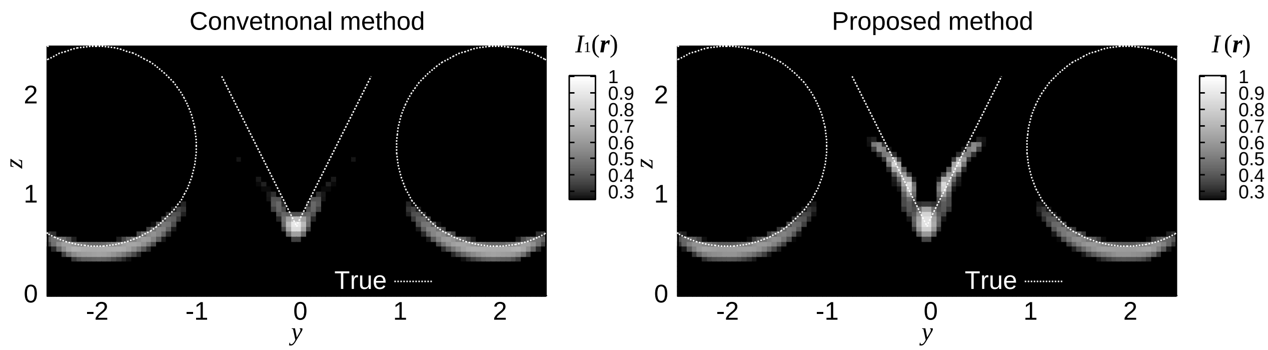

Figure 2: Estimated images with the conventional (left) and the proposed method (right).

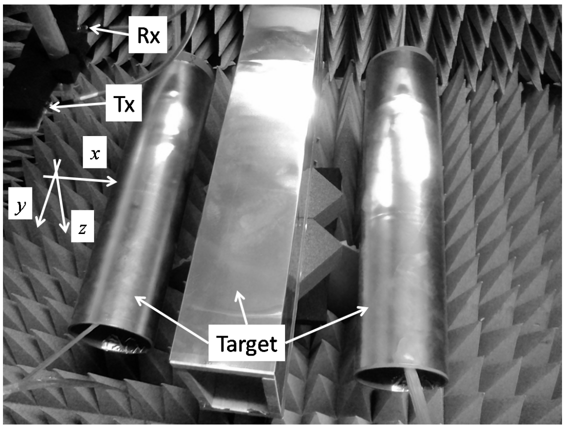

Figure 3: Arrangement of the antenna and the multiple targets in the experiment.

Here, we assume that only the positive images of $I_1(\boldsymbol{r})$ and $I_2(\boldsymbol{r})$ are necessary for the target boundary extraction. Then, the proposed method determines the final image $I(\boldsymbol{r})$ as,

$$I(\boldsymbol{r}) = I_1(\boldsymbol{r})H(I_1(\boldsymbol{r})) + I_2(\boldsymbol{r})H(I_2(\boldsymbol{r})), \tag{3}$$

where $H(x)$ is defined as

$$H(x) = \begin{cases} 1 & (x \geq 0)\ , \\ 0 & (x < 0)\ . \end{cases} \tag{4}$$

The proposed method uses only the initial image $I_1(\boldsymbol{r})$ and directly emphasizes the target regions which double scattered waves passed through. The right hand side of Fig. 2 shows the example of the proposed method viewed at $y = 0$, when the same data in the left side hand of Fig. 2 is used. $\sigma_{\rm FZ} = 0.5\lambda$ is set. This result verifies that the proposed method enlarges the reconstructible region, and the area around the triangular side becomes visible. This is because the double scattered waves are effectively focused on the triangular side by using Eq. (2).

4. PERFORMANCE EVALUATION IN EXPERIMENT

This section shows the experimental investigation of the proposed algorithm. Fig. 3 shows the experimental setup with both cylindrical and rectangular targets. The UWB pulse with a 10 dB-bandwidth of 2.0 GHz and a center wavelength λ of 93.75 mm is used. The pair of the transmitting and receiving antennas is scanned on the $z = 0.0\lambda$ plane, for $-3.0\ \lambda \leq x \leq 3.0\lambda$ and $-1.0\lambda \leq y \leq 1.0\lambda$, respectively, with each sampling interval set to 0.1λ. The antenna has an elliptic polarization, and the major polarimetric axis is along the y-axis. The data is coherently averaged by 1024 times. The direct scattered signal from the trapezoidal target can be obtained by eliminating the reflection signal without a target.

Fig. 4 shows the output of the Wiener filter viewed at $Y = 0$ in the experiment. The S/N of the double scattered wave is around 25 dB. The left hand side of Fig. 5 shows the estimated image at

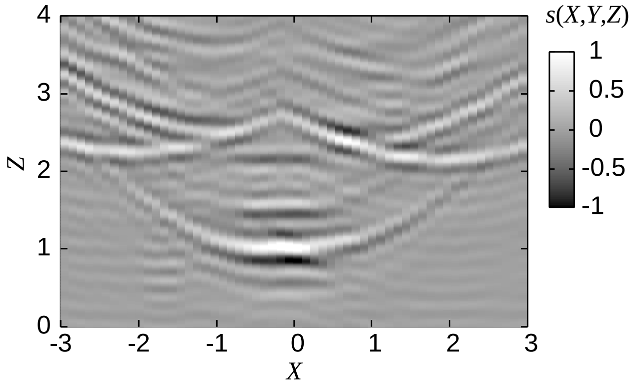

Figure 4: Output of the Wiener filter in the experiment at $Y = 0$.

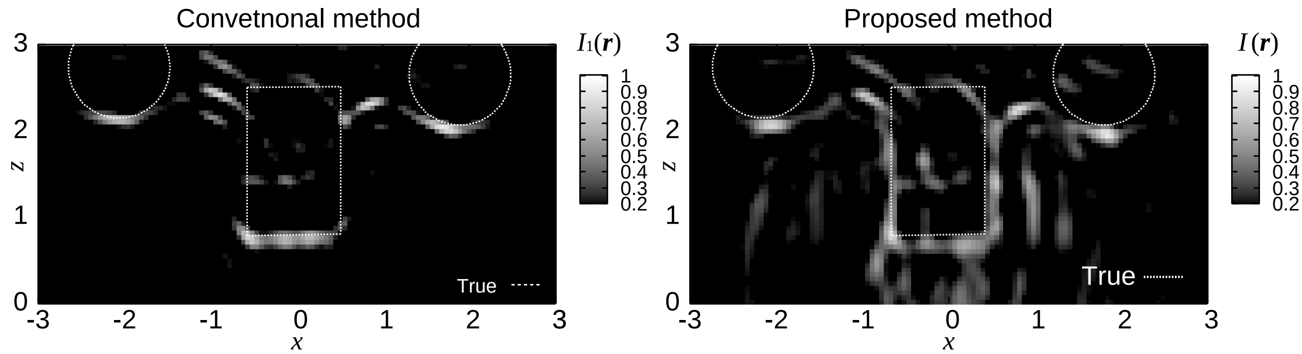

Figure 5: Estimated images with the conventional method (left) and proposed method (right) in the experiment ($y = 0$).

$y = 0$ with the conventional method. This figure shows that only the bottom part of the rectangular target is reconstructed, and the target shape is hardly identified. The right hand side of Fig. 5 shows the estimated image with the proposed method, where the bi-static extension is applied. Contrarily, this image reconstructs the side of the rectangular target, and offers a significant information to identify the target shape. This result verifies that the proposed method effectively enhances the visible area on target surfaces even in a real environment. Moreover, it is noteworthy that this method does not require a target modeling or a priori information of the surroundings, and yet it is a substantial improvement from the conventional works [4, 5, 6]. However, the calculation time to obtain an each cross-section image, is required around 100 minutes with a single Xeon 2.8 GHz processor. Thus, the acceleration of the imaging speed becomes our future work.

5. CONCLUSION

This paper proposes the direct shadow region imaging algorithm based on the aperture synthesis for double scattered waves. In the conventional SAR, the greater part of a complex target or multiple targets falls into a shadow region because it uses only a single scattered wave. To overcome this problem, we extend the SAR algorithm to use double scattered waves. The results from the numerical simulation and experiment verify that the proposed algorithm can enhance the visible region and offers a significant target image even in a real environment. In addition, it is a substantial advantage of the proposed method that it does not require the priori information of surroundings or target models. Although the proposed method requires a great deal of calculation, this algorithm can expand the application range of the near field radar in cluttered situations.

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