Double-layered Boundary Extraction Using Extended Envelope with Multi-static UWB Radars

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Abstract - **Microwave ultra-wide band (UWB) radars with higher range resolution and penetration ability for low lossy medium are promising as non-destructive testing for aging transportation infrastructure or non-invasive internal inspection for human body such as cancer or brain stroke detection. While there are many studies for reconstructing complex permittivity for object based on the solution of domain integral equation, they suffer from extremely high computation cost and inaccuracy around discontinuous boundary due to relying on non-linear and multi-dimensional optimization approach. As another approach alleviating such problem, the boundary extraction based methods such as RPM or Envelope have been developed by incorporating ray tracing based dielectric constant estimation. This paper extends the above method for multi-static observation model, which has a possibility expand the reconstruction area compared with that obtained by mono-static model. The results from numerical simulation show that our extension model considerably enhances an accuracy for double layered boundary extraction, combined by the dielectric constant estimation.**

Index Terms — **Microwave UWB radar, Envelope method, Inverse scattering problem, Dielectric boundary extraction**

1. Introduction

There is a strong demand for microwave UWB sensors for safe and higher-resolution internal imaging, which has potential for wide variety applications, such as non-destructive testing for crack detection of aging road or tunnel with non-contact measurement, or non-invasive medical screening for the human body, known as breast tumor detection or brain stroke detection. UWB radar has a distinct advantage for higher range resolution, and deeper penetration ability especially for lower frequency. One of the most serious drawback of this radar system is lower spatial resolution, compared with that obtained by ultrasound, MRI or X-ray based sensors. As highly accurate and spatial resolution imaging techniques beyond the traditional delay-sum based approaches, such as beamforming or time-reversal methods, the range points migration (RPM) [1] or Envelope methods [2] have been developed, for extracting dielectric boundaries. However, these methods should be combined with efficient dielectric constant estimation method to maintain its reconstruction accuracy, especially for object buried in dielectric medium.

As classical approach to extract the permittivity distribution not only dielectric constant but also conductivity, the solution for domain integral equation [3] has been developed. However, such method usually suffers from massive computational cost and inaccuracy around discontinuous and higher contrast of permittivity distribution, because they quire multi-dimensional and non-linear optimization problems. As less computational and higher accuracy dielectric constant estimation, the method [4] has been developed, which is based on the incorporation of accurate boundary extraction method as Envelope [2] and the ray tracing propagation delay estimation. However, these methods are only oriented to monostatic observation model, and some cases have shown that a shape of buried target could not be completely reconstructed due to lack of reflection from a part of inner target. As solution for this difficulty, this paper extends the method [4] to the multi-static observation, which increases different reflection paths, and has possibility to expand the potential reconstruction area. The results in numerical simulation show that our extended method successfully reconstructs a whole shape of inner objects, which cannot be achieved by the conventional model, in simultaneously providing accurate dielectric constant estimation for double-layered medium.

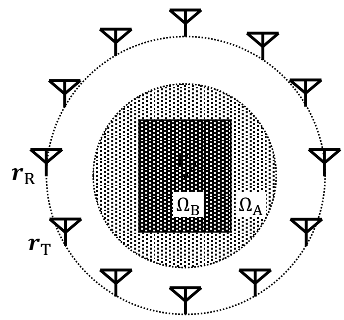

Fig. 1. System model.

2. System Model

Figure 1 shows the system model. This paper deals with the two-dimensional problem, for simplicity. It is assumed that a dielectric object has a double layer structure. The regions for outer and inner medium are defined as Ω_A and Ω_B, respectively. A number of omni-directional antennas are arranged on the circumference of circle, centered at $\boldsymbol{r}_c$, which completely surrounds the dielectric object, as shown in Fig. 1. $s(\boldsymbol{r}_T, \boldsymbol{r}_R, R)$ is defined as the output of the Wiener filter, where the transmitting and receiving antennas are located at $\boldsymbol{r}_T = (X_T, Z_T)$ and $\boldsymbol{r}_R = (X_R, Z_R)$, respectively, model, one antenna transmits a pulse and the other antennas receive a reflection echo at the same instant, and the location of the transmitting antenna is subsequently and $R = ct/2$ is

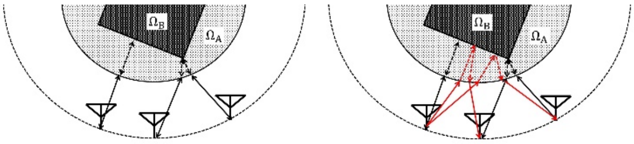

Fig. 2. Propagation path (left: mono-static, right: multi-static).

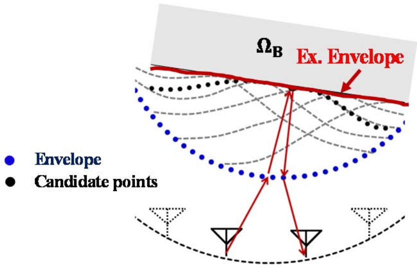

Fig. 3. Candidate curves and their envelope.

expressed using time t. In the multi-static switched to a different location of array arrangement. From these data, $s_1(\boldsymbol{r}_\mathrm{T}, \boldsymbol{r}_\mathrm{R}, R)$ are defined, where $\| \boldsymbol{r}_\mathrm{T} - \boldsymbol{r}_\mathrm{R} \| \leq \Delta X$ holds, and $s_2(\boldsymbol{r}_\mathrm{T}, \boldsymbol{r}_\mathrm{R}, R)$ are defined, where $(\boldsymbol{r}_\mathrm{T} + \boldsymbol{r}_\mathrm{R})/2 = \boldsymbol{r}_\mathrm{c}$ holds, respectively. The range points extracted from the local maxima of $s_1(\boldsymbol{r}_\mathrm{T}, \boldsymbol{r}_\mathrm{R}, R)$ and $s_2(\boldsymbol{r}_\mathrm{T}, \boldsymbol{r}_\mathrm{R}, R)$ are defined as $\boldsymbol{q}_1 \equiv (\boldsymbol{r}_{\mathrm{T},1}, \boldsymbol{r}_{\mathrm{R},1}, \mathrm{R}_1)$ and $\boldsymbol{q}_2 \equiv (\boldsymbol{r}_{\mathrm{T},2}, \boldsymbol{r}_{\mathrm{R},2}, \mathrm{R}_2)$ respectively, the extraction process is detailed in [4]. Each set including $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$ is denoted Q_1 and Q_2, respectively.

3. Proposed Method

This section describes the methodology of double-layered boundary extraction in multi-static observation model. Figure 2 shows that multi-static model takes more independent paths, resulting in image expansion. In this method, the set of range points $\boldsymbol{q}_{\mathrm{A},1}$, denoted as $Q_{\mathrm{A},1}$, is extracted from Q_1, where $s_1(\boldsymbol{q}_{\mathrm{A},1})$ has the maximum value at each antenna combination, regarded as the measured range from the antenna to the outer dielectric boundary. The outer dielectric boundary points are estimated and interpolated by sequentially applying the RPM [1] and Envelope methods [2] to the range points $\boldsymbol{q}_{\mathrm{A},1}$. Second, the remaining range points are extracted from Q_1 as $\boldsymbol{q}_{\mathrm{B},1}$. The set of all $\boldsymbol{q}_{\mathrm{B},1}$, denoted as $Q_{\mathrm{B},1}$, should satisfy $Q_{\mathrm{B},1} = Q_1 \cap Q_{\mathrm{A},1}$. To reconstruct the inner dielectric boundary $\partial\Omega_\mathrm{B}$, the extended Envelope method [4] is extended to multi-static model. Figure 3 illustrates the reconstruction principle of the extended Envelope method in this model. In this method, the candidate curve of the inner boundary point of each range point $\boldsymbol{q}_{\mathrm{B},1}$ is calculated by ensuring that the estimated outer dielectric boundary points $\boldsymbol{p}_{\mathrm{A},1}$ and their normal vectors satisfy Snell's law with the assumed ϵ_A. It should be noted that, in multi-static case, the incident and exiting points on the outer boundary is not located to same position. Except for this point, the same principle in mono-static case can be applied that the outer envelope of the candidate curves is then extracted as the inner dielectric boundary. Note that, dielectric constants for both medium Ω_A and Ω_B are estimated by the same approach [4] using outer and inner boundary extracted by this method.

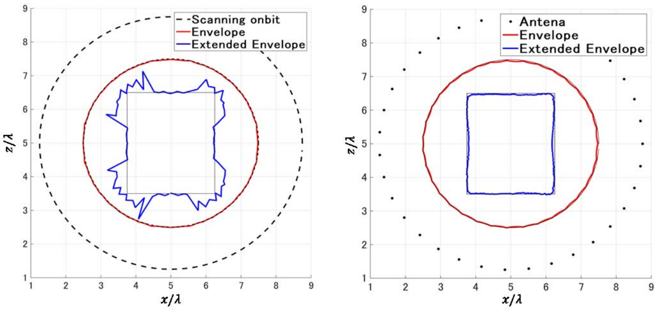

Fig. 4. Boundary reconstruction results (left: mono static, right: multi-static).

4. Analysis in Numerical Simulation

This section describes the numerical simulation based evaluation for our method. The target and antenna arrangement are as shown in Fig 1. The number of array antennas is 36, which is equally spaced. The received data are generated by FDTD method. The dielectric constants of Ω_A and Ω_B denote $(\epsilon_\mathrm{A}, \epsilon_\mathrm{B}) = (3.0, 5.0)$, where the conductivities are both 0.01 S/m. In this case, the dielectric constants for each medium is estimated as $(\widehat{\epsilon_\mathrm{A}}, \widehat{\epsilon_\mathrm{B}}) = (3.0, 4.5)$. The left and right sides of Fig. 4 shows the reconstructed boundary using $(\widehat{\epsilon_\mathrm{A}}, \widehat{\epsilon_\mathrm{B}})$ by mono-static and multi-static configurations, respectively, where the number of scanning samples in mono-static model is 100. This figure demonstrates that while a mono-static model hardly reconstructs a whole part of inner target, the multi-static model offers perfect boundary in such case.

5. Conclusion

This paper extended the extended Envelope based boundary extraction method to multi-static observation, which would contribute to complete a reconstruction image. Numerical simulation example demonstrated that our extension considerably enhances the reconstruction accuracy without changing an equivalent aperture size with accurate dielectric constant estimation. This work was supported by Grant-in-Aid for Young Scientists (A) by JSPS KAKENHI Grant Number 26709030.

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