Accurate Boundary Extraction Method by Range Points Migration for Microwave Non-destructive Monitoring

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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. The traditional delay-and-sum (DAS) based imaging algorithm inherently suffers from an insufficient resolution to identify a detailed structure of buried targets. As promising alternative, the range points migration (RPM)-based boundary extraction approach has been developed. This paper focuses on the acceleration for this method, by exploiting the feature of Envelope outer boundary extraction. The results from numerical simulation and experimental data demonstrate that our proposed method accurately reconstructs the three-dimensional shape of air cavity buried in concrete object with considerably reduced computational cost.**

***Index Terms*—Microwave non-destructive testing(NDT), Range points migration(RPM), Three-dimensional (3-D) imaging**

I. INTRODUCTION

Microwave ultra-wideband (UWB) radar, with its high range resolution and ability to penetrate a dielectric medium, is promising for various internal imaging applications. In particular, non-destructive testing of aging walls, roads and bridges, is emergent and highly demanded application, to avoid the unpredictable collapse of buildings or traffic infrastructures, where cavities or cracks within the concrete material need to be detected. Various microwave imaging algorithms have been developed, mostly divided into two categories, one is based on the confocal approach, *e.g.* beamformer [1], and the other is based on the tomographic inverse scattering scheme [2]. However, the conformal approach (delay-and-sum (DAS) based) requires an expensive computational cost and suffers from boundary extraction problem. Furthermore, since the tomographic based inverse scattering approach requires a large number of unknowns and mostly needs to solve the nonlinear optimization problem, it suffers from a sluggish convergence and a severe dependency on an initial estimator.

To overcome the above issue, the range points migration (RPM) based imaging method has been developed, which converts an observed time delay to a corresponding scattering center by the Gaussian kernel estimator [3], [4]. The number of studies has demonstrated that the RPM associated algorithms achieve an accurate imaging of an object buried in concrete with real measurement, where the 1/100 order wavelength accuracy is available for boundary extraction [5]. This algorithm uses the prior estimation of outer boundary using Envelope method [6], and a propagation path is calculated by each discretized outer boundary point using the Snell's law. Thus, the computational cost and reconstruction accuracy significantly depend on a discretization interval of outer boundary, which incurs an extremely large computational costs, especially in the three-dimensional (3-D) problem. As a solution for this problem, this paper introduces an acceleration of the RPM method by focusing on the notable property of the Envelope method as, it can provide a continuous outer boundary, and then, an orbit of propagation path can be also continuously derived. Using this property, this method calculates the intersection point of the candidate curves by minimizing a cost function, namely, a discretization process is not required. The 3-D numerical simulation and the real experimental test, using concrete material including air cavity, demonstrates that our proposed method remarkably reduces the computational cost without sacrificing a reconstruction accuracy, and the advantage from the DAS based method, in terms of boundary reconstruction accuracy.

II. SYSTEM MODEL

Figure 1 shows the system model. It assumes that a homogeneous, low lossy, and non-dispersive dielectric media (*e.g.* concrete) includes an air cavity. A set of transmitting and receiving antenna is scanned along a surface surrounding a dielectric object, and records a reflection electric field. $s(\boldsymbol{L}, R)$ is defined as a signal after applying the matched filter to a recorded signal, where $\boldsymbol{L}$ denotes the transmitting and receiving antenna location, and $R = \mathrm{c}t/2$ is expressed by time t, and c is the speed of light in the air. The range points extracted from the local maxima of $s(\boldsymbol{L}, R)$ are divided into two groups, one is defined as $\boldsymbol{q}_{1,i} \equiv (\boldsymbol{L}_{1,i}, R_{1,i})$ where each member having maximum $s(\boldsymbol{L}, R)$ as to R. The remaining range points are categorized into $\boldsymbol{q}_{2,j} \equiv (\boldsymbol{L}_{2,j}, R_{2,j})$.

III. RPM BASED BOUNDARY EXTRACTION METHOD

There are many studies aiming at microwave imaging for buried object, and most of them are based on the confocal imaging approach, mainly using delay-and-sum (DAS) process. The accurate DAS based imaging is achieved by considering the propagation path in dielectric medium with accurate outer boundary model. However, even if the accurate outer boundary and propagation path model are given, the DAS based method suffers from inaccuracy for continuous-shaped

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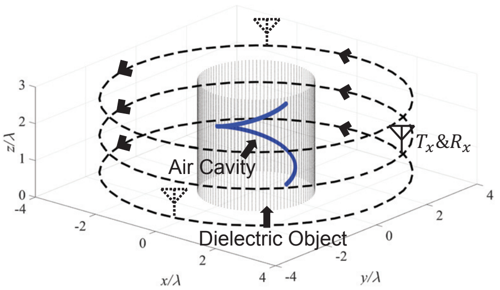

Fig. 1: System model.

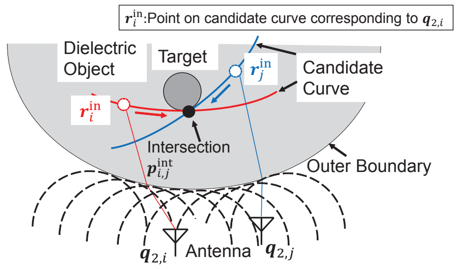

Fig. 2: Relationship of outer boundary, candidate curves and their intersection point for RPM-based internal imaging.

boundary extraction because it assumes the scattering point is invariant according to observation point motion, which is often invalid in most cases assuming continuous boundary object. Also, the complex-value based DAS requires sufficiently dense sampling interval (within half of wavelength) of observation points to avoid the grating lobe effect. In particular, a higher dielectric constant case, this interval should be considerably smaller, and incurs a large data acquisition time and data amount to be processed.

A. Acceleration of RPM based method

As a solution for the above difficulty, the RPM based internal imaging method has been developed, which achieved accurate boundary extraction by considering the scattering center variance. However, the original RPM-based method [4], designed for non-destructive testing application, basically requires a calculation of the intersection points among the three orbits of propagation paths, named as candidate curves, for all possible combinations of range points $\boldsymbol{q}_2$. In [4], each candidate curve is expressed as discretized form, each of which corresponds to a discretized point on outer boundary obtained by the Envelope method using $\boldsymbol{q}_1$. Thus, in the 3-D problem, an extremely large number of discretized points must be processed for accurate calculation of intersection points among the candidates.

As an essential solution for this problem, this paper introduces a new RPM-based algorithm without a discretization approach for an outer boundary and a candidate curve. We focus on the notable feature of Envelope method that it can express outer dielectric boundary in continuous form, by extracting outer envelope of spheres, each of which has

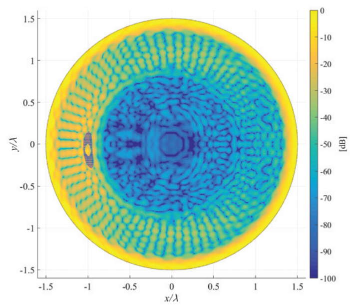

Fig. 3: Intensity image processed by DAS algorithm at the cross-section on $z = 200$mm plane.

the center location as $\boldsymbol{L}_{1,i}$ and radius $R_{1,i}$. Then, candidate curve is also continuously derived using Snell's law and outer boundary for each $\boldsymbol{q}_{2,i}$. Then, the intersection point $\boldsymbol{p}_{i,j,k}^{\mathrm{int}}$ among the three candidate curves derived from $\boldsymbol{q}_{2,i}, \boldsymbol{q}_{2,j}, \boldsymbol{q}_{2,k}$ is calculated by minimizing the following cost function;

$$(\hat{\boldsymbol{r}}_i^{\mathrm{in}}, \hat{\boldsymbol{r}}_j^{\mathrm{in}}, \hat{\boldsymbol{r}}_k^{\mathrm{in}}) = \arg\min_{(\boldsymbol{r}_i^{\mathrm{in}}, \boldsymbol{r}_j^{\mathrm{in}}, \boldsymbol{r}_k^{\mathrm{in}})} \{\|\boldsymbol{r}_i^{\mathrm{in}} - \boldsymbol{r}_j^{\mathrm{in}}\|^2 + \|\boldsymbol{r}_i^{\mathrm{in}} - \boldsymbol{r}_k^{\mathrm{in}}\|^2 + \|\boldsymbol{r}_j^{\mathrm{in}} - \boldsymbol{r}_k^{\mathrm{in}}\|^2\}, \quad (1)$$

where $\|*\|$ is the Euclidean norm, $\boldsymbol{r}_i^{\mathrm{in}}$ denotes a point on candidate curve corresponding to $\boldsymbol{q}_{2,i}$. An intersection point as $\boldsymbol{p}_{i,j,k}^{\mathrm{int}}$ is represented as $\hat{\boldsymbol{r}}_i^{\mathrm{in}}$. Figure 2 shows the relationship among outer boundary, candidate curves and their intersection point. After calculating $\boldsymbol{p}_{i,j,k}^{\mathrm{int}}$ for all possible combinations of $\boldsymbol{q}_{2,i}$, $\boldsymbol{q}_{2,j}$ and $\boldsymbol{q}_{2,k}$, an optimal scattering center for $\boldsymbol{q}_{2,j}$ is determined by the RPM algorithm detailed in [4].

IV. Performance Evaluation

A. Evaluation in Numerical Simulation

At first, the 3-D numerical simulation is investigated for performance analysis of the proposed method. The Gaussian modulated current with the z-axis polarized form is given as the source signal, whose center frequency is 3.0 GHz and effective bandwidth is 2.0 GHz. The center wavelength in the air is $\lambda =$100mm in this case. Figure 1 also shows the setup in this simulation. The set of transmitting and receiving antennas is scanned along cylindrical surface, whose radius 400 mm and 300 mm height. The sampling interval along azimuth direction is 36 for, and that along the z-axis is 7 for $0 \leq z \leq 300$mm. The dielectric constant and conductivitity of concrete object is set to 7.0 and 0.001 S/m, respectively. The air cavity forms spiral structure with diameter 10 mm as in Fig. 1. Figure 3 shows the cross-section of the DAS image, and it shows that there are many undesirable responses caused by grating lobe, and while we can see the focused intensity around the actual cavity, its blurry image is hardly acceptable for cavity shape estimation. On the contrary, Figs. 4 and 5 show the reconstructed boundary points obtained by the original RPM and the proposed RPM with acceleration. These results clearly demonstrate that the RPM based imaging offers remarkably accurate boundary extraction, which could not be obtained

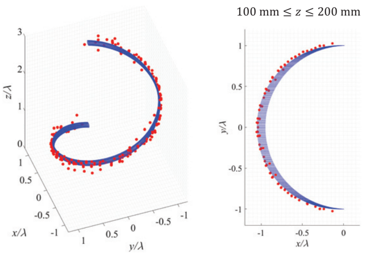

Fig. 4: Reconstructed boundary points (red solid circles) by the original RPM.

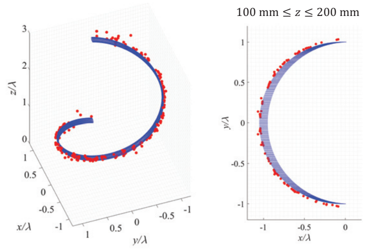

Fig. 5: Reconstructed boundary points (red solid circles) by the proposed method.

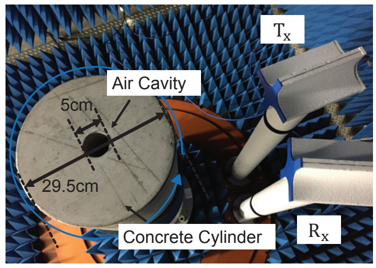

Fig. 6: Experimental setup for air cavity embedded in concrete cylinder.

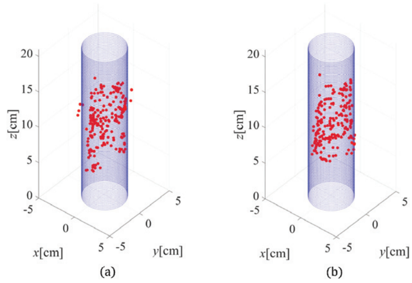

Fig. 7: Reconstructed points for air cavity by the conventional method (a), and the proposed method (b).

by the DAS based method. Furthermore, the original RPM requires 3.8×10^4 s for reconstruction process using Intel(R) Xeon(R) CPU E5-2620 2.4 GHz processor and 128 GB RAM, while the proposed method only requires 1.4×10^4 s. The 20 times acceleration is achieved by the proposed method without sacrificing the reconstruction accuracy, where the RMSEs(Root mean square errors) are 11.6 mm for the original RPM and 5.1 mm for the proposed method, respectively.

B. Evaluation with Experimental Data

This section describes an experimental validations for each method, using concrete cylinder including air cavity. Figure 6 shows the scene of this experimental setup. Two vertically polarized dipole antennas are used as the transmitting and receiving antennas with the fixed separation at 15.0 cm. A cylindrical concrete object with the relative permittivity as 9.6 includes a cylindrical air cavity along vertical axis. The radii of concrete and air cavity cylinders are 29.5 cm and 5 cm, respectively, and their heights are both 29.5 cm. To simulate 3-D scanning model, the concrete object is rotated with 10 degrees interval, where the distance from the rotation center to antenna is set to 40 cm. This object is also moved along the z-axis for 0 cm $\leq z \leq$ 20.5 cm with 4.1 cm interval. The reflection data are obtained by VNA(Vector Network Analyzer), where a frequency is swept from 1.0 GHz to 2.6 GHz with 10 MHz interval. The average of signal-to-noise ratio (SNR) is approximately 29 dB. Figure 7 shows the reconstruction results for air cavity boundary in each method. The RMSEs are 6.59 mm for the conventional method and is 6.20 mm for proposed method, whereas, the calculation time is 5.7×10^5 s for the conventional method and is 5.3×10^3 s for proposed method using the same processor in Sec.IV-A. This result denotes that our proposed method remarkably enhances the imaging speed (approximately 107 times) without degrading the reconstruction accuracy.

V. Conclusion

This paper proposed the acceleration algorithm of the RPM based internal boundary extraction scheme, by introducing the feature of the Envelope based outer boundary extraction. The numerical and experimental 3-D validation demonstrated that the proposed method remarkably enhanced the reconstruction accuracy, compared with that of DAS based method, and considerably reduces the computational cost from that required by the original RPM. This work was supported by JSPS KAKENHI Grant Number 17H03274.

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