Acceleration of RPM-based Microwave Imaging for Non-destructive Testing

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***Abstract*—A microwave ultra-wideband (UWB) radar has an advantage for high range resolution and deep penetration depth in a concrete object, and is promising for non-destructive testing for aging transportation infrastructure. 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 imaging method has been developed. However, this method faces a serious problem in terms of an expensive computational cost, particular in three-dimensional case. This paper, then, introduces an acceleration of the RPM-based imaging method by exploiting the feature of Envelope outer boundary extraction. The results from experimental data demonstrate that this method accurately reconstructs the shape of air cavity buried in concrete object with considerably reduced computational cost.**

Keywords–Microwave UWB radar, Non-detractive testing (NDT), Range points migration(RPM), Three-dimensional imaging

I. INTRODUCTION

There is a strong demand for microwave UWB sensors for higher-resolution internal imaging, which is suitable high speed non-destructive testing (NDT) for crack detection of aging road or tunnel by non-contact measurement. Various microwave imaging algorithms have been developed, mostly divided into two categories, one is based on the conformal 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 shape estimation for non-point wise object. 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]. The literature has revealed that the RPM achieves an accurate imaging of an object buried in concrete with real measurement, where the 1/100 order wavelength accuracy is available for boundary extraction [4]. This algorithm uses the prior estimation of outer boundary using Envelope method [5], 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.

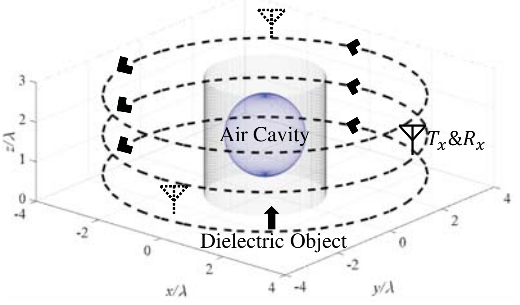

Fig. 1: System model.

To address with the above mentioned, this paper proposes an acceleration of the RPM method by focusing on the notable property of the Envelope method as, it can provide a continuous (not discretized) outer boundary, and then, an orbit of propagation path (named as candidate curve) 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 experimental test, using concrete material including air cavity, demonstrates that our proposed method remarkably reduces the computational cost without sacrificing a 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 remained range points are categorized into $\boldsymbol{q}_{2,j} \equiv (\boldsymbol{L}_{2,j}, R_{2,j})$.

III. PROPOSED METHOD

The original RPM-based method [3], designed for non-destructive testing application, basically requires a calculation

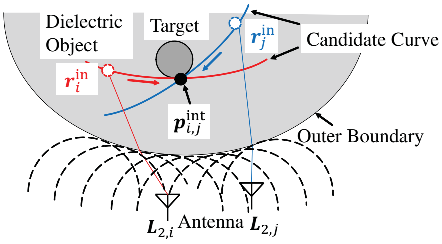

Fig. 2: Relationship of outer boundary, candidate curves and their intersection point for RPM-based internal imaging.

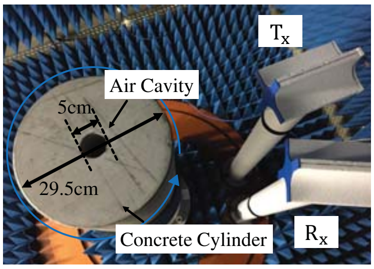

Fig. 3: Experimental setup for air cavity embedded in concrete cylinder.

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 [3], 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 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 $\boldsymbol{p}_{i,j,k}^{\rm int}$ 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;

$$(\hat{\boldsymbol{r}}_i^{\rm in}, \hat{\boldsymbol{r}}_j^{\rm in}, \hat{\boldsymbol{r}}_k^{\rm in}) = \mathop{\rm arg\ min}_{\boldsymbol{r}_i^{\rm in},\boldsymbol{r}_j^{\rm in},\boldsymbol{r}_k^{\rm in}} \{\|\boldsymbol{r}_i^{\rm in} - \boldsymbol{r}_j^{\rm in}\|^2 + \|\boldsymbol{r}_i^{\rm in} - \boldsymbol{r}_k^{\rm in}\|^2 + \|\boldsymbol{r}_j^{\rm in} - \boldsymbol{r}_k^{\rm in}\|^2\}, \tag{1}$$

where $\|*\|$ is the Euclidean norm, $\boldsymbol{r}_i^{\rm in}$ denotes a point on candidate curve corresponding to $\boldsymbol{q}_{2,i}$. An intersection point as $\boldsymbol{p}_{i,j,k}^{\rm int}$ is represented as $\hat{\boldsymbol{r}}_i^{\rm in}$. Figure 2 shows the relationship among outer boundary, candidate curves and their intersection point. After calculating $\boldsymbol{p}_{i,j,k}^{\rm int}$ 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 [3].

IV. EVALUATION WITH EXPERIMENTAL DATA

This section describes an experimental validations for each method, using concrete cylinder including air cavity. Figure 3 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 4 shows the reconstruction results for air cavity boundary in each method. The RMSEs(Root mean square errors) 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 with Intel(R) Xeon(R) CPU E5-2620 2.4 GHz processor and 128 GB RAM. This result denotes that our proposed method remarkably enhances the imaging speed (approximately 107 times) without degrading the reconstruction accuracy.

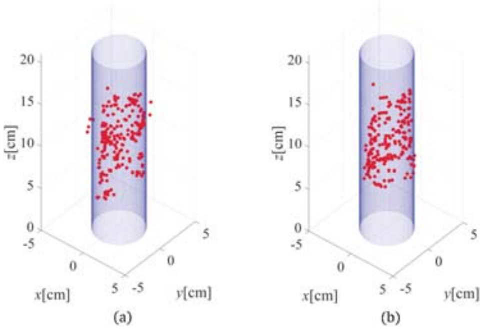

Fig. 4: Reconstructed points for air cavity by the conventional method (a), and the proposed method (b).

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