ELLIPSE BASED IMAGE EXTRAPOLATION METHOD WITH RPM IMAGING FOR THROUGH-THE-WALL UWB RADAR

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ABSTRACT

Through-the-wall radar (TWR) technique with UWB (ultra wide-band) signals are promising candidates for non-destructive testing or reliable human detection buried under collapsed walls in disaster scenes. As an efficient 3-dimensional imaging approach, the range points migration (RPM) method has been established, which can transcend the performance limitation of the conventional delay-and-sum approaches, in terms of computational burden, accuracy and spatial resolution. This paper extends the RPM method to the TWR imaging model, called as TW-RPM, where the principle of the original RPM is appropriately extended to this model by considering the propagation path and delay in wall. In addition, this paper introduces the image expansion scheme, based on ellipse fitting approach. As a notable point, this fitting process is not carried out in real space but in data space, which is spanned by range points (a set of antenna location and range) to avoid the extrapolating error due to TW-RPM imaging process. The FDTD (finite time domain difference) based numerical simulation shows that our proposed method accurately expands the TW-RPM image even in narrower aperture case.

***Index Terms*—** Through-the-wall radar (TWR), UWB radars, Range points migration (RPM), Ellipse based extrapolating, Image expansion

1. INTRODUCTION

There are significant demands for target recognition in through-the-wall radar (TWR) applications, aiming at detecting a survivor buried into collapsed wall, or counting the number of suspects or terrorists barricaded into rooms. Microwave UWB(Ultra Wideband) radar is most promising in terms of higher range resolution and favorable ability of wall penetrating. There are many research aiming at efficient TWR imaging, such as synthetic aperture [1], time reversal approaches [2] or non-linear optimization for multi-dimensional issue [3]. However, this type of methods, namely based on waveform focusing approach, has a number of substantial drawbacks, in terms of insufficient spatial resolution and accuracy or large computational burden. On the contrary, we have already developed an accurate and high-resolution imaging method as range points migration (RPM) method, which focuses the observed ranges measured at each antenna location [4, 5]. The effectiveness of RPM has been widely reported in short-range radar and acoustic imaging studies [6, 7, 8]. However, the image reproduction region obtained by RPM and other conventional methods is, usually severely limited by the aperture size, which is itself restricted by obstacles such as rubble in disaster zones and indoor sensing problems.

To overcome this problem, this paper proposes an novel image extrapolation method for the through-the-wall issue by exploiting the unique feature of RPM method. This method assumes that a target is expressed as an aggregate of ellipsoid, such as human body, and extrapolates a part of target as a part of ellipse. First, we extend the RPM method to TWR imaging model (called as TW-RPM, Through Wall Range Points Migration), where the propagation path and delay are appropriately considered under Snell's law. Next, the reconstruction image by the TW-RPM is extrapolated by ellipse based fitting. The notable point of this method is that an ellipse based fitting scheme is carried out not in real space (space where target and antenna exist) but in data space (consisted of observed range and antenna location) to avoid the fitting error caused by TW-RPM imaging.

The results from numerical simulation show that our proposed method remarkably expands an image region reconstructed by the original RPM, which contributes more accurate target recognition issue in the through-the-wall problem.

2. SYSTEM MODEL

The system model is shown in Fig. 1. Each target is assumed to have an ellipse shape with a clear boundary. An omni-directional antennas is scanned along the x-axis. A planar wall with a uniform relative permittivity $\epsilon_{\rm w}$ and thickness $d_{\rm w}$ is set parallel to the scanning axis. It is assumed that $\epsilon_{\rm w}$ and $d_{\rm w}$ are known constants. $s(\boldsymbol{L}, R')$ is defined as the output of the matched filter to the received electric field at the antenna location $\boldsymbol{L} = (X, 0)$, where $R' = {\rm c}t/(2)$ is expressed by the time t and the speed of the radio wave c. $\boldsymbol{q} = (\boldsymbol{L}, R)$ is

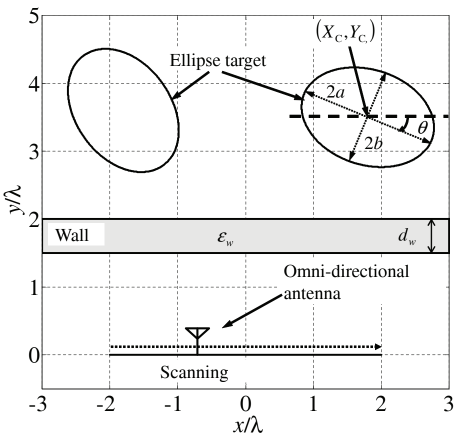

Fig. 1. System model.

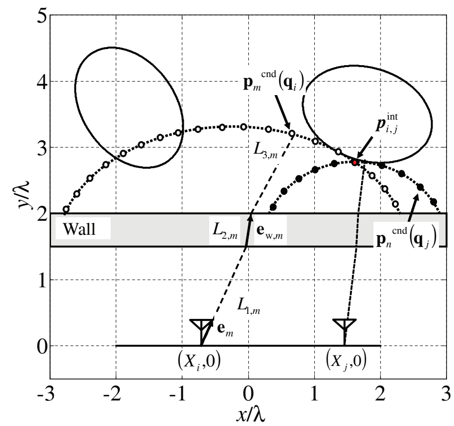

Fig. 2. Target candidate point $\boldsymbol{p}_i^{\mathrm{cnd}}(\boldsymbol{q})$ in TW-RPM method.

defined as the range point, which is extracted from the local maxima of $s(\boldsymbol{L}, R')$ as to R', where R denotes the extracted range.

3. PROPOSED METHOD

3.1. TW-RPM Method

In this section, we extend the RPM method (called as TW-RPM), originally assuming free space imaging, to the TWR model as follows. Figure 2 shows the principle of the TW-RPM method. For each extracted range point as $\boldsymbol{q}_i$, the propagation path from antenna to target through the wall is determined by the Snell's law. The candidate point for target boundary as $\boldsymbol{p}_m^{\mathrm{cnd}}(\boldsymbol{q}_i)$ as in Fig. 2 is calculated as;

$$\boldsymbol{p}_m^{\mathrm{cnd}}(\boldsymbol{q}_i) = (L_{1,m} + L_{3,m})\boldsymbol{e}_m + \frac{L_{2,m}}{\sqrt{\varepsilon_{\mathrm{w}}}}\boldsymbol{e}_{\mathrm{w},m} \tag{1}$$

where m denotes the discretized index of front side wall, $L_{1,m}$, $L_{2,m}$ and $L_{3,m}$ are the propagation paths as shown in Fig. 2, $\boldsymbol{e}_m$ and $\boldsymbol{e}_{\mathrm{w},m}$ are also the propagation unit vector out and in a wall, respectively, which can be obtained by d_{w} and ϵ_{w}. Next, the intersection point between the candidate curves represented as $\boldsymbol{q}_i$ and $\boldsymbol{q}_j$ is determined as $\boldsymbol{p}_{i,j}^{\mathrm{int}}$;

$$\boldsymbol{p}_{i,j}^{\mathrm{int}} = \arg\min_{\boldsymbol{p}_m^{\mathrm{cnd}}(\boldsymbol{q}_i)} \|\boldsymbol{p}_m^{\mathrm{cnd}}(\boldsymbol{q}_i) - \boldsymbol{p}_n^{\mathrm{cnd}}(\boldsymbol{q}_j)\|^2 \tag{2}$$

Based on the original RPM principle [4], the target point corresponding to the range point $\boldsymbol{q}_i$ is determined as $\boldsymbol{p}_i$;

$$\begin{aligned}\boldsymbol{p}_i \;=\; & \arg\max_{\boldsymbol{p}_{i,j}^{\mathrm{int}}} \sum_k s(\boldsymbol{q}_j) \exp\left(-\frac{\|\boldsymbol{p}_{i,j}^{\mathrm{int}} - \boldsymbol{p}_{i,k}^{\mathrm{int}}\|^2}{2\sigma_{\mathrm{r}}^2}\right) \\ & \times \exp\left(\frac{-|X_i - X_k|^2}{2\sigma_D^2}\right)\end{aligned} \tag{3}$$

where $\boldsymbol{q}_i \neq \boldsymbol{q}_j$, $\boldsymbol{q}_i \neq \boldsymbol{q}_k$, $\boldsymbol{q}_j \neq \boldsymbol{q}_k$ hold, and σ_r and σ_D are empirically determined.

3.2. Ellipse fitting in data space

The most simple approach for the extrapolating ellipse shape target is that the fitting in the real space is carried out using the estimated TW-RPM target points. As method comparison, we briefly introduce the fitting scheme in the real space, first. To deal with the multiple targets situation, the clustering for the TW-RPM target points is applied here, where the detail process is described in [9]. Here, we define $\boldsymbol{P} \equiv (a, b, X_{\mathrm{C}}, Y_{\mathrm{C}}, \theta)$ as the parameters of the ellipse whose major axis is a, minor axis is b, the center of focal point is $(X_{\mathrm{C}}, Y_{\mathrm{C}})$ and angle from the x axis to the major axis is θ as shown in Fig. 1. In the real fitting scheme, the parameter $\boldsymbol{P}$ is estimated as;

$$\hat{\boldsymbol{P}}_i^{\mathrm{R}} = \arg\min_{\boldsymbol{P}} \sum_{m=1}^{M_i} \| \boldsymbol{r}_{m,i} - \boldsymbol{r}_m(\boldsymbol{P}) \|^2, (i = 1, ..., C) \tag{4}$$

where $\boldsymbol{r}_{m,i} = (x_{m,i}, y_{m,i})$ denotes the location of the m th estimated target boundary point in the i cluster, and $\boldsymbol{r}_m(\boldsymbol{P})$ denotes the location of the ellipse boundary point, which has a minimum distance to point $\boldsymbol{r}_{m,i}$. M_i denotes the total number of the estimated target points in the ith cluster. Note that, since the TW-RPM imaging itself is not perfect conversion process from the range point $\boldsymbol{q}$ to the target point $\boldsymbol{r}$, this approach severely suffers from the degradation of the ellipse extrapolation, when the estimated target points are distributed in a small region of whole target shape. Thus, the extrapolation result becomes extremely sensitive to small errors of target points caused by TW-RPM imaging process.

As a solution for this problem, this paper introduces the fitting scheme in data space. We focus here on a one-to-one correspondence between an estimated target point and a range

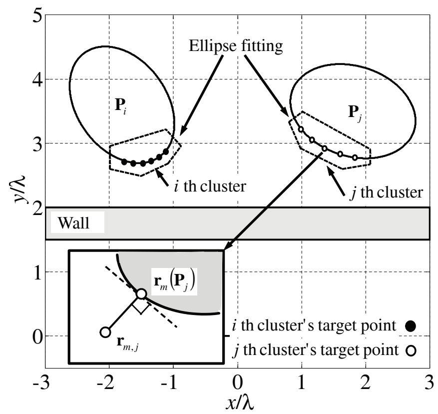

Fig. 3. Fitting scheme in real space.

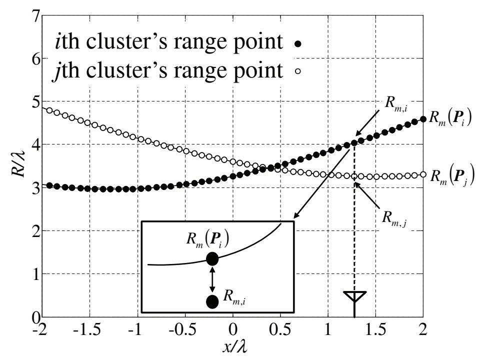

Fig. 4. Fitting scheme in data space (the propose method).

point, which is unique property of RPM [4] and also of TW-RPM. After the clustering, this method determines the parameter $\boldsymbol{P}$ as

$$\hat{\boldsymbol{P}}_i^{\mathrm{D}} = \arg\min_{\boldsymbol{P}} \sum_{m=1}^{M_i} |R_{m,i} - R_m(\boldsymbol{P})|^2 \tag{5}$$

where $(X_{m,i}, R_{m,i})$ denotes the range point corresponding to the mth estimated target point in the ith cluster. $R_m(\boldsymbol{P})$ denotes the minimum range from $(X_{m,i}, 0)$ to the ellipse expressed by the parameter $\boldsymbol{P}$. While the estimated target points by TW-RPM are used for clustering, the fitting process itself is completed without TW-RPM imaging. Then, the fitting accuracy of this method depends only on the range errors measured at each antenna.

4. PERFORMANCE EVALUATION IN NUMERICAL SIMULATION

This section describes the performance evaluation of the proposed method. The three targets behind planar wall are assumed. The dielectric constant and conductivity are set as $\epsilon_{\mathrm{w}} = 5.0$ and $\sigma_{\mathrm{w}} = 0.005$ S/m, respectively. The thickness of wall is set as $d_{\mathrm{w}} = 0.04\lambda$. The antenna is scanned for the range $-2.0\lambda \le x \le 2.0\lambda$. Each received signal is generated by FDTD (finite difference time domain) method. The left and right sides of Fig. 5 show the extracted range points and the imaging points by TW-RPM after clustering. The average S/N is around 30 dB, which is defined as the ratio of peak instantaneous signal power to the averaged noise power, after applying the matched filter. As mentioned in Sec. 3, while it is generally difficult to cluster the range points in data space due to a cross point, the clustering in real space is not difficult because the target points should be separated in the real space. Figures 6 and 7 denote the extrapolated images obtained by the fitting scheme in the real space and in the data space, namely, the proposed idea. Here, in both approaches, the simulated annealing algorithm is used to avoid falling into local optimum. In addition, to emphasize the extrapolated image statistically, these figures illustrate only the region for which the focused region of the ellipse boundaries as $I_i(x, y)$, obtained from the results of the simulated annealing, exceeds a certain threshold [9]. As shown in Fig. 6, the fitting approach in real space does not work well. This is because the target points by TW-RPM include a certain error caused by the imaging process of the TW-RPM. On the contrary, the extrapolated image obtained by the proposed method accurately expands all the three target boundaries in avoiding the errors caused by the TW-RPM imaging. It should be also noted that the accuracy of the extrapolated image by the proposed method is around 1/100 transmitting wavelength, which cannot be obtained by the traditional aperture synthesis or beamforming approaches.

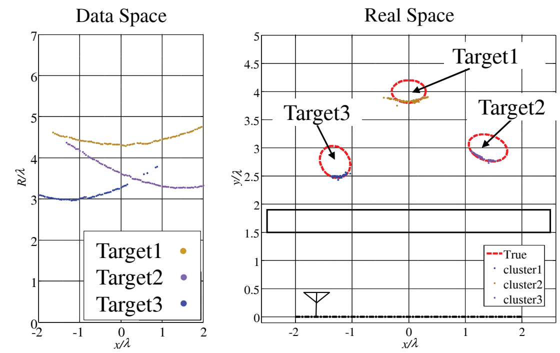

Fig. 5. Clustered range points in data space (left) and target points in real space (right) by TW-RPM method.

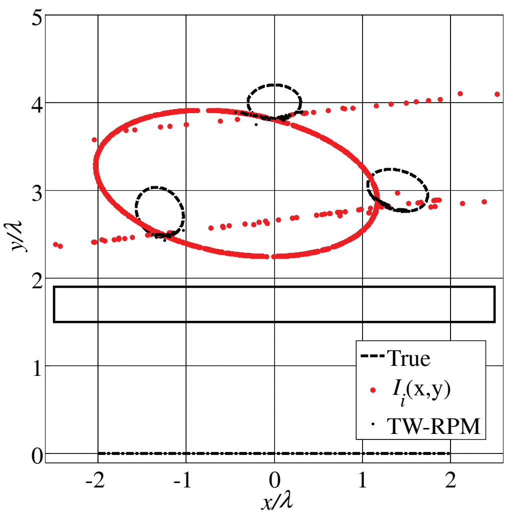

Fig. 6. Extrapolated image by fitting in the real space.

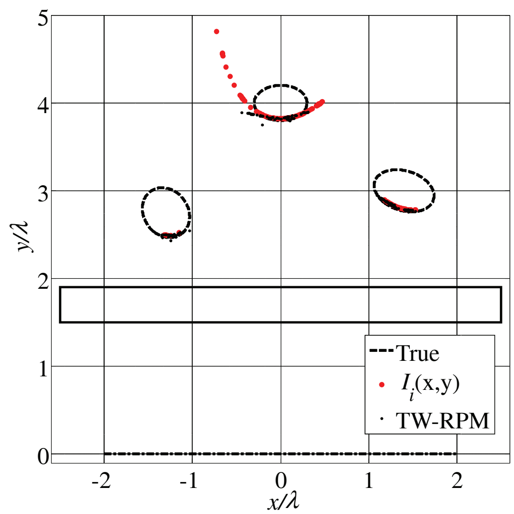

Fig. 7. Extrapolated image by the proposed method.

5. CONCLUSION

This paper first proposed the TW-RPM method, which was extended the original RPM to TWR imaging model by considering propagation delay in wall. In addition, this paper introduces the accurate target extrapolating method for target points estimated by the TW-RPM method. As significant features of this method, the extrapolating process can be carried out by using only range information to avoid the errors caused by the imaging process. This process can be derived from the unique feature of the TW-RPM method, that it maintains the one-to-one correspondence relationship between a range point and a target point. For more expansion of the target image, it is our future work to exploit the multipath environment, where the equivalent aperture size can be expanded.

6. REFERENCES

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