Revised Range Point Migration Method for Rapid 3-D Imaging with UWB Radar

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***Abstract*—Surveillance UWB imaging radar systems require rapid radar imaging methods. One such method, called SEABED, has been demonstrated to work well for simple-shaped targets, but not for complex-shaped targets. To resolve the difficulties, the RPM method was developed to generate better images even for complex-shaped targets, albeit at the cost of processing speeds. This paper proposes an alternative method which is a hybrid of the SEABED and RPM methods that can quickly generate high-quality images for complex-shaped targets. To show its effectiveness, the performances of the three imaging methods are compared using simulations and experiments.**

I. Introduction

Although a variety of imaging methods for UWB radar systems have been proposed [1], [2], [3], [4], [5], most of them are time-intensive and cannot be applied to real-time applications. To meet this need, we developed SEABED (shape estimation algorithm based on the boundary scattering transform (BST) and extraction of directly scattered waves) [6]. SEABED can provide accurate images for simply-shaped targets, but for more complex-shaped targets, these images are significantly degraded because of interference of multiple echoes. The range-point-migration (RPM) method had been proposed to overcome this difficulty [7], by optimizing the most likely direction-of-arrival (DOA) to avoid the interference effect. Although the RPM method produces excellent imaging capability, intensive computations during optimization processing severely compromise calculation speeds. This paper presents a revised RPM method that is more than ten times faster than the bistatic RPM, though still maintaining a high-quality imaging capability. The proposed method replaces the optimization process with weighted averaging to boost the computational speed. The performance of the proposed method is investigated in numerical and measurement studies.

II. System Model and Bistatic RPM Method

The measurement system consists of a transmitter-receiver pair positioned in the $z = 0$ plane along the x axis at a fixed distance $2d$. The midpoint between the transmitter and receiver is labeled $(X, Y, 0)$. With the transmitter-receiver pair being rastered at discrete intervals across a portion of the $z = 0$ plane, UWB pulses are transmitted and pulse echoes are received. Given antennae midpoint $(X, Y, 0)$, the signal received is labeled $s(X, Y, Z)$, where $Z = ct/2$. Here, c is the speed of the electromagnetic wave and t is the time interval between transmission and reception.

The RPM method has been developed to mitigate difficulties with the SEABED [7]. The main feature of the RPM method is the optimization of an evaluation function to estimate DOA or target position.

$$w_{i,j} = |s_i s_j| \exp\left(-\frac{(X_i - X_j)^2}{\sigma_X^2} - \frac{(Z_i - Z_j)^2}{\sigma_Z^2}\right), \quad (1)$$

where s_i is the signal value $s_i = s(X_i, Y_i, Z_i)$ at the i-th peak point (X_i, Y_i, Z_i) that satisfies $\partial s/\partial Z = 0$. The evaluation function $F(\theta_i)$ for the i-th peak can be expressed as

$$F(\theta_i) = \sum_{j \neq i} w_{i,j} \exp\left(-\frac{\left(\theta_i - \tan^{-1}\left(\frac{Z_i - Z_j}{X_i - X_j}\right)\right)^2}{2\sigma_\theta^2}\right), \quad (2)$$

where the summation is calculated only for j satisfying $Y_j = Y_i$. Here, θ must satisfy the condition $|\theta_i| < \pi/4$. By finding the optimum θ_i that maximizes Eq. (2), we obtain an estimate of the quasi-wavefront orientation. Next, we calculate $\partial Z/\partial X = \tan(\theta_i)$. In a similar way, we can estimate $\partial Z/\partial Y$. Finally, these derivatives are substituted into Bistatic-IBST equations [8].

III. Proposed Revised RPM Method

Since the optimization of the function in Eq. (2) is time consuming, we replace this process by the following weighted average. The relative orientation of peaks around the i-th peak is estimated with a weighted average as

$$\theta_i = \frac{\sum_{j \neq i, Y_j = Y_i} w_{i,j} \tan^{-1}\left(\frac{Z_i - Z_j}{X_i - X_j}\right)}{\sum_{j \neq i, Y_j = Y_i} w_{i,j}}, \quad (3)$$

where $\left|\tan^{-1}\left(\frac{Z_i - Z_j}{X_i - X_j}\right)\right| < \pi/4$, and the summations are over pairs of peaks with the same sign in the 2nd derivative. From this, we can estimate the partial derivative of the i-th range point in terms of X and Y as described in the previous section.

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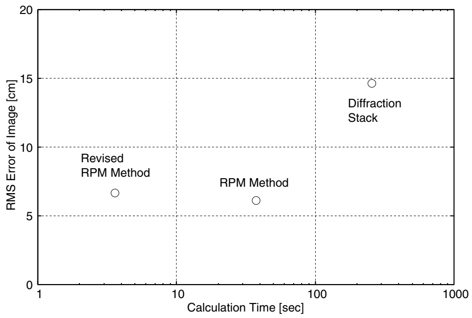

Fig. 1. Calculation time and RMS error of images generated with three methods.

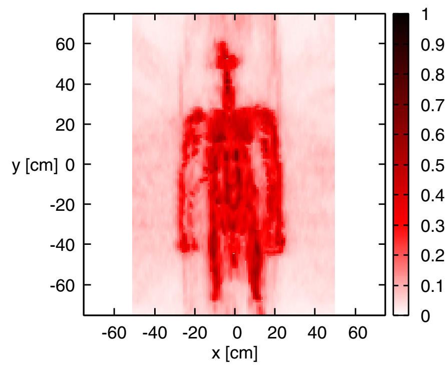

Fig. 2. Image generated using diffraction stack migration from the measured data with a mannequin (calculation time: 4 min 38 sec).

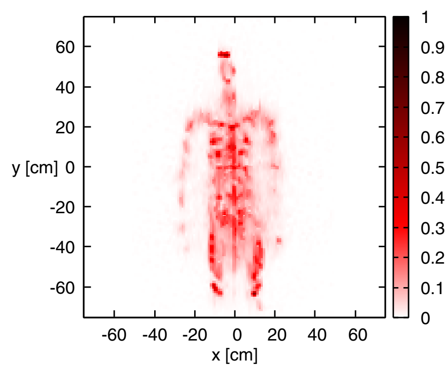

Fig. 3. Image generated using proposed revised RPM method from the measured data with a mannequin (calculation time: 3.6 sec).

IV. Performance Evaluation

We evaluate the calculation time and image quality of the three methods from simulation and measurement data. The parameters we assume in this section are following. The distance between the antennas is 5.0 cm, giving $d = 2.5$ cm. The antennas scan from locations at 1.0 cm intervals ranging 75.0 cm $\times$ 150.0 cm. The diffraction-stack migration calculates a target image for $-50\text{cm} \leq x \leq 50\text{cm}$, $-80\text{cm} \leq y \leq 80\text{cm}$ and $47\text{cm} \leq z \leq 67\text{cm}$ with a 1 cm grid width along each axis. We set $\sigma_X = \sigma_Y = 0.8\text{cm}$, $\sigma_Z = 0.3\text{cm}$ and $\sigma_\theta = \pi/100$.

First, we apply diffraction-stack migration, the RPM method, and the proposed revised RPM method to simulated data. Simulated data are generated assuming $6 \times 6 = 36$ point targets in the plane $z = 50$ cm. The root mean square (RMS) error values and calculation times are plotted in Fig. 1. Although the RMS error of the proposed method is slightly larger than the conventional RPM method, the difference is insignificant, whereas the calculation speed of the proposed method is remarkably improved.

Next, we apply the methods to experimental data to further verify their performance in realistic scenarios. In our measurement, a human body phantom with conductive surface was placed 50.0 cm apart from the antenna scanning plane. Figs. 2 and 3 show the images obtained using the diffraction stack migration and the revised RPM method, respectively. Both images successfully depict a human body shape, though the calculation times differ significantly. With processing times of 278 sec, 51.9 sec, and 3.6 sec, the revised RPM method is 77.2 times and 14.4 times faster than the diffraction stack migration and the RPM method respectively.

V. Conclusion

In this paper, we described a fast 3-dimensional imaging method for UWB radar array systems. The proposed method is an expansion of the conventional RPM method that calculates the relative orientation of the distributed peaks using weighted averaging. We compared imaging performance and computation speed using simulated and experimental data. The imaging capability of the proposed method is almost the same as the original RPM method, but significantly the signal processing speed is more than ten times faster than the original RPM method.

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