Multiple Arcs Based Image Extrapolation Method for Millimeter Wave UWB Radar

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***Abstract*—Range points migration (RPM) method is a successful 3-D imaging algorithm with higher accuracy and less computational cost. Due to the limitation of radar aperture size, usually, the boundary points estimated by RPM method only cover a small portion of target surface. Therefore image extrapolation method is needed for improving the image result of RPM method. The conventional image extrapolation method is established based on ellipsoid fitting. However, such a high freedom optimization problem leads to extremely high computational cost. In order to accelerate the computation, we propose a novel image extrapolation method for based on multiple arcs. In the proposed method, instead of ellipsoids, a group of arcs are estimated to describe the targets. In this way, original 3-D problem is degenerated to a 2-D one, which contributes a significant reduction of computational cost. The numerical simulation results show that the proposed method can realize image extrapolation in success with significantly higher accuracy and computational speed.**

I. Introduction

With super-resolution, ultra-wideband (UWB) millimeter wave radar has many promising applications, such as short range sensor for security systems or rescue robots having potential for human body identification in darkness or in a disaster area, where a robot installed with array antennas on its body moves around the indoor environment. In recent years, researchers have proposed various radar imaging algorithms, such as the synthetic aperture radar (SAR) algorithm [1], time-reversal algorithms [2], and range migration methods [3]. However, their computational costs are often impractically large for applications.

To overcome these difficulties, the successful algorithm, named range points migration (RPM) has been proposed[4]. This algorithm directly converts a group of range points, which is the the original measurements of the UWB radar, into a group of boundary points of the targets. The number of studies have revealed that the RPM method retains significantly higher accuracy and much less computational cost. However, due to the limitation of radar aperture size, usually, the boundary points estimated by RPM method only cover a small portion of target surface. This fact causes difficulties to recognize the target structure from RPM image intuitively. In order to improve the image results, image extrapolation method is necessary.

Conventionally, the image extrapolation is realized based on ellipsoid fitting. Mathematically, the ellipsoid fitting is a 9-variables optimization problem. Such a high freedom optimization problem incurs extremely high computational cost[5]. To alleviate the problem in terms of computational cost, we propose a novel image extrapolation algorithm using multiple arcs. In the proposed method, instead of conventionally used ellipsoids, a group of arcs are employed for describing the targets. The final image is like a sketch painting, in which painters use much lines to express a 3 dimensional shape. The estimation of each arc is done on a local 2 dimensional coordinate system . Therefore, with multiple arcs method, we degenerate the original 3-D fitting problem to a 2-D one, which contributes a significant reduction of computational cost. We test the performance of the proposed method for simulated UWB radar data, and compare its performance with conventional ellipsoid fitting method. The numerical simulation results show that both of the proposed method can realize image extrapolation in success, however, the proposed multiple arcs based method has significantly higher accuracy and computational speed than ellipsoid fitting method.

II. Principle of Multiple Arcs Method

It is generally difficult to extrapolate a target shape without any prior information, and then, we introduce the assumption that the target can be expressed as a combination of several convex parts which can be approximated by an ellipsoid. For such a target, we first use RPM method to extract range data, i.e., the original data of UWB radar, for each parts, then, the image extrapolation is implemented for each part.

We define two crossing arcs as an arc pair. The arc pair estimation is the fundamental of the proposed arc sketching method. The estimation procedures are summarized as follows. The system model for the problem is shown in Fig. 1(a). A 5×5 array antenna is used in the model. Here, the red triangles represent the transmitting antennas, and all the antennas can serve as receiving antennas.

There is a fact that, in the case of the radar aperture size is much smaller than target scale, different transmitting and receiving pattens with co-linearly base line, i.e., the straight line determined by transmitting and receiving antenna locations, will have almost the same reflection plane. For example, as shown in Fig. 1(b), if we focus on the transmitting and receiving patterns $\{$B, B$\}$, $\{$B, M$\}$, and $\{$B, N$\}$, we can estimate an arc on their common reflection plane (the blue plane) for expressing one boundary line of the target.

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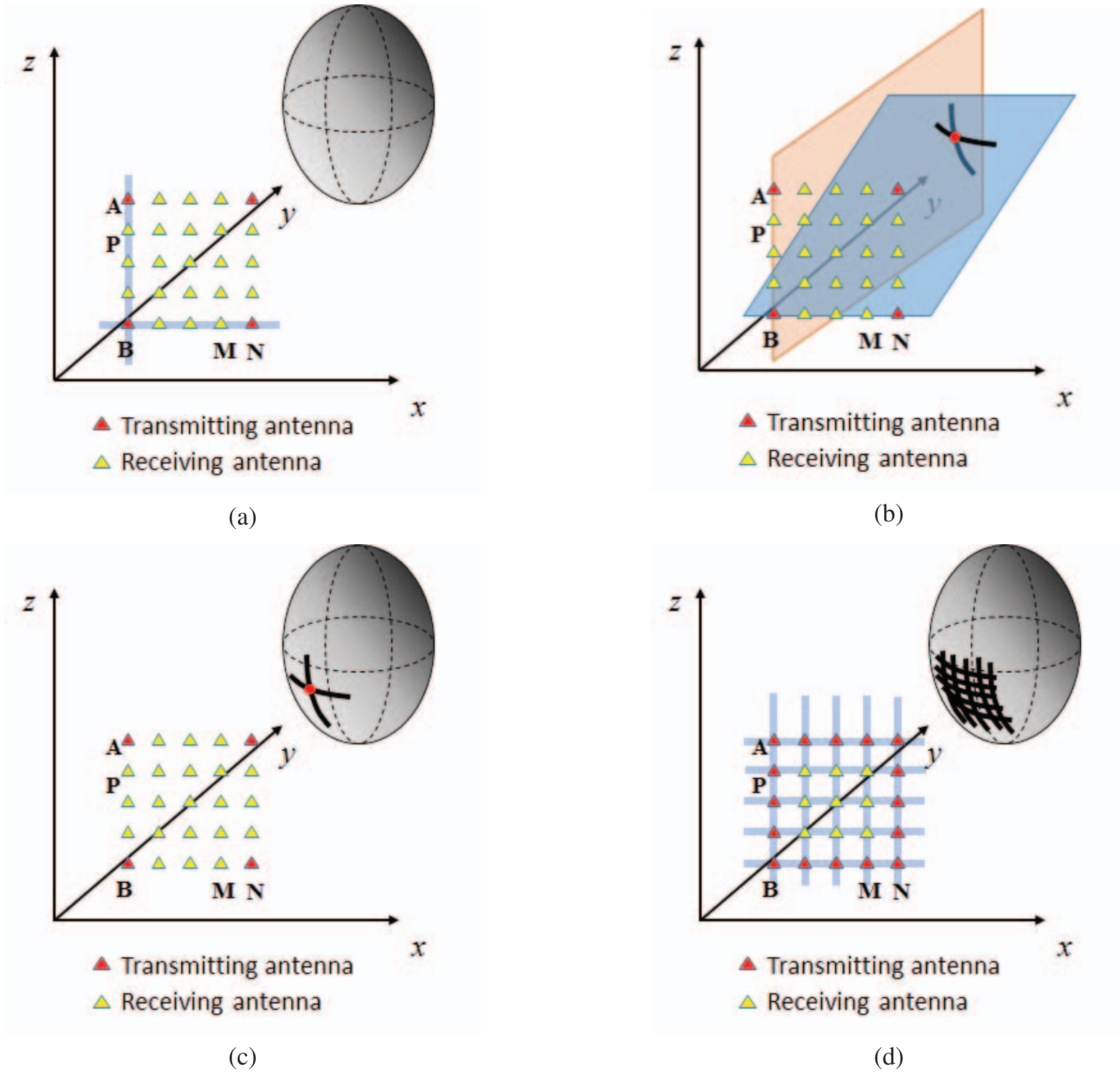


Fig. 1. The sketch of (a) the system model, (b) estimation of an arc pair, (c) the estimated arc pair which is approximately on the target surface, and (d) multiple arcs for image extrapolation by considering various transmitting and receiving patterns with collinear baselines.

Here, {m, n} means using m, n as transmitting and receiving antennas, respectively. Similarly, if we focus on patterns {B, B}, {B, P}, and {B, A} with baseline on another direction, we can also estimate another arc on their common reflection plane (the red plane). However, the common reflection plane is not unique, for example, all the planes passing B, M, and N can be their possible common reflection plane. Note that the pattern {B, B} is used for estimating both of the arcs, and the reflection point corresponding to {B, B} should be unique. Subsequently, we adjust the attitudes of blue and red planes to find the case that the reflection points for {B, B} on the two arcs are coincide with each other to determine the spatial position of the arc pair. The determined arc pair is approximately on the target surface, as shown in Fig. 1(c). Finally, we consider all the transmitting and receiving patterns with collinear baseline to determine various arc pairs for sketching the target shape, as shown in Fig. 1(d).

In this method, different from conventional methods, the final estimated target is no longer expressed by a surface. Instead, we use several arcs to express the target shape just like a sketch painting. In this way, the original 3 dimensional ellipsoid fitting problem is degenerated to a 2 dimensional arcs estimating problem, which contributes a significant reduction of computational cost. Moreover, in conventional methods, to determine the extrapolated surface, we need to select the common parts of all the candidate ellipsoids. The selection is implemented by setting several case-by-case empirical thresholds for defining the requirements of parts which can be accepted as common parts. In the proposed method, those empirical thresholds are not needed, which leads to much higher flexibility for practical applications.

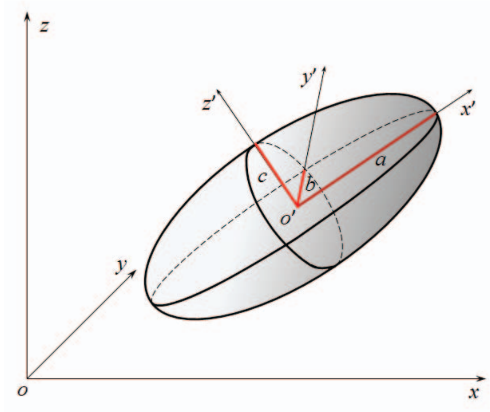


Fig. 2. Geometric of ellipsoid parameters.

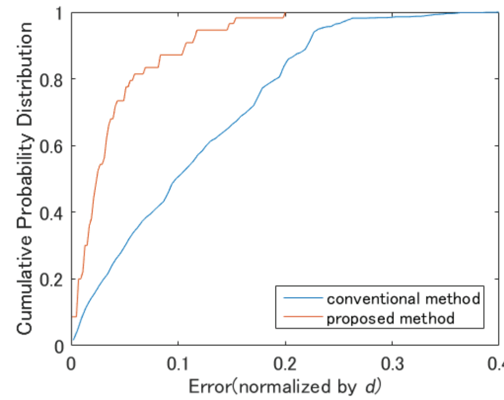


Fig. 3. The comparison of the cumulative probability distribution of the errors. Here, the error is normalized by $d = 50\lambda$, i.e., the internal distance between two neighboring antenna of the array.

III. Numerical Simulation

In the simulation, the spatial coordinates system are normalize by d, which is the internal distance between two neighboring antenna of the array. Here, the internal distance d is set as $d = 50\lambda$. We note the nine independent parameters of an ellipsoid as $p_{el} = [x_0, y_0, z_0, a, b, c, \theta_x, \theta_y, \theta_z]$, where, x_c, y_c, z_c are coordinates of the center, a, b, c are the radius in the local coordinate axises x', y', z' direction, as shown in Fig. 2, and $\theta_x, \theta_y, \theta_z$ represent the rotation angles of the $x' - y' - z'$ coordinate system around x, y, z axis, respectively. The ellipsoid target used for simulation has the parameters $[4, 4, 5, 1.2, 1, 0.7, 0, \pi/8, 0]$. The transmitting signal forms a pulse modulated signal, whose center frequency is 140GHz and 10dB bandwidth is 10GHz, pulse repetition interval is 37.5 μsec, and the number of pulse hits is 56. The spatial position of the antennas are the same as shown in Fig. 1(d). The red antennas are transmitting antennas and all the antennas can serve as receiving antennas. Note that, the imaging extrapolation accuracy is greatly effected by the accuracy of the range data. As the pre-procedure of image extrapolation, we need to cluster the range points, and extract range points for each convex part of the targets. In order to show the performance of the proposed methods, here, we do not consider the clustering error. Therefore, we design the simulation for single target. In the proposed method, the extrapolation rate k_e is defined as

$$k_e = 100(\frac{S_{extra}}{S_0} - 1)\ \% \tag{1}$$

where S_{extra} represents the area of the extrapolated part, and S_0 represents the area of the part covered by theoretical reflection points. The noise is directly added to the range point as

$$R_{ij} = R_{ij}^{true}[1 + k_n \epsilon] \tag{2}$$

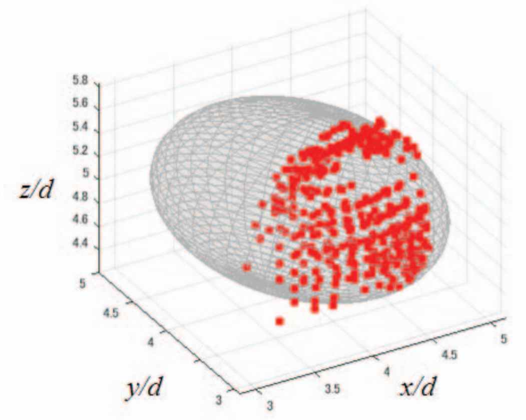
where R_{ij}, and R_{ij}^{true} are range data with, and without noise, respectively, $\epsilon \in [-1, 1]$ is a random number, and $k_n > 0$ represents the noise level.

In the simulation, we set the noise level $k_n = 0.001$, and extrapolation rate $k_e = 400\%$. Fig. 4(a) shows the result generated by the conventional ellipsoid fitting based method. In this method, six candidate ellipsoids are estimated for expressing the target. The final result is generated by selecting the approximately common part of the candidate ellipsoids. Fig. 4(b) shows the $z = 5$ cross section of the result shown in (a), which is the cross section passing the center of the target. Fig. 4(c) shows the result generated by the proposed multiple arc based method, and the boundary points generated by the RPM method (red points). Fig. 4(d) shows the $z = 5$ cross section of the result shown in (c). Considering the true reflection points shown in Fig. 4(c), we can find that both of the conventional ellipsoid fitting method and the proposed multiple arc method have successful extrapolation results. To evaluation the accuracy of the results, we define the error of the result as the distance between the estimated boundary point and the target. The comparison of the cumulative probability distribution (CPD) of the accuracies is shown in Fig. 3. The comparison result shows that the accuracies of proposed method concentrates at a lower error value than the conventional method. Here, the unit of the accuracy is d, which is the internal distance between two neighboring antenna of the array. The comparison of computational speed is is shown in Table I. Here, the CPU used in the simulation is Intel(R) Xeon(R) CPU E5-2637 @ 3.5 GHz 3.50 GHz.

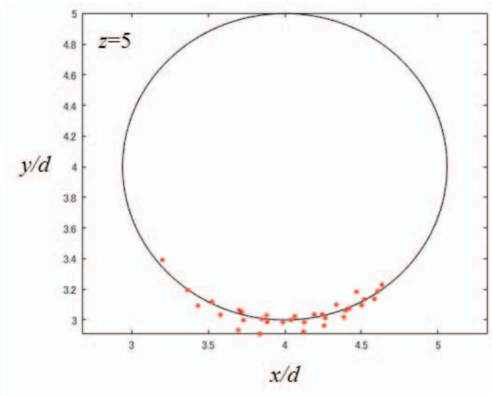
TABLE I
The comparison of computational speed

Elllipsoid Fitting	$855.7s$
Proposed method	$4.3s$

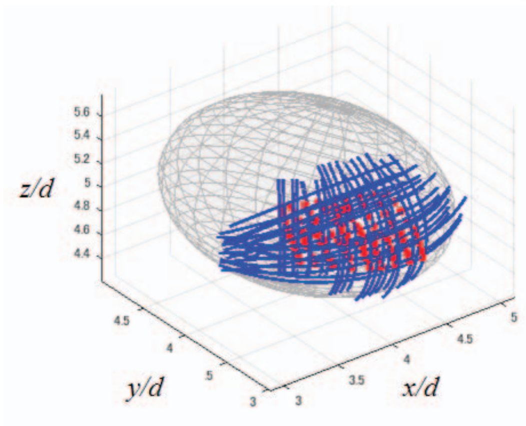
The result shows that with the dimension reduction process, the proposed multiple arcs method in this paper have much higher computational speed than conventional ellipsoid fitting method. With a high computational speed, the proposed method is possible to be used in real-time imaging applications.



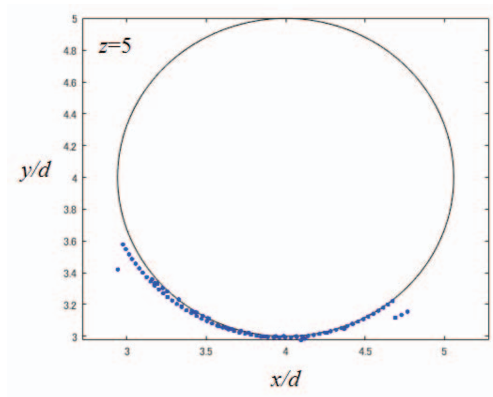
(a)



(b)



(c)



(d)

Fig. 4. (a) The result generated by conventional ellipsoid fitting based method for $k_n = 0.001$, (b) $z = 5$ cross section of the result shown in (a), (c) The result generated by the proposed multiple arcs based method for $k_e = 400\%$ & $k_n = 0.001$, and the boundary points estimated by the RPM method, and (d) $z = 5$ cross section of the result shown in (c). Here, the coordinate system is normalized by d, i.e., the internal distance between two neighboring antenna of the array.

IV. Conclusion

In this paper, we have propose a novel image extrapolation algorithm for ultra-wide band millimeter wave radar based on multiple arcs method. In this method, different from conventional ellipsoid fitting based methods, we have used various arcs to express the target shape just like a sketch painting. In this way, the original 3 dimensional ellipsoid fitting problem has been degenerated to a 2 dimensional arcs estimating problem, which has contributed a significant reduction of computational cost. The numerical simulation results have shown that the proposed method can realize image extrapolation in success with significantly higher accuracy and computational speed. Moreover, in the proposed method, empirical thresholds, such as the thresholds for selecting the common parts of all the candidate ellipsoids in conventional ellipsoid fitting method, are not needed. Therefore, the proposed method has much higher flexibility for practical applications.

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