Nonparametric UWB Radar Imaging Algorithm for Moving Target Using Multi-static RPM Approach

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***Abstract*—Ultra-wideband (UWB) pulse radar is promising technology for the imaging sensors of rescue robots operating in disaster scenarios, where optical sensors are not applicable because of dusty air or strong backlighting. An UWB radar imaging algorithm for a target with arbitrary motion has already been proposed. That algorithm is based on a circular approximation of the target boundary, and employs measured distances. Although it obtains an accurate target motion and image with few antennas for some targets, it is hardly applicable to complex target shapes, particularly if targets have specular surfaces or surface edges. As a substantial solution to this problem, this paper proposes an original imaging algorithm for a moving target with arbitrary shape, which is based on normal vector matching on the target surface with multi-static observations. Specifically, this study extends the existing RPM (Range Points Migration) algorithm, which is a super-high-resolution and accurate imaging approach, to the multi-static radar model. Numerical simulations show that our proposed algorithm accomplishes extremely accurate target surface extraction, and motion estimation at the order of $1/100$ wavelength, even for a noisy environment.**

***Key words*—UWB pulse radar, Moving target, Range points migration, Shape estimation.**

I. Introduction

There have been great natural or human disasters around the world in recent years, such as huge earthquakes, tsunamis and the meltdown of the nuclear power plant. In such disastrous situations, rescue or restoration robots are indispensable tools that can be used so that human workers are not placed at risk. Ultra-wideband (UWB) pulse radar is promising technology for imaging sensors of such robots because it has high range resolution that is suitable for a typical disaster scene, where optical sensors are hardly applicable because of dusty air or strong backlighting. Various imaging algorithms for UWB radar systems have been developed in recent decades. Although synthetic aperture radar is one of the most popular imaging tools [1], its computational burden becomes impractically large, particularly for 3-D problems, and it is thus hardly applicable to real-time applications such as the imaging sensors of rescue robots. By contrast, the high-speed imaging algorithm SEABED (Shape Estimation Algorithm based on Boundary scattering transform and Extraction of Directly scattered waves) achieves direct and nonparametric imaging based on reversible transforms between the time delay and target boundary [2]. The drawback of SEABED is that small range errors are enhanced by the differential operation in the imaging process. As an accurate and flexible imaging algorithm, the RPM (Range Points Migration) algorithm has been proposed [3]. RPM is based on direct group mapping from observed range points to target boundary points and retains accuracy by avoiding the task of connecting observed range points. All the above algorithms assume static objects.

As an effective imaging algorithm for a moving target, a revised SEABED algorithm, which uses two fixed antennas to estimate the motion and shape of a moving target in the 2-D problem, has been developed [4], [5]. However, this algorithm cannot be applied to arbitrary motion of a target since it assumes that the target moves in a line parallel to the antenna baseline. To overcome this problem, the revised SEABED algorithm has been extended [6] to achieve accurate imaging of a target with arbitrary motion by approximating the target as part of a circle measured by three antennas. Although this algorithm works well for several examples of arbitrary motion, it is hardly applicable to non-circular shapes, particularly targets having specular or edge structures on their surfaces. In general, the imaging accuracy of model fitting techniques like that of the extended SEABED algorithm [6] is highly dependent on the target shape.

As a substantial solution to the above problem, this paper proposes a novel imaging algorithm for a moving target with arbitrary shape, based on normal vector matching on the target surface with multi-static observations. For simplicity, this paper assumes that the target is in translational motion. Employing this method, first, the conventional mono-static RPM algorithm is extended to the multi-static model. Note that the multi-static RPM has a significant advantage in that it offers accurate target boundary points and their normal vectors without a derivative operation, and it is an essential part of the proposed method to simultaneously accomplish nonparametric imaging and motion estimation. Results obtained from numerical simulation verify the effectiveness of the proposed algorithm even in noisy situations.

II. System Model

The system model used in this paper is shown in Fig. 1. This paper deals with 2-D problems and the TE mode wave for simplicity. It assumes that the target has arbitrary shape with a clear boundary and is in translational motion. A number of omni-directional antennas are arranged along

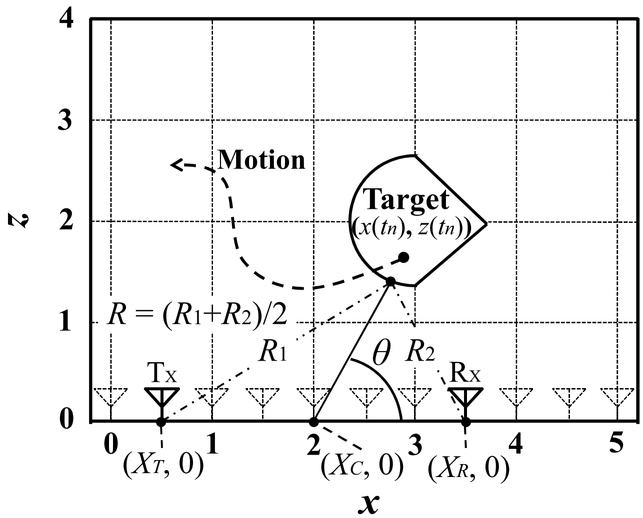

Fig. 1. System model in 2-D problem.

the x-axis at fixed intervals. The transmitting current is a mono-cycle pulse. Here, it is assumed that observation data are acquired instantaneously and the target motion during the data acquisition interval is negligible. The n-th observation time is defined as $t_n = (n-1)\Delta t$ $(1 \leq n \leq N)$, where Δt denotes the interval of the observation event. The real space, in which the target and antennas are located, is normalized by the central wavelength λ of the pulse. The locations of the transmitting and receiving antennas are defined as $(x, z) = (X_T, 0)$ and $(X_R, 0)$, respectively. For each combination of X_T and X_R, the output of the Wiener filter is denoted $s(X_T, X_R, R')$, where $R' = c\tau/2\lambda$ is defined with delay time τ and speed of the radio wave c. (X_T, X_R, R) is defined as the range point, which is extracted from the local maxima of $s(X_T, X_R, R')$ as to R'.

III. Proposed Imaging Algorithm for a Moving Target

This section presents an overview and the problem of the conventional imaging algorithm for a moving target [6], and presents our proposed algorithm employing multi-static observations. The original mono-static RPM is first extended to the multi-static radar model, and the algorithm for estimating the target motion trajectory, which is based on unit normal vector matching using the multi-static RPM algorithm, is then proposed.

A. Problem with the Conventional Algorithm

The conventional algorithm [6] determines a target boundary as a circle using its curvature calculated from the ranges measured with three antennas, and estimates the motion of the target by tracking the center of the circle. However, this algorithm assumes a fixed curvature on the target boundary, and thus, its imaging accuracy is poor in the case of more complicated target boundaries having an edge or a specular surface, in which case the apparent curvature changes in each observation event.

B. Multi-static RPM Algorithm

To solve the problem with the conventional algorithm, a nonparametric imaging algorithm for a moving target is proposed here. First, the existing RPM is extended to a multi-static model. The original RPM accomplishes extremely accurate boundary extraction employing a mapping from the group of range points to the group of target points [3]. Whereas this method assumes a mono-static observation, it is readily extended to multi-static observation. The multi-static RPM is based on the simple principle that a target boundary point should exist on an ellipse formulated as $\sqrt{(x-X_T)^2+z^2} + \sqrt{(x-X_R)^2+z^2} = 2R$. Thus, each target point (x, z) can be calculated from the corresponding angle of arrival θ as shown in Fig. 1. The optimum θ for each range point (X_T, X_R, R) is calculated as

$$\theta_{\rm opt}(\boldsymbol{q}) = \arg\max_{\theta} \sum_{i=1}^{N_{\rm q}} s(\boldsymbol{q}_i) \exp\left[-\frac{\{\theta - \theta(\boldsymbol{q}, \boldsymbol{q}_i)\}^2}{2\sigma_\theta^2}\right] \times \exp\left[-\frac{(X_T - X_{T,i})^2 + (X_R - X_{R,i})^2}{2\sigma_X^2}\right], \quad (1)$$

where $\boldsymbol{q} = (X_T, X_R, R)$, $\boldsymbol{q}_i = (X_{T,i}, X_{R,i}, R_i)$, and $\theta(\boldsymbol{q}, \boldsymbol{q}_i)$ denotes the angle from the x-axis to the line connecting the point $((X_T + X_R)/2, 0)$ and the point of intersection of the two ellipses determined by $\boldsymbol{q}$ and $\boldsymbol{q}_i$. σ_θ and σ_X are empirically determined, and $N_{\rm q}$ is the total number of range points. The target point (x, z) is obtained as

$$\left.\begin{array}{l} x = X_C + a\, \cos\theta_{\rm opt} \\ z = b\, \sin\theta_{\rm opt} \end{array}\right\}, \quad (2)$$

where $X_C = (X_T + X_R)/2$, $a = R$, and $b = \sqrt{R^2 - (X_T - X_C)^2}$.

As a notable characteristic of the RPM algorithm, each unit normal vector on a target point (x, z) is calculated, employing the law of reflection, as

$$\boldsymbol{e} = \frac{-(b\cos\theta, a\sin\theta)}{\sqrt{b^2\cos^2\theta + a^2\sin^2\theta}}. \quad (3)$$

C. Algorithm for Estimation of the Target motion Trajectory

The proposed algorithm estimates target motion by tracking the unit normal vectors on the target points obtained by the multi-static RPM. The locations of these target points at t_n are denoted $\boldsymbol{p}_j(t_n)$ $(j = 1, .., N(t_n))$, where $N(t_n)$ denotes the number of target points handled by RPM at t_n. If the target motion is only translational (i.e., there is no rotation), the unit normal vector at target points should be invariant. That is, the optimum target point $\hat{\boldsymbol{p}}_i(t_n; \boldsymbol{p}_i(t_{n-k}))$, which is regarded as having the same location as $\boldsymbol{p}_i(t_{n-k})$ at t_{n-k} on the target boundary, is calculated as

$$\hat{\boldsymbol{p}}_i(t_n; \boldsymbol{p}_i(t_{n-k})) = \arg\min_{\boldsymbol{p}_j(t_n)} \epsilon(\boldsymbol{p}_j(t_n), \boldsymbol{p}_i(t_{n-k})) \quad \text{if } \epsilon(\boldsymbol{p}_j(t_n), \boldsymbol{p}_i(t_{n-k})) < \rho, \quad (4)$$

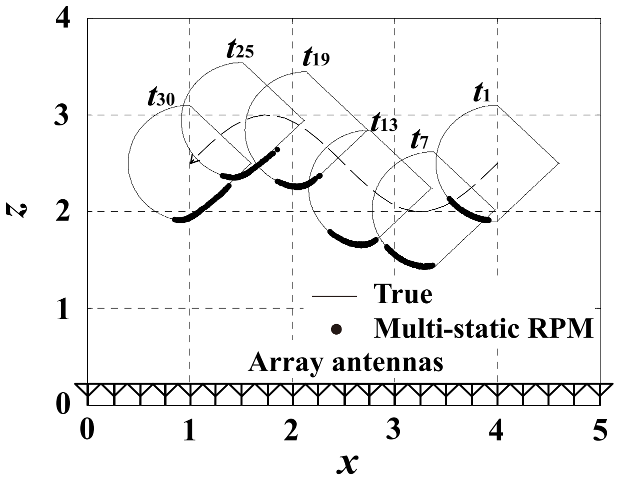

Fig. 2. Target boundary points obtained by multi-static RPM algorithm at t_1, t_7, t_{13}, t_{19}, t_{25}, and t_{30}.

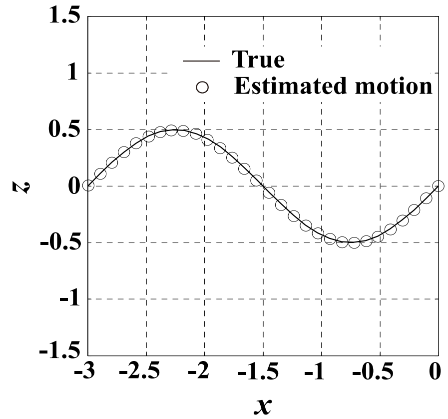

Fig. 3. Target motion trajectory obtained by the proposed algorithm.

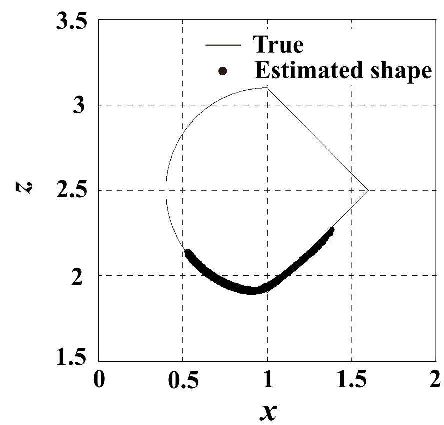

Fig. 4. Reconstructed target image compensated by the target motion trajectory.

where ρ is a threshold. $\epsilon(\boldsymbol{p}_j(t_n), \boldsymbol{p}_i(t_{n-k}))$ is defined as

$$\epsilon(\boldsymbol{p}_j(t_n), \boldsymbol{p}_i(t_{n-k})) = |\boldsymbol{e}_j(t_n; \boldsymbol{p}_j(t_n)) - \boldsymbol{e}_i(t_{n-k}; \boldsymbol{p}_i(t_{n-k}))|, \quad (5)$$

where $\boldsymbol{e}_j(t_n; \boldsymbol{p}_j(t_n))$ denotes the unit normal vector on $\boldsymbol{p}_j(t_n)$. The threshold ρ is employed to select appropriate corresponding pair of points, which should exist in the overlapping area of target points obtained by RPM between t_n and t_{n-k}. If $\epsilon(\boldsymbol{p}_j(t_n), \boldsymbol{p}_i(t_{n-k})) \geq \rho$, it is judged that the corresponding pair of points does not exist and the pair is not used for motion estimation. The motion vector $\boldsymbol{V}_n^{(n-k)}$ from t_{n-k} to t_n is calculated as

$$\boldsymbol{V}_n^{(n-k)} = \frac{1}{L} \sum_{l=1}^{L} \{\hat{\boldsymbol{p}}_l(t_n; \boldsymbol{p}_l(t_{n-k})) - \boldsymbol{p}_l(t_{n-k})\}, \quad (6)$$

where L is the total number of $\epsilon(\boldsymbol{p}_j(t_n), \boldsymbol{p}_i(t_{n-k}))$ satisfying $\epsilon(\boldsymbol{p}_j(t_n), \boldsymbol{p}_i(t_{n-k})) < \rho$.

Finally, the motion vector $\boldsymbol{V}_n^{(1)}$ at t_n is calculated by smoothing plural motion vectors $\boldsymbol{V}_n^{(n-s)} (s = 1, .., k)$ to suppress cumulative errors [7] that can arise from the quantization error in RPM imaging.

IV. PERFORMANCE EVALUATION IN NUMERICAL SIMULATIONS

The performance of the proposed algorithm is evaluated through numerical simulations. FDTD (Finite Difference Time Domain) method is employed for the calculation of received signals. The calculation parameters assumed in the simulation are described below. The target motion is defined as $(x(t_n), z(t_n)) = (x_0 + v_x t_n, z_0 + v_f \sin(2\pi t_n / \{(N-1)\Delta t\}))$, where $N = 30$, $(x_0, z_0) = (4, 2.5)$, $v_x = -0.1$, and $v_f = -0.5$. The number of antennas is 21 located at $0 \leq x \leq 5$, $\sigma_\theta = \pi/50$, $\sigma_x = 0.8$, $k = 6$.

Figure 2 shows the target boundary points obtained by using a multi-static RPM algorithm at each observation time. This result indicates that the multi-static RPM provides an accurate image regardless of the observation event. Fig. 3 shows the target motion trajectory estimated by the proposed algorithm. The figure shows that the true and estimated curves of motion are almost identical, and the proposed algorithm estimates the target motion trajectory accurately in the case of the target boundaries having an edge and a specular surface. That is, the proposed algorithm has a nonparametric property for imaging a moving target, which is a notable advantage over the conventional method [6]. Fig. 4 shows the reconstructed target shape compensated by the target motion trajectory. This result indicates that the proposed algorithm has been successful in expanding the image area of the target. In addition, the RMS (Root Mean Square) error of the reconstructed shape is approximately 0.013λ, and mainly results from the deformation of the scattered waveform detailed in [3].

Next, the performance is evaluated for the noisy case. Gaussian white noises are added to the received signals. Here, the signal-to-noise ratio S/N is defined as the ratio of the peak instantaneous signal power to average noise power after applying a matched filter [3]. Fig. 5 shows the target boundary points obtained by the multi-static RPM for $\mathrm{S/N} = 25$ dB.

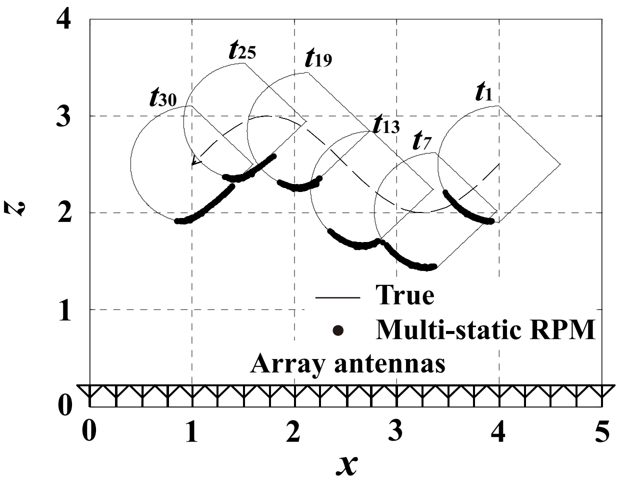

Fig. 5. Target boundary points obtained by multi-static RPM algorithm for $\mathrm{S/N} = 25$ dB at t_1, t_7, t_{13}, t_{19}, t_{25}, and t_{30}.

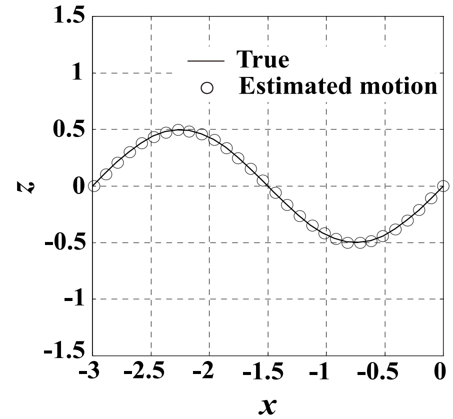

Fig. 6. Target motion trajectory obtained by the proposed algorithm for $\mathrm{S/N} = 25$ dB.

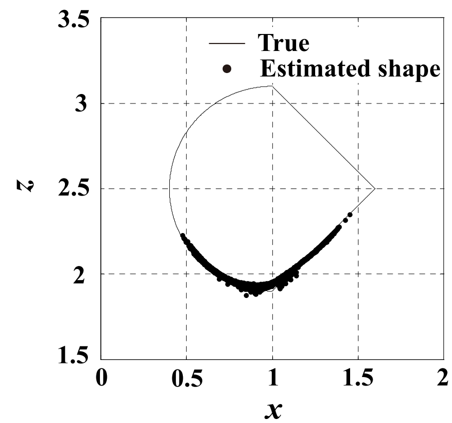

Fig. 7. Reconstructed target image compensated by the target motion trajectory for $\mathrm{S/N} = 25$ dB.

The figure verifies that the multi-static RPM retains sufficient accuracy even for a noisy environment. Figs. 6 and 7 show the target motion trajectory estimated by the proposed algorithm and the reconstructed target shape combined by the target motion trajectory for $\mathrm{S/N} = 25$ dB, respectively. The RMS error of the reconstructed shape is around 0.024λ. That is, the RMS error of the reconstructed shape is within 0.024λ for $\mathrm{S/N} \geq 25$ dB. These results show that the proposed algorithm provides highly accurate moving target imaging even for a noisy environment. In principle, since the accuracy of motion estimation mainly depends on the accuracy of the multi-static RPM, the proposed algorithm will work well for any translation motion as long as the accuracy of the multi-static RPM is sufficient.

V. CONCLUSION

This paper proposed a novel imaging algorithm for a moving target with arbitrary shape, which is based on normal vector matching on the target surface using RPM extended to multi-static observations. First, it was revealed that the conventional algorithm suffers the problem that its imaging accuracy is considerably distorted in the case of the target boundaries having edges or specular surfaces because it is based on a circle approximation of the target boundary using measured distances. Since the proposed algorithm is a nonparametric technique in principle, it would be more versatile than the conventional algorithm in the reconstruction of target shape. Finally, the results in numerical simulation including noisy case exemplify that the proposed algorithm accomplishes extremely accurate moving target imaging at the order of $1/100$ wavelength, even in the target with an edge and a specular surface.

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