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An adaptive threshold-based unambiguous robust Doppler beam sharpening algorithm for forward-looking MIMO Radar

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Abstract— **The ambiguity problem in forward-looking Doppler beam sharpening is considered. Doppler beam sharpening (DBS) has shown its potential to improve cross-range resolution for automotive radar applications. However, it suffers from ambiguities when targets are positioned symmetrically with respect to the vehicle trajectory. A new approach named 'Robust Unambiguous DBS with Adaptive Threshold' (RUDAT) is proposed to address the problem of ambiguities. It combines DBS with multiple-input-multiple-output (MIMO) radar processing, and is robust to non-ideal movements of the vehicle and fluctuations in the targets' reflectivity. The performance of the proposed method is compared to existing approaches using simulated data with point-like and extended targets, demonstrating good preliminary results.**

Keywords— **Doppler beam sharpening, Beam scan, Forward-looking radar, MIMO radar processing.**

I. Introduction

Radar is a key sensor in automotive applications, as it can provide robust sensing capability in adverse weather conditions. To meet the requirements of autonomous driving, radar needs to provide an acceptable angular resolution with the constraint of limited size. Hence, multiple-input-multiple-output (MIMO) radar has been exploited in current automotive radars due to its ability to achieve high angular resolution with a few antennas [1].

By combining the vehicle movement with MIMO processing, a larger effective (i.e., virtual) aperture array will be formed and provide finer angular resolution. A lot of research is ongoing in this field. An approach forming a synthetic aperture for automotive MIMO radar has been explored in [2], which only can enhance the resolution in a limited region. A SAR-inspired method in [3] uses back projection to image the whole scene based on targets' estimated trajectory with a high computational cost. The 'time tag' approach was introduced in [4] to extend the MIMO aperture coherently, solving the MUSIC rank deficiency problem and reducing the computational cost of the conventional SAR algorithm.

Doppler beam sharpening is an alternative way of using motion information and has been proposed in different studies [5]–[7]. However, it is challenging to use Doppler beam sharpening (DBS) in the forward-looking direction, which is especially of interest for autonomous vehicles, because the symmetric targets on both sides of the trajectory have the same Doppler history, leading to ambiguity. Lack of angular resolution at the boresight region is also another problem for forward-looking radar, but not considered in this paper.

Several algorithms have been proposed in forward-looking SAR to tackle the ambiguity problem, i.e., Bistatic SAR [8], [9], frequency diverse array [10], multibeam DBS approach [11], and multichannel radar [12]. For automotive applications, the incoherent integral from MIMO image and Doppler image is proposed in [13] to increase a cross-range resolution across most of the radar's field of view. Side lobe errors will also be suppressed during the process. One potential weakness is that this method has a strict requirement for vehicle movement, i.e., the movement must be in the boresight direction of the radar. An unambiguous DBS method named '*UDFMBSC*' proposed in [14] combines the MIMO processing with DBS in the signal domain with reasonable computing power. However, it only works when the symmetric targets have comparable radar cross-sections.

To make the '*UDFMBSC*' suitable for more complicated vehicle movements and cope with the diverse reflectivity of different targets in the scene, this paper proposes a new approach named 'Robust Unambiguous DBS with Adaptive Threshold' (*RUDAT*). The problem of ambiguous symmetric targets for non-ideal forward-looking vehicle trajectory is addressed via additional phase shift compensation. Targets with different reflectivity are retrieved by applying an adaptive threshold instead of a peak search as in [14]. The proposed method is validated with simulations with point-like and extended targets, showing good performances.

The rest of the article is organized as follows. In Section II, the fundamentals of the *RUDAT* method are provided, including signal model, problem formulation and the proposed approach. The simulation results and evaluations for ideal point targets and complex extended targets are provided in Section III. Finally, conclusions are drawn in Section IV.

II. Fundamentals

A. Signal model

The received signal will be the superposition of the emitted frequency modulated continuous wave (FMCW) MIMO radar's signal reflected by targets in the field of view. It can be written as:

$$z(i,l,k) = \sum_{\mathbf{o}=1}^{K} \alpha_{\mathbf{o}} \tau(i) exp[j2\pi f_0 \frac{id}{c} sin\theta_{\mathbf{o}}] \times exp[-j2\pi(f_0 \frac{2v_{\mathbf{o}}}{c} Tl + \mu\gamma_{\mathbf{o}} \frac{k}{fs})] \quad (1)$$

where z indicates the digitized signal; i is the index of antenna elements counted in the virtual uniform linear array relative to the 1st antenna element; $l = \lfloor \frac{t}{T} \rfloor$ with $t' = t - lT$ where T is the pulse repetition interval; $t' \in [0, T_c]$ with $i = 0, 1, 2, ..., M-1$ where M is the number of antenna elements in the array, T_c is the chirp duration; $k = 0, 1, 2, ..., K_d - 1$ where $K_d = T_c f_s$ is the maximum number of samples within one chirp and f_s is the fast time sampling frequency; $\mathbf{o}$ is the target's index, K is the total number of targets; $\alpha_{\mathbf{o}}$ is the constant complex amplitude related to the characteristics of the target $\mathbf{o}$; $\tau(i)$ is the waveform diversity function; f_0 denotes the starting frequency of the chirp; d is the space interval between adjacent antenna elements; c is the speed of light; $\theta_{\mathbf{o}}$ is the azimuth of target $\mathbf{o}$; $v_{\mathbf{o}}$ is the radial velocity between target $\mathbf{o}$ and radar; μ is the frequency modulation rate; $\gamma_{\mathbf{o}} = \frac{2D_{\mathbf{o}}}{c} \ll T_c$ with $D_{\mathbf{o}}$ being the distance between antenna and target $\mathbf{o}$.

B. Problem formulation

The radar imaging ability in the forward direction is paramount for autonomous driving. The angle profile of detected scatter points can be obtained either from the MIMO digital beam forming $P_F(\theta)$, or using Doppler beam sharpening $P_S(\theta)$. It has been proved that, compared with MIMO, the Doppler beam sharpening can improve angular resolution in a large part of the field of view [13]. However, it will suffer from the ambiguity problem for symmetric targets, which comes from the inherent geometry of forward-looking radar.

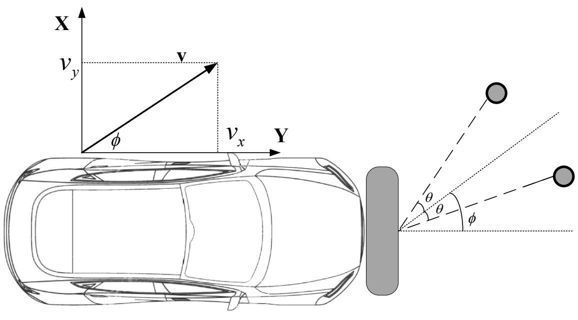

Fig. 1. The assumed scenario for forward-looking radar.

Here, a generic 1-D MIMO array placed in the x direction is considered, as shown in Fig. 1. The platform where the radar is installed is moving at speed $v = [v_x, v_y]$, with two static objects located in the far field of the MIMO array. When the vehicle is moving toward the two static targets, both of them will appear symmetric with respect to the trajectory of the radar, and they will experience the same Doppler velocity $\sqrt{v_x^2 + v_y^2}\cos(\theta-\phi)$, where $\phi = \arctan(\frac{v_x}{v_y})$. This makes them indistinguishable using conventional Doppler beam sharpening.

'UDFMBSC' proposed in [14] solved the ambiguity problem based on two properties and assumptions. First, the Doppler is symmetric with respect to the boresight of the radar, as the movement is only in the forward direction. Thus, the spatial frequencies of the ambiguous targets have the same symmetry as an odd function. Second, a peak search approach will work based on the assumption that the symmetric targets have similar reflectivity. In reality, the diverse radar cross-section of targets and non-uniformity of the vehicle movement is common in automotive driving. 'UDFMBSC' will fail in those cases.

C. Proposed method

Assuming that each range-Doppler cell only contains one or two targets, i.e., target index $i \in [1, 2]$, '*UDFMBSC*' [14] uses a peak searching approach on the auto-convolution of the ambiguous targets' spatial frequency to decide the real location of the target. To make the algorithm robust to more complicated vehicle movements and to the different reflectivity of targets, some extra steps are proposed here. It should be noted that the following processing is within one coherent processing interval (CPI), thus the rotation caused by possible drifting is slow and negligible.

First, the target will be detected in the range dimension. Its corresponding Doppler cell will be calculated by $\sqrt{v_x^2 + v_y^2}\cos(\theta - \phi)$. The targets in the same detected range-Doppler cells will be ambiguous after Doppler beam sharpening, i.e., the targets located at azimuth angle $(\theta - \phi)$ and $(-\theta - \phi)$. Then, the angle vector of this cell will be extracted for further processing.

If there is only one target in the azimuth angle $(\theta - \phi)$, then the Fourier transform $X(f, \theta)$ of the angle vector can be expressed as:

$$\begin{aligned} X(f,\theta) &= s_i(f, \beta(\theta)) \\ &= a_i \pi N_a \text{sinc}(\frac{N_a(f + \beta(\theta))}{2}) e^{j\pi N_a (f + \beta(\theta))} \end{aligned} \quad (2)$$

where a_i is the reflection coefficient of the target i, and $\beta(\theta) = \frac{d\sin(\theta-\phi)}{\lambda}$.

If another target is located at the ambiguous position $(-\theta - \phi)$, there will be two targets in the detected range-Doppler cell. Similarly, the Fourier transform of the angle vector $X(f, \theta)$ will be by superposition:

$$X(f,\theta) = s_1(f, \beta(\theta)) + s_2(f, \beta(-\theta)) \quad (3)$$

The peak searching approach described in [14] comes from the odd function $\sin(-\theta)$, noticing that:

$$\delta(\theta) = -\delta(-\theta) = \beta(\theta) + \frac{d\cos\theta\sin\phi}{\lambda} = \frac{d\sin\theta\cos\phi}{\lambda} \quad (4)$$

Here, the extra frequency shift $\delta(\theta)$ is implemented on the Fourier transform of the angle vector $X(f, \theta)$ as a compensation to maintain the odd-function property. After this, the auto-convolution will be calculated on the Fourier transform to obtain $\chi(\Omega, \theta)$. The auto-convolution for the one target case $\chi_1(\Omega, \theta)$ is expressed as:

$$\begin{aligned}\chi_1(\Omega, \theta) = S_i(\Omega, \delta(\theta)) = \exp[j\frac{\pi N_a}{2}(-\Omega + 2\delta(\theta))] \\ \text{sinc}(\frac{N_a(-\Omega + 2\delta(\theta))}{4})a_i^2\pi^2 N_a\end{aligned} \tag{5}$$

Correspondingly, the auto-convolution $\chi_2(\Omega, \theta)$ for the two targets' case will be:

$$\begin{aligned}\chi_2(\Omega, \theta) = S_1(\Omega, \delta(\theta)) + S_2(\Omega, \delta(-\theta)) \\ + 2a_1a_2\pi^2 N_a \text{sinc}(\frac{N_a(\Omega)}{4})\exp[j\frac{\pi N_a}{2}(\Omega)]\end{aligned} \tag{6}$$

For both cases, $\chi^{-1}(\max(\chi(\Omega))$ will be $2\delta(-\theta)$, $2\delta(\theta)$, or $\frac{M_\Omega}{2}$ depending on the reflectivity of the targets, with each value being proportional to $\pi^2 N_a a_1^2$, $\pi^2 N_a a_2^2$ or $2a_1a_2\pi^2 N_a$, respectively. $\frac{M_\Omega}{2}$ denotes the middle position index of the frequency. Note that the two targets' case always satisfies the following equation:

$$\chi_2(\frac{M_\Omega}{2}) >= \sqrt{\chi_2(\Omega_m) * \chi_2(M_\Omega - \Omega_m)} \tag{7}$$

On the contrary, the one target case will follow:

$$\chi_1(\frac{M_\Omega}{2}) < \sqrt{\chi_1(\Omega_m) * \chi_1(M_\Omega - \Omega_m)} \tag{8}$$

This will be set as the adaptive threshold-based criterion for the ambiguity detector. The adaptive threshold-based criterion for distinguishing one or two targets is only based on the radar signal data itself, which makes the proposed method robust to the diversity of the movement and the reflectivity.

Based on the theoretical analysis above, the algorithm is summarized in the pseudocode shown in Algorithm 1.

Algorithm 1 Proposed *RUDAT* method

Obtain the range estimation after 2D FFT on fast time & slow time. Select the angle-Doppler matrix $\mathbf{X}(i, l)$ and the corresponding angle profile $P_F(\theta)$ and $P_S(\theta)$ from digital beam forming and Doppler beam sharpening.

for Φ in $[-\frac{\pi}{2}, \frac{\pi}{2}]$do

$l_\Phi = (2(v_x \sin\Phi v_y \cos\Phi N_d Tc)/\lambda$

$X(f) = \sum_{i=-M_\Omega/2}^{M_\Omega/2} \mathbf{X}(i, l_\phi)\exp(-j2\pi f i)$

$\chi(\Omega) = \sum X(f + \delta(\theta) - \beta(\theta)\lambda X(\Omega - f + \delta(\theta) - \beta(\theta))$

if $\chi(\frac{M_\Omega}{2}) < \sqrt{\chi(\Omega_m) * \chi(M_\Omega - \Omega_m)}$

$P(\Phi) = P_F(\Phi)/\max(P_F(\Phi) \times P_S(\Phi)$

else

$\text{Si}(\Phi) = \begin{cases} 1 & P_F(\Phi) > P_F(2\phi - \Phi) \\ 0 & P_F(\Phi) < P_F(2\phi - \Phi) \end{cases}$

$P(\Phi) = \text{Si}(\Phi)\text{P}_\text{F}(\Phi)/\max(\text{P}_\text{F}(\Phi)) \times \text{P}_\text{S}(\Phi)$

end

endfor

The unambiguous angle profile can be obtained.

III. Results and Discussion

To validate the proposed method, especially in the case of targets with diverse reflectivity and non-ideal forward-looking motion, a simulated 2×4 MIMO radar was used. The center frequency is set as 77 GHz, the bandwidth is 1 GHz, the PRI is 100 us, and the sampling rate is 32 Msps.

The MIMO antenna on the forward-looking radar was located at the coordinate centre, with targets placed at the same range bin of 10 m to ensure that targets are in the far-field (Fraunhofer distance [15]). When the radar moves with velocity $[0, 15]m/s$, the Doppler symmetric line will be at $\theta = 0$. Two symmetric targets at azimuth angles of $\pm 40°$ with a six-times difference between their reflectivity, and one target with the same RCS as the stronger one in the two symmetric targets at an azimuth angle of $50°$ are simulated. The proposed approach is compared with the traditional DBF, DBS methods, and *UDFMBSC* as shown in Fig. 2. The DBS profile shows 4 symmetric targets. With the proposed method, the targets are estimated at the correct position. The two targets at $50°$ and $40°$ are separated and estimated at $49.7°$ and $39.2°$ due to the narrow DBS beam. The proposed approach can successfully estimate the weaker target at -$39.2°$, whereas the *UDFMBSC* fails, proving the effectiveness of the adaptive threshold.

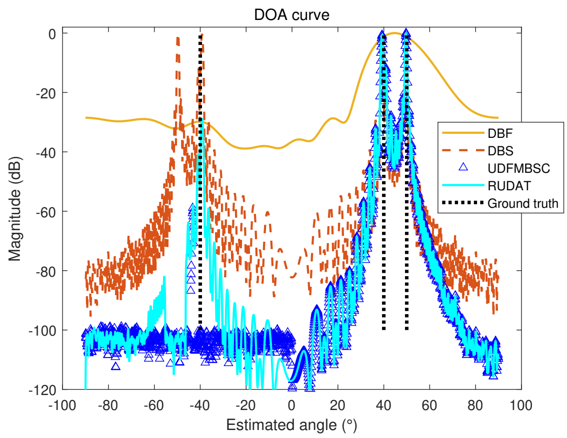

Fig. 2. Simulated performance comparison between the conventional DBF, DBS, *UDFMBSC* and proposed *RUDAT* method for the first scenario.

The second simulation is performed with the radar moving with velocity $[3, 15]m/s$, i.e. with a component not in the forward-looking direction. Here, the Doppler symmetric line will be located at approximately $\theta = 11.3°$. Two symmetric targets at an azimuth angle of $40°$ and $27.6°$ are simulated, as shown in Fig.3. The proposed *RUDAT* method successfully solves the ambiguity problem in this geometry, whereas the *UDFMBSC* fails.

The car model in [14] is also used here as an extended target. The simulated radar is moving at $[3, 15]m/s$ with four static car models located at 10 m range from the radar. The four cars are divided into two groups located at an azimuth angle of $48.6°$ & $26°$, symmetrically with respect to the motion trajectory at $\theta = 11.3°$. The two cars in each group are separated by $3m$, and the group on the right-hand side

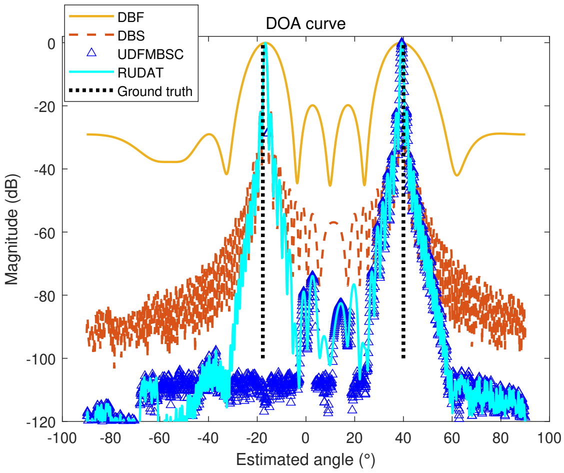

Fig. 3. Simulated performance comparison between the conventional DBF, DBS, *UDFMBSC* and proposed *RUDAT* method for the second scenario.

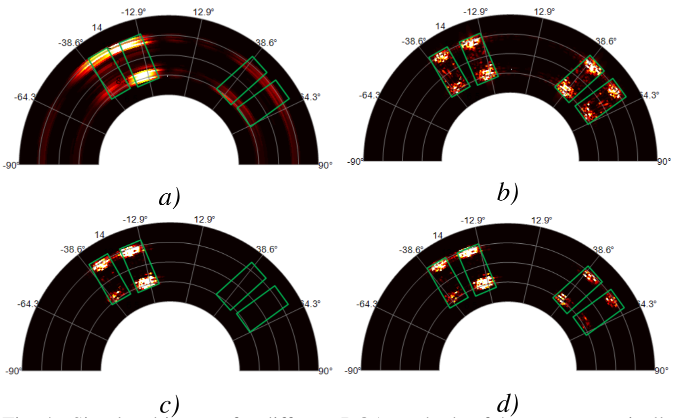

Fig. 4. Simulated images for different DOA methods of 4 cars symmetrically located with respect to the movement of the radar. a) DBF-based method b) DBS-based method c) *UDFMBSC*. d) *RUDAT*

is three times weaker than the other in terms of reflectivity. The result is shown in Fig. 4. The DBF-based method can only distinguish the two groups without separating the targets within the group, whereas the DBS-based method provides more details but cannot determine whether the two groups are real or come from ambiguity. The *UDFMBSC* method fails as expected, whereas the *RUDAT* successfully separates the four cars in this challenging situation, i.e. non-ideal forward movement of the radar and diverse targets' reflectivity. It also provides more detailed images, simplifying subsequent processing stages such as classification that may use them.

IV. Conclusion

In this paper, a 'Robust Unambiguous DBS with Adaptive Threshold' (*RUDAT*) algorithm is proposed to improve angular resolution, using MIMO processing in combination with DBS to solve its ambiguity in forward-looking radar. In simulations with point-like and extended targets, the proposed method is shown to outperform alternative algorithms by coping with differences in reflectivity between targets and being robust to non-ideal vehicle movements, i.e. velocity components not in the forward-looking direction. For a target at the angle of arrival of 40 degrees from the trajectory with 10m/s, the algorithm improves azimuthal resolution of 8 elements' MIMO in 6 times. However, one limitation of the approach is that movement of target's will degrade DBS performance, thus also influencing the performance of the proposed *RUDAT*. the forward-looking DBS method suffers from the blind zone as well [7], which needs to be addressed in future work.

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