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Target Localization Using MIMO-Monopulse: Application on 79 GHz FMCW Automotive Radar

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***Abstract*— A novel target azimuth estimation algorithm called "MIMO-Monopulse" is proposed by combining monopulse approach with multiple-input multiple-output (MIMO) radar. Chebyshev and Zolotarev weighting are applied to synthesis sum and difference pattern of MIMO-monopulse. A new visualization method for monopulse ratio is discussed. Finally, the proposed algorithm is verified successfully by processing real data from a 79 GHz FMCW automotive radar.**

***Keywords*— DoA, MIMO, monopulse, FMCW, automotive radar, target angle estimation**

I. Introduction

Different sensors are used in automotive active safety systems (such as collision avoidance, blind spot detection, and the parking aid) in advanced drive assistance systems (ADAS) to monitor the surrounding environment of a vehicle. Compared with other sensors, like camera and light detection and ranging (LiDAR) sensors, millimeter wave radar has advantages of robust performance against low visibility environmental situations such as rough weather and limited lighting conditions.

Automotive radar system utilizes millimeter-wave band to detect the range, velocity, and azimuth of targets. Commercial 24 GHz and 77 GHz automotive radar have been well developed and 79 GHz is the future solution for short-range radar which has been defined by European Commission in 2004 [1]. With 4 GHz bandwidth it will provide fine down-range resolution. The cross-range estimation is however much more course so the improvement real-time target azimuth estimation algorithm, therefore, becomes a potential field of research.

Super-resolution (subspace-based) algorithms such as MUSIC and ESPRIT can improve the estimation performance but suffer when only a few measurements (snapshot) are available [2], [3]. In these methods, eigenstructure analysis requires knowing the exact number of targets to determine the effective rank of the correlation matrix. Moreover, super-resolution algorithms are computationally expensive, thus they are not suitable for real-time automotive-radar applications.

Compared with subspace-based algorithms, monopulse has potential benefits of saving computation cost, having less requirements (no need to know the number of targets) and capability to work using single snapshot and it naturally provides benefits in target tracking radar systems [4], [5].

The concept of combining MIMO and monopulse (MIMO-monopulse) has been studied in the literature, but most of them utilize distributed MIMO with widely separated transmitters and receivers. The application of collocated MIMO-monopulse has not been considered yet.

In this paper, a novel monopulse based angle estimation algorithm is proposed for collocated MIMO radar and applied to the automotive radar. Section II discusses how to combine monopulse with MIMO processing and introduce Chebyshev and Zolotarev weightings to synthesis sum and difference pattern of MIMO-monopulse. The application of proposed method to different (simulated and collected) data sets are given in in Section III. Finally, recommendations and possible future work are discussed in Section IV.

II. MIMO model and DoA estimation

Let us suppose that the MIMO radar system has two uniform linear arrays (ULA) with M_T transmitters and M_R receivers. Under far-field assumption, the line-of-sight direction of planar wave reflected from targets are assumed to be parallel, and thus the transmitted signals are delayed consecutively increasing to each element in an antenna array. Such delay includes both the time that the transmitted wavefront reaches the target and the received wavefront reaches the receiver element. In ULA, this phase shift is increasing linearly.

Suppose that the transmitted signals at each transmitter are $\mathbf{s}_i, i = 1, ..., M$. A snapshot from all transmitters are sampled as $\mathbf{s} = [\mathbf{s}_1, \mathbf{s}_2, ..., \mathbf{s}_M]$, where transmitted signals $\mathbf{s}_i$ are orthogonal to each other for simutaneous transmission.

The transmitter $\mathbf{a}_T$ and receiver $\mathbf{a}_R$ steering vectors in the direction of θ, which indicates the phase delay of each element in antenna array, are expressed as

$$\begin{aligned} \mathbf{a}_T(\theta) &= \begin{bmatrix} 1 & e^{j2\pi\frac{d_T}{\lambda}\sin(\theta)} & \dots & e^{j2(M_T-1)\pi\frac{d_T}{\lambda}\sin(\theta)} \end{bmatrix}^T \\ \mathbf{a}_R(\theta) &= \begin{bmatrix} 1 & e^{j2\pi\frac{d_R}{\lambda}\sin(\theta)} & \dots & e^{j2(M_R-1)\pi\frac{d_R}{\lambda}\sin(\theta)} \end{bmatrix}^T \end{aligned} \quad (1)$$

where λ is the wavelength, d_T and d_R are the inter-element spacing of the transmitters and the receivers, respectively. The steering vector of virtual array is formulated through the

Kronecker product of transmitter and receiver array steering vectors

$$\mathbf{a}(\theta) = \mathbf{a}_T(\theta) \otimes \mathbf{a}_R(\theta). \tag{2}$$

Then the MIMO signal model can be expressed as

$$\mathbf{x} = \mathbf{ABS} + \mathbf{n}, \tag{3}$$

where $\mathbf{A}$ is the steering matrix, $\mathbf{B}$ is the amplitude of k^{th} target and $\mathbf{S}$ is the received signal matrix

$$\begin{aligned} \mathbf{A} &= \begin{bmatrix} \mathbf{a}(\theta_1) & \cdots & \mathbf{a}(\theta_k) \end{bmatrix}^H \\ \mathbf{B} &= \begin{bmatrix} \beta_1 & & \\ & \ddots & \\ & & \beta_k \end{bmatrix} \\ \mathbf{S} &= \begin{bmatrix} \mathbf{s}_1 & \cdots & \mathbf{s}_k \end{bmatrix}. \end{aligned} \tag{4}$$

The white noise $\mathbf{n}$ is assumed to be spatially independent and identically distributed (i.i.d.). Consider the MIMO array model, 3D processing can be applied on the received signals to achieve range, Doppler (velocity), and angle information of targets.

III. Angle Estimation Using MIMO-Monopulse

The monopulse technique for arrays is based on delay-and-sum beamformer. In conventional digital beamforming (DBF), we estimate the signal of interest arriving from a specific direction. The output of conventional beamformer can be expressed as [6]

$$y = \mathbf{w}^H \mathbf{x}. \tag{5}$$

where $\mathbf{w}$ is the weighting vector, $\mathbf{x}$ is the received signal and $(\bullet)^H$ is the complex conjugate transpose (Hermitian transpose). The response of beamforming, which is maximum at the direction of steering θ, can be written as

$$P(\theta) = \mathbf{w}^H \mathbf{a}(\theta) \tag{6}$$

where $\mathbf{a}(\theta)$ is the steering vector (also known as array manifold vector) [6]. A collocated MIMO radar system uses virtual array to generate sum and difference beams which are utilized by DBF. Then, DoA can be determined by computing the monopulse ratio R which is defined as the ratio of difference to sum beamforming output.

For amplitude comparison monopulse (AMC), the left and right beams are generated by two beamforming vectors centered at a look direction θ_0 but separated by a squint angle shift θ_s to left and right [7]. The difference of voltage of left and right beams will be zero if the target is precisely located at θ_0. For phase comparison monopulse (PCM), the antenna array can be divided into two equal sub-arrays to compare phase information. Consider a array of M elements. The left $M/2$ elements consists of left sub-array while the rest of elements consists of the right one [8].

The performance of MIMO-monopulse can be further improved through the synthesis of array pattern. The goal of the synthesis is to obtain the beam pattern with the desired property through choosing the weighting of each element. In monopulse technique, on the one hand there is a need of maximizing the gain of beam pattern. On the other hand, the difference patterns are concerned with both to minimize the first null beamwidth and to maximize the normalized difference slope on look direction, which guarantees the sensitivity of DoA estimation.

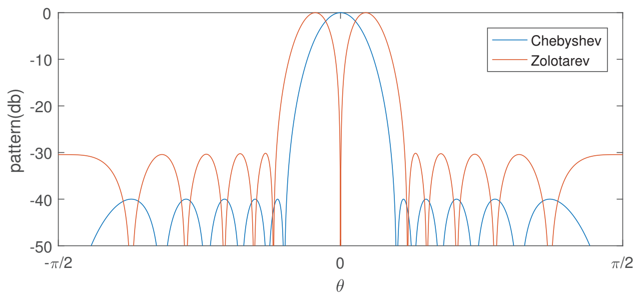


Fig. 1. Sum (Chebyshev) and difference (Zolotarev) beam pattern of the proposed synthesis

The Dolph-Chebyshev synthesis of linear arrays with sum patterns gives the array element excitations that provide an optimum array factor in the sense that for a specified sidelobe level, number of array elements, and interelement spacing, the beamwidth between the first nulls is the narrowest possible [9]. It provides the minimum null-to-null mainlobe width for a given sidelobe level, or minimum sidelobe level for a given null-to-null mainlobe width.

A difference pattern can be defined as optimum in the Chebyshev sense if it has the narrowest first null beamwidth and largest normalized difference slope on boresight for a specified sidelobe level. Such patterns have all sidelobes at the same required level. McNamara realized that a class of functions known as Zolotarev polynomials did possess exactly the properties required for ideal linear array difference beam synthesis which have characteristics similar to the Dolph-Chebyshev sum beam [10]. Implementation of the Zolotarev polynomial requires knowledge of elliptic integrals, Jacobi moduli, and Jacobi eta, zeta, and elliptic functions, which is complex to realize. In literature, a close approximation to the Zolotarev pattern which is easy to implement through using the Chebyshev pattern, has been developed for the linear array case [11]. For a uniform virtual linear array, one can generate the Zolotarev pattern with 30 dB peak to sidelobe ratio (PSL) with respect to the Chebyshev pattern with 40 dB PSL as illustrated in Figure 1.

If the radar scans over a target, the sum beam output will be maximum when the target is exactly in the look direction θ_0, and the difference beam output will then be zero, thus the monopulse ratio will be exactly zero. If the target has a small offset angle from the look direction $(\theta - \theta_0)$ the small output of the difference beam, the error voltage is used to estimate this angle. The *error voltage* is computed by taking the either real part or imaginary part of monopulse ratio, which depends on the method of generating sum and difference beams [12]. For the proposed synthesis of beam pattern, we use the imaginary

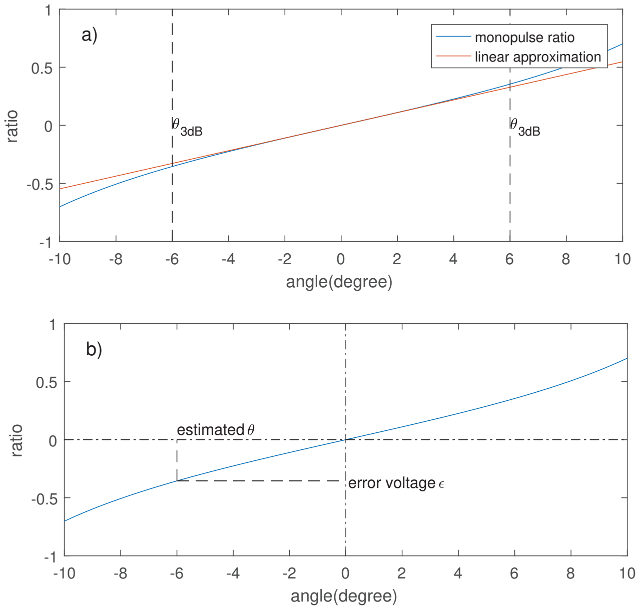


Fig. 2. (a) Monopulse ratio and linear approximation ; (b) Error voltage and inverse mapping

part of monopulse ratio to compute error voltage

$$\epsilon = \Im\left\{\frac{\mathbf{w}_\Delta^H \mathbf{x}}{\mathbf{w}_\Sigma^H \mathbf{x}}\right\}, \tag{7}$$

where $\mathbf{w}_\Delta$ and $\mathbf{w}_\Sigma$ are the weight vectors of difference and sum beam patterns, respectively. Once an error voltage is computed, it can be evaluated by a *monopulse response curve (MRC)* [13] to realize the angle estimate $\hat{\theta}$ of the target. The MRC is defined as the imaginary part of the monopulse ratio with the angle to be estimated:

$$M(\theta) = \Im\left\{\frac{\mathbf{w}_\Delta^H \mathbf{a}(\theta)}{\mathbf{w}_\Sigma^H \mathbf{a}(\theta)}\right\} \tag{8}$$

Then the angle is estimated by inverse mapping the error voltage through the MRC, which is expressed as:

$$\hat{\theta} = M^{-1}(\epsilon) \tag{9}$$

Figure 2 shows the linear approximation region of the monopulse ratio where the realization of angle estimation is possible. Having a wider linear region is crucial to estimate the target's DoA. It should be noted that, the use of Chebyshev and Zolotarev pattern optimizes the sidelobe levels (as shown in Figure 1) and increase the sensitivity of the monopulse ratio due to a better linear region as illustrated in Figure 2.

IV. Implementation

As is discussed in section II, the MIMO-monopulse algorithm estimates the angle of targets within the main beam through monopulse ratio. To cover a wide area of bearing, multiple beams will be generated simultaneously to the broad field of view by DBF, normally with intersections at the points of 3dB in sum pattern, which guarantees the linear approximation of monopulse ratio within each beam. Compared with DoA estimation using beam scan, which requires a dense grid of scanning to locate the maximum point of response pattern, MIMO-monopulse dramatically reduces the computational cost, meanwhile still provides very accurate angle estimation performance. For DBF, another problem is that the estimation error is determined by the interval of searching the peak of the beam pattern. It is apparent that the small interval leads to the improvement of angle estimation accuracy, but for MIMO-monopulse the estimation error is fixed using the same MRC.

The MIMO-monopulse is simulated on Matlab to estimate the angle of targets. Compared with monopulse which is widely used in phased-array radar, the main difference of MIMO-monopulse is that the radiation of the antenna array is omnidirectional. Thus before estimating the angle of targets using MIMO-monopulse, a pre-detection is required to determine which beam the target located is in, since there are multiple beams generated by MIMO antenna elements. After the beam is detected, monopulse is used to estimate the exact angle of the target within this selected beam according to the inverse mapping of linear approximation region, which is illustrated in Fig. 2 (b). To cover the whole field of view of angle, only several beams are required to be generated, and the estimation of DoA is only a linear mapping, which guarantees the fast computation by MIMO-monopulse.

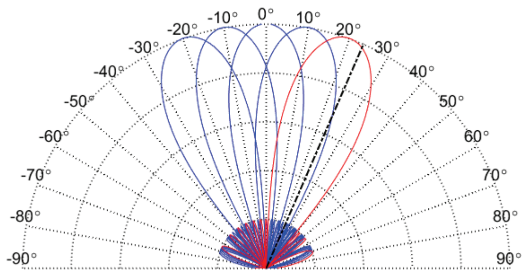
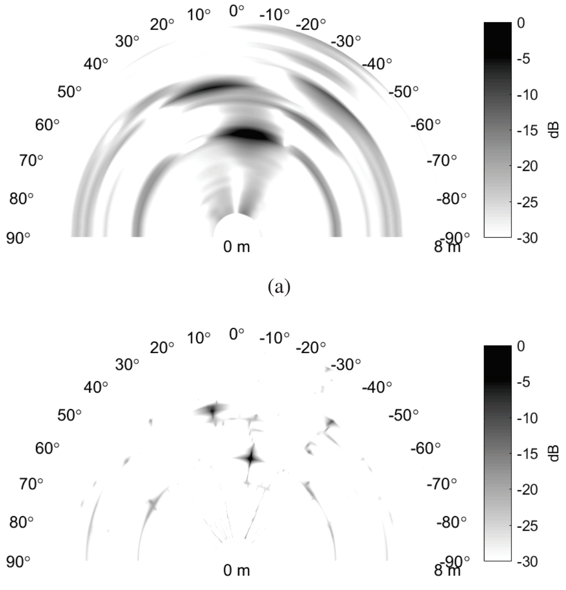


Fig. 3. MIMO-monopulse scan by generating multiple beams simultaneously. Target is at 23 degrees within the red beam steered to 20 degrees

The performance of the proposed algorithm is validated through Dolphin T2V2 radar chip-set provided by NXP Semiconductors N.V. To demonstrate the algorithm, we utilize the proposed approach to process the real data from an indoor measurement using ideal corner reflectors as targets.

The Dolphin T2V2's MIMO array consists of 3 transmitters and 4 receivers which allows synthesizing a 12 elements linear virtual array. First, the virtual array is calibrated using a known source at 0 degrees to compensate the amplitude and phase error of the steering vector. Mutual coupling effect is not considered during the calibration since the mutual coupling between array elements is measured negligibly small.

The output of monopulse ratio is not straightforward to be visualized like the response pattern of DBF. In order to demonstrate the monopulse ratio in a range-azimuth map, we propose to map the monopulse ratio to dB scale and take the inverse, which generates a peak at the direction of a target instead of zero crossing in monopulse ratio.



(a)

(b)

Fig. 4. Experimental results: DoA estimation of two corner reflector in an indoor environment by a) DBF, b) MIMO-monopulse.

Besides, in MIMO-monopulse, each element in the antenna array is omnidirectional, which radiates waves in wide azimuth and receives reflections from all directions. Therefore the output will not only include the monopulse ratio from the target within the main lobe but also the monopulse ratio from side lobes. These sidelobes can generate zero crossings similar to the response of the target, which we call it *monopulse ambiguity* for MIMO radar. To solve this ambiguity in MIMO-monopulse, we propose the following visualization procedure. Consider within a local linear region, the monopulse ratio spans within [-1,1], and the 0 point is at the direction of the target. To visualize the output of MIMO-monopulse, we mapped the ratio into dB and taken the inverse of it, which generates an infinite large peak at the estimated angle. If we only keep the range of [0,50] dB, which is the scale of sum pattern in Figure 1, the monopulse ratio generates multiple maximum peaks at all the angles of the nulling in difference beam. A window function is derived from normalizing sum beam to [0,1], and multiplied with the monopulse ratio. After this processing, only the peak at the direction of the target is retained, and all the rest of peaks will be suppressed to the level of side lobes in sum pattern. Eventually, a *pattern* is obtained to visualize the result of MIMO-monopulse, thus the MIMO-monopulse output can be demonstrated in a similar way of DBF pattern, in which the targets can be visibly detected using a fixed threshold, as is compared with DBF range-azimuth map in Figure 4.

It should be noted that this procedure is nonlinear and only needed for visualization of the monopulse ratio in range-angle domain similar to DBF output for comparison. For target detection and tracking, the monopulse ratio can be directly used without the visualization step described above.

V. Conclusion

In this paper, we propose the MIMO-monopulse algorithm for precise and fast azimuth estimation, which is not commonly applied for automotive radar. The monopulse estimator is realized digitally on MIMO radar through utilizing Chebyshev and Zolotarev synthesis of sum and difference patterns, which both suppress sidelobe level and reduce the estimation error. The MIMO-monopulse has much less computational cost through generating multiple monopulse beams compared with conventional beam scan method, but it still provides accurate angle estimation (within linear region). The application of the proposed algorithm for an outdoor experiment of real targets (like cars and pedestrians) on a moving platform is currently in progress.

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