Title: Doppler Ambiguity Resolution in Coded FMCW MIMO Radar

The main problem solved in this invention is the extension of maximum unambiguous velocity with ability to perform super-resolution Doppler estimation in MIMO radar. We solve this problem by designing a new staggered PRF co-pulsing scheme for the transmitter and developing advanced signal processing algorithms tailored to the new pulsing scheme at the receiver. The state-of-the-art approaches usually compute the unambiguous velocity based on ambiguous velocity estimates and have no high resolution capability. On the contrary, the new scheme invented here estimates the unambiguous velocity directly from the data in slow-time domain and is able to achieve hyper-resolution. Moreover, the BPM transmission scheme makes better use of transmitting power so that the overall radar performance can be improved.

Detailed description of each component of the invention and how the invention works to achieve the advantages over the existing technology are as below

1) Radar system architecture

Referring to **Figure-1**, the invention proposed here constitutes a radar hardware system as described below.

The radar system has multiple identical transmit channels. Each transmit channel consists of a waveform generator (component 100) to generate the FMCW waveform with specified signal parameters, a transmit radio frequency (RF) front-end (component 101) to modulate the generated waveform to a dedicated RF frequency with desired power. The transmit channels operate in either TDM or CDM mode. Each transmit channel is connected to one dedicated transmit antenna (component 102) through the RF front-end.

The radar system has multiple identical receive channels for signal reception. Each receive channel is connected to one receive antenna (component 103) via the receive front-end. Receive front-end (component 104) consists of a bandpass filter for out-of-RF-band interference suppression, low noise amplifier to amplify the signal power in RF domain, an RF mixer (component 105) that mixes the receiving RF signal with a copy of the transmit waveform, followed by receive the baseband and digital front-end receiver.

The baseband receiver (component 106) includes bandpass filter amplifier and analog-to-digital converter (ADC). The digital front-end (component 107) includes digital decimation filters to reduce the data rate, and other modules which compensate DC offset, receiver gain imbalance, and phase imbalance.

The output of digital front-end is going through the memory (component 108) for either data buffering or storage and then fed to a signal processing unit. Memory unit is also used for storage of intermediate data produced during signal processing steps. Signal processing units take the radar raw data as input and perform steps like range compression, Doppler estimation, angle estimation, point cloud generation, tracking, and target classification. Signal processing can be implemented on field programmable gate array (FPGA), digital signal processor (DSP), and more advanced computational devices such as graphic processing unit (GPU). Some of the signal processing steps may be carried out on-board the main radar processor, while the rest on peripheral devices like micro-controller unit (MCU).

2) Transmit and receive antenna array configuration as referred in **Figure-2**

In order to achieve high resolution in angle estimation, the transmit antenna array (component 200) and receive antenna array (component 201) may be configured in such a way that the requirement on the desirable resolution is satisfied. There are various ways to configure the antenna array. The rule-of-thumb is that the array design should satisfy the angular resolution requirement and be suitable for DOA estimation with appropriate signal processing algorithms. Here, we illustrate a one-dimensional array design to estimate the azimuth angle. The extension to two-dimensional array design is straightforward.

Let the number of elements in transmit and receive arrays be N and M, respectively. We design the receive array to be a uniform linear array (ULA). The inter-element spacing is half of the operating wavelength. From the theory of MIMO radar, target echoes from different transmitters are separable at any single receiver. Thus, signals at a given receive element due to each transmit antenna result in N transmit-receive channels. The signal at each receive antenna has distinct phase information arising from different spatial locations of each receive antenna. Meanwhile, the transmit antennas also have different spatial positions resulting in additional phase information in each transmit-receive channel. Overall, the N transmit antennas and M receive antennas form a virtual array of NM virtual transmit-receive channels.

In order to achieve maximum antenna array aperture of the virtual transmit-receive array, when we employ a ULA of M elements as Rx array, the Tx array elements should have a spacing of at least Md_R to avoid overlapping. Moreover, to reduce the grating lobes, the spacing in Rx is half wavelength and the spacing in Tx is M times of half wavelength. For the purpose of illustration, we depict the case with N=2 Tx and M=4 Rx antennas. The Rx antennas are separated by half wavelength and the Tx antennas twice of wavelength. The overall virtual array has, thus, NM=8 elements with half wavelength spacing.

3) CDM staggered PRF co-pulsing transmit scheme.

One key novelty of this invention is the CDM co-pulsing of staggered PRFs. Although general full rank coding matrix can be used, we illustrate the invention using binary phase coding mode (BPM). The new CDM staggered PRF transmit scheme has the following features: (1) we use two PRFs that are transmitted one after the other; (2) the whole frame consists of multiple, say, N_p, subframes; N_p must be an even number which is required in the Doppler processing; (3) PRF is staggered on a sub-frame basis; 4) each subframe consists of multiple blocks of CDM transmission of pulses from different transmit antennas; 5) All transmit signals, irrespective of the PRFs employed, have same pulse duration T_p; 6) The two PRFs are chosen in such a way that (a) the maximum velocity is extended directly to the desirable value, which is proportional to the difference between two PRIs, and (b) the desired Doppler resolution is reached based on two PRFs and the number of subframes; 7) this co-pulsing scheme is transitionally invariant so that the high-resolution signal processing method can be applied.

This CDM transmission scheme is depicted in **Figure-3**. There are two transmit antennas and CDM adopts the BPM mode. The BPM transmit coding matrix is of dimension 2x2, defined as $[+, +; +, -]^T$ with superscript T meaning matrix transpose, since there are two transmitters. To generalize, the coding matrix can be constructed with Hadamard matrix of same dimension as that of transmit antenna array. There are N_p subframes and each subframe can have multiple blocks although we only illustrate 2 blocks. In transmission, the first pulse is transmitted at all the transmit antennas with the specified coding, i.e., $[+, +]^T$ the first column of the transmit coding matrix, and pulse duration T_p and PRI T_1. Then the second pulse is transmitted at all the transmit antennas with the specified coding $[+, -]^T$ corresponding to the second column of the transmit coding matrix, with the same pulse duration and PRI as the first pulse. This is the first block, i.e., Block(1,1) of the first subframe, associated with a PRF of 1/

T_1. Then a second block of Block(1,2) can be transmitted by repeating the first block in the first subframe. Then the transmission starts the second subframe. In the second subframe, there are also two blocks, i.e., Block(2,1) and Block(2,2) to transmit. In the first block, the Tx antennas will transmit the first pulse, coded with the first column of coding matrix, of duration T_p and PRI of T_2 followed by the second pulse, coded with the second column of coding matrix, of same pulse duration and PRI of T_2. The second block is a repeat of the first block. In such a way, the two PRFs stagger on a subframe basis and, in each subframe, a CDM is adopted with a fixed PRF. The transmission will repeat for N_p subframes.

4) Overall processing flowchart

The overall system operation flowchart is described in the following, referring to **Figure-4.** The system starts with step 400, i.e., the transmission of signal waveforms according to the designed CDM staggered PRF co-pulsing scheme. By the time the first pulse is transmitted from the first antenna, the receive antenna array starts to receive the signal reflected back from the target environment. The signal impinging on the receive antenna array will goes through the entire receiver chain, i.e., step 401, to radar memory for data storage and processing.

After the received signal is collected by digital signal processor, the first step is range compression (step 402), which is usually accomplished by fast Fourier transform (FFT) operation. Range compression will be conducted for every pulse recorded at every receive channel. After the range compression of all the pulses received at all the receive channels, the Doppler processing (step 403) is carried out for every range bin (or range cell) on the range-compressed data. For each range cell, a data matrix is formed by arranging signals of the same transmit code across all Rx array elements. In particular, the data matrix has M rows corresponding to M Rx antennas and N_c=2N_p columns corresponding to all the pulses transmitted from the same transmit code. With the data matrix for each range cell, an eigenspace-based method for Doppler processing is designed by taking advantage of the CDM staggered co-pulsing scheme.

After the Doppler processing, a range-Doppler (RD) map is obtained associated with each column of the transmit coding matrix. Then, RD integration is conducted by processing all RD maps (step 404). This is followed by RD detection that is achieved through the conventional constant false alarm rate (CFAR) methods. Detection yields estimates of the target's range and Doppler (step 405). Based the range and Doppler information of each target, data in the spatial domain corresponding to the virtual antenna array are first formed by decoding processing and then used for angle estimation (step 406). Subsequently, a point cloud is generated by computing the Cartesian coordinates of each target from its range and angle estimates (step 407).

Advanced radar data processing is carried out with the point cloud obtained in step 407. Applications that directly exploit point cloud from different radar frames are target tracking and classification. Usually, target tracking is improved by leveraging the information of vehicle motion available with motion sensors. Compensating for the vehicular motion improves both tracking and classification. Further, with data from other sensors, data fusion and high-level perception is possible to support more advanced and specific radar functions for various detection, classification, tracking, positioning and mapping applications.

More detailed descriptions on signal processing steps are given in the following .

5) Range compression and Doppler processing for data cube at the receive array

The processes of range compression and Doppler processing is described as follows.

With each column of transmit coding matrix, N_c pulses are transmitted. The corresponding reflected signals are collected by the receive array with each pulse resulting in N_1 samples determined by the sampling frequency and pulse duration. Thus, for each code column, the resulting radar raw data can be arranged in a data cube comprising M data matrices, corresponding to M receive antennas. Each data matrix is of size N_1xN_c. Since each data matrix consists of signal samples in range (fast-time) and pulse (slow-time) domain, we term it a range-pulse (RP) data matrix. For each data cube, range compression and Doppler processing are conducted on every RP data matrix. The raw data cube related to one code column has dimension of N_1xN_cxM .

Range compression is performed on every column of each RP data matrix in the data cube; a column corresponds to the data samples of one pulse. Range compression is usually carried out by FFT processing although other spectrum analysis techniques are also applicable here. After range compression, each column is of length N_r, as per the size of FFT. The resulting RP data matrix is now range frequency-pulse matrix of size N_rxN_c. The new range compression data cube is of dimension N_rxN_cxM. For each range cell, the data is a space-time (ST) matrix of dimension N_cxM. The Doppler processing is then performed on this ST data matrix For each range cell, the Doppler processing on the ST data matrix leads to a Doppler data array of length N_d. After Doppler processing for every range cell, a range-Doppler map is formed.

The aim of Doppler processing is to generate the Doppler spectrum for each range cell based on the ST data matrix. Consider Q target in the ST data matrix and each with speed v_q relative to the radar and DOA θ_q, the received ST data for the *m-th* receiver and *n-th* code column can be modeled in a vector form as

$$\boldsymbol{x}_n(m) = \begin{bmatrix} \boldsymbol{u}_n(v_1) & \dots & \boldsymbol{u}_n(v_Q) \end{bmatrix} \begin{bmatrix} s_n(m,\theta_1) \\ \vdots \\ s_n(m,\theta_Q) \end{bmatrix} + \boldsymbol{n}_n(m) \tag{1}$$

where $\boldsymbol{n}_n(m)$stands for the noise component and the following definitions are used:

$$\boldsymbol{u}_n(v_q) = \begin{bmatrix} e^{-j2\pi f_c 2v_q t_n(1)/c} \\ e^{-j2\pi f_c 2v_q t_n(2)/c} \\ \vdots \\ e^{-j2\pi f_c 2v_q t_n(N_c-1)/c} \end{bmatrix}, \tag{2}$$

and

$$s_n(m,\theta_q) = \alpha_q e^{-j2\pi f_c(n-1)d_T sin(\theta_q)/c} e^{-j2\pi f_c(m-1)d_R sin(\theta_q)/c} \quad . \tag{3}$$

Then, the ST data matrix for n-th transmit code column is formed as [$\boldsymbol{x}_n$(1),…, $\boldsymbol{x}_n$(M)]. There are various method to estimate Doppler from ST matrix. We adopt an eigenspace-based method in our design.

The signal sample covariance matrix is estimated as

$$\mathbf{R} = \frac{1}{M}\sum_{m=1}^{M} \boldsymbol{x}_n(m)\boldsymbol{x}_n(m)^H. \tag{4}$$

The dimension of Rx array might be limited because antenna array size is relatively small. Therefore, estimating the covariance matrix directly as in (4) may not achieve accurate result. Here we present an improved covariance matrix estimation based on the concept of temporal domain smoothing, that leads to the estimate of the covariance matrix as $\mathbf{R}_s$.

Eigenvalue decomposition of the covariance matrix is

$$\boldsymbol{R}_s = \mathbf{U}\boldsymbol{\Lambda}\mathbf{U}^H, \tag{5}$$

where $\mathbf{U}$ is the matrix whose columns are the eigenvectors of $\mathbf{R_s}$. $\boldsymbol{\Lambda}$ is the diagonal matrix consisting of the eigenvalues of $\mathbf{R_s}$ and $\mathbf{U}^H$is the Hermitian of $\mathbf{U}$. From the eigenvalue distribution, number of targets is estimated, and noise-subspace $\mathbf{U}_n$ is constructed.

Then, the estimated spectrum of Doppler velocity is

$$P(v) = \frac{1}{\tilde{\boldsymbol{u}}_n(v)\mathbf{U}_n\mathbf{U}_n^H\tilde{\boldsymbol{u}}_n(v)^H}, \quad (6)$$

where

$$\tilde{\boldsymbol{u}}_n(v) = \boldsymbol{u}_n(1{:}\,N_s; v) \quad (7)$$

with $\boldsymbol{u}_n(1{:}\,N_s; v)$ representing the first N_s rows in the vector of $\boldsymbol{u}_n(v)$.

6) RD integration

After range-Doppler processing, the initial raw data cube related to one code column turns into a range-Doppler map of size N_rxN_d (component 603). In order to perform detection in the range-Doppler domain, data cube formed by all range-Doppler maps from all the code columns is integrated to reduce noise and enhance detection performance. RD map integration processing may take non-coherent integration, which is usually performed by summing up squared magnitudes. After integration, a final RD map is obtained and used later for detection. It should be noted that conventional method integrates *NM* individual RD maps while the new invention integrates *N* RD maps. This difference comes as a result of the fact that for each code column, the new invention coherently processes data from all *M* receive channels while the conventional method processes data from each of *M* channels separately. This implies that the new invention can achieve more coherent processing gain than the conventional method, from which RD detection and range/velocity estimate benefit.

7) RD detection and range/velocity estimation

Based on the RD map, detection is carried out to determine the presence of a target at the range-Doppler cell of interest. The RD detection employs conventional constant false alarm rate (CFAR) methods. There are many CFAR algorithms with varying detection performance and computation complexity. Detection yields information about target's range and Doppler. We term this step RD detection and range/velocity estimation (step 405).

9) Angle estimation

After RD detection and range/velocity estimation, angle estimation is carried out on every detected range-Doppler cell. The processing steps are detailed as follows.

First, the range-Doppler cell where the presence of target was found during RD detection, is selected. Then, corresponding to this range, the ST data matrix is chosen from each range compression data cube associated with every code column. For each ST data matrix, a discrete-time Fourier transform (DFT) is performed to retrieve the phase information of signal at every Rx antenna. For every range compression data cube, DFT processing generates one data array of size *M*x1. Then, we stack all *N* data arrays to obtain an augmented virtual array of size *NM*x1 as

$$\boldsymbol{y}(\theta) = [y_{11}(\theta) \quad \ldots \quad y_{NM}(\theta)]^T \quad (8)$$

Then decoded data is obtained by a decoding processing that is performed on the data array to inverse the coding effect in the transmit. After that, decoded data is processed to generate angle estimation using any high-resolution DOA estimation method. Besides that, FFT can also be used to estimate the angle in ULA virtual array.

9) Point cloud and other functionalities

After obtaining the angle estimate for the range-Doppler cell, the point cloud is generated by converting the target's range and angle to its Cartesian coordinates. Based on the point clouds, other functionalities are performed. For example, tracking and classification on the point cloud is possible after compensating for the platform motion.

The essential characteristic required by any components of the invention are as below

1) From Figure-1, radar system has following essential characteristics: component 100-radar waveform generator to generate FMCW waveforms; component 101-transmit front-end that processes the waveform before the transmit antenna; component 102-transmit antenna; component 103-receive antenna; component 104-receive front-end; component 105-mixer; component 106-receive baseband; component 107-digital front-end; component 108-memory; component 109-signal processing unit.
2) From Figure-2, Tx-Rx configuration has the following essential characteristics: component 200-transmit antenna array consisting of multiple transmit antennas in a specifically designed arrangement; component 20-receive antenna array consisting of multiple receive antennas in a specifically designed arrangement. The arrangement of Tx and Rx arrays ensures that MIMO processing is applied to improve the angular resolution.
3) From Figure-3, CDM staggered PRF co-pulsing transmit scheme has the following essential characteristics: i) each frame consists of multiple sub-frames such that the number of sub-frames is an even number; ii) in each sub-frame, the transmission is conducted in a CDM mode across all the transmit antennas using same PRF; iii) two PRFs are designed to achieve the maximum unambiguous velocity; iv) two PRFs alternates between the sub-frames; v) a fixed pulse duration is used for all the pulses although the pulse repetition interval varies between sub-frames; vi) the time duration for one frame is determined by the velocity resolution.
4) From Figure-4, the overall system processing flow including the following essential characteristics: i) the overall system operation starts with step 400: signal is transmitted according to the designed TDM staggered PRF co-pulsing scheme; ii) step 401 refers to the receive operation in the radar system; iii) step 402 performs range compression at each Rx antenna for every pulse transmitted from all transmit antennas; iv) step 403 corresponds to the Doppler processing used to estimate the velocity and the Doppler processing method is specifically designed to exploit the CDM staggered PRF transmit scheme for velocity estimation; v) step 404 performs the integration of RD maps corresponding to all transmit antennas; vi) step 405 carries out detection on the integrated RD map and estimate targets' ranges and velocities; vii) step 406 performs angle estimation for every range-Doppler bin; viii) step 407 converts the range-angle information to a 3D rectangular coordinate system to generate a point cloud; ix) the radar data processing and applications includes but not limited to target classification , tracking, data fusion and perception, as well as other general radar applications such as detection, positioning, and mapping etc.

And about whether it is possible to change or replace any of the components by equivalent components without changing the invention are a below

1) waveform generator can be changed to generate other waveforms;
2) when the transmit waveform is changed, the receiver mixer can be changed or removed accordingly;
3) Tx antenna array and Rx antenna array can be changed in the following ways: a) adding/removing antenna elements in the Tx and Rx; b) change the ULA into other array configuration such as non-uniform linear array; c) change the 1D array into 2D array
4) When the antenna arrays are changed, suitable signal processing methods for DOA estimation can be applied.

Claims

While some embodiments of the invention have been described by the illustrations with diagrams, as a person skilled in the art will recognize that the invention can be carried out with many modifications, variations, and adaptations without departing from the scope of this invention defined in the following claims.

1. A method of Doppler ambiguity resolution in phase coded FMCW MIMO radar, comprising:
    a. A number of *N* transmitters and a number of *M* receivers where the transmitters will be activated for transmission according to a waveform scheme and the receivers will be activated for reception once the transmission is started
    b. A waveform scheme consisting of phase coded staggered PRF co-pulsing transmission
    c. A method of signal processing for Doppler processing based on the receiver array and the waveform scheme
    d. A method of detection based on the range-Doppler data from all the receivers and all the phase code columns;
    e. A method of array formation based on the range-Doppler data of all the receivers and all the phase code columns
2. The method of claim 1, wherein:
    a) the transmitters are configured in desirable form such as a uniform linear array of desirable separation;
    b) the receivers are configured in desirable form such as uniform linear array;
    c) both the transmitters and receivers are configured in such a way that the aperture size of the MIMO virtual array can be maximized without undesirable features such as high sidelobe level.
3. The method of claim 1, wherein:
    a) the transmission has two different PRFs that are transmitted through sub-frames alternatively in a co-pulsing scheme;
    b) one sub-frame is associated with one PRF that may consist of multiple transmission blocks;
    c) each transmission block is determined by the phase coding block, e.g., in a two transmitter case, a 2x2 phase coding block;
    d) a number of *Np* subframes are transmitted with *Np* being an even number considering the co-pulsing scheme.
4. The method of claim 3, wherein:
    a) the transmission at the transmitters is phase coded FMCW waveform where the phase coding can be illustrated with binary phase although it can be other forms such as orthogonal coding as mentioned in claim 3;
    b) the transmission of all the transmitters is activated simultaneously and with each assigned a phase value according to the phase coding scheme;
    c) the waveform of each transmitter is same with that of other transmitter;
5. The method of claim 4, wherein:
    a) the pulse duration of the waveforms associated with different PRF is same
    b) the waveforms of different PRFs have same number of samples after receiving

6. The method of claim 3, wherein:
   the two PRFs are configured in such a way that the maximum desirable velocity can be satisfied.
7. The method of claim 1, wherein a data matrix after range compression at all the *m*-th receiver for each column of the phase coding matrix is modeled in equation 1(mentioned in the Description document) with a spectrum estimation method based on this model for Doppler estimation;

8. The method of claim 7, wherein the spectrum estimation method is designed with eigenvalue based high resolution method as expressed in equation 4 (mentioned in the Description document) although other method can be applied as well;
9. The method of claim 8, wherein the spectrum estimation based on eigenvalue method can exploit the co-pulsing structure with smoothing to improve the performance;
10. The method of claim 1, wherein detection of target is conducted based on averaged range-Doppler data from all the receivers and all the phase code columns;
11. The method of claim 10, wherein the detection method can from the family of CFAR such as os-CFAR and any other suitable method;
12. The method of claim 1, where in the virtual array formation is conducted by a decoding process
13. A radar sensor comprising,
    a) a number of transmitters and a number of receivers configured to maximize the virtual aperture of MIMO radar;
    b) transmitters transmitting according to a dedicated staggered-PRF co-pulsing scheme;
    c) processing methods includin range processing, Doppler processing, detection, DOA estimation and perception based on point cloud.