Title: Ambiguity Resolution in code-division multiplexing frequency modulation Continuous wave (CDM-FMCW) Radar

Multiple input multiple output (MIMO) radar with FMCW is the mainstream radar system adopted in automotive vehicles. One method to implement the FMCW MIMO radar is the CDM modulation in the slow time domain. As compared with time-division multiplexing (TDM) modulation, CDM modulation has better performance in terms of antenna array gain and clutter suppression. One problem about applying MIMO CDM-FMCW radar is that the maximum unambiguous velocity is reduced by the number of transmitters as compared to phased array radar with single transmitter. There are some existing technologies aiming to extend the maximum unambiguous velocity of MIMO TDM-FMCW radar. However, those methods in general requires specific hardware configuration and complex waveform design and signal processing methods that are not efficient for practical applications. This patent proposes an efficient method without special requirements on hardware configuration and complicated algorithms for the CDM-FMCW MIMO radar.

Detailed description of each component of your invention, e.g. functions of each component, and interaction between respective components

1) Figure-1: Radar system architecture

Referring to Figure-1, the invention proposed here constitutes a radar system 001 as described below.

The radar system has multiple identical transmitting channels. Each transmitting channel consists of waveform generator, component 100, to generate FMCW waveform with specified configurations, transmitter radio frequency front-end, component 101, to modulate the generated waveform to dedicated RF frequency with desired power and phase controller 102 to modulate the FMCW chirps with desired phases at different transmit channels. The transmitting channels may operate in certain mode such as CDM. Each transmitting channel is connected to one transmit antenna, component 103, through the RF front-end to transmit the waveform.

The radar system has multiple identical receiving channels for signal reception. Each receiving channel is connected to one receive antenna, component 104, via receiving front-end. Receiving front-end, component 105, may consist of bandpass filter for out-of-RF band interference suppression, low noise amplifier for signal power amplification in RF domain, a RF mixer 106, that mixes the receiving RF signal with a copy of transmitting waveform, followed by baseband receiver 107 and receiver digital front-end 108.

Baseband receiver, component 109, may include bandpass filter, low noise amplifier, analog-to-digital converter (ADC), while digital front-end, component 108, may include digital filtering to reshape the sampling rate, and may also include functions such as DC offset compensation, Rx gain imbalance, and phase imbalance.

After the digital front-end, the received signal goes to memory, component 109, and signal processing unit 110. Signal processing components will take the radar raw data from memory to perform functions like range compression, Doppler estimation, angle estimation, point cloud generation. With the point cloud, perception unit 111 can carry out such functionalities as segmentation, target classification and tracking. Signal processing and perception can be

conducted on field programmable gate array (FPGA), DSP, and even more advanced computation devices such as GPU.

2) Figure-2: Transmitting and receiving antenna array

In order to achieve high resolution in angle estimation, the transmitting antenna array, component 200, and receiving antenna array, component 201, may be configured in such a way that the requirement on desirable aperture size of virtual array is met. The number of transmit antenna and receive antenna can be exemplified but not limited to what is shown in Figure-2. With two transmit antenna and N Rx antenna, there are $2N$ virtual antenna elements with larger aperture size after MIMO processing. Following the MIMO radar configuration, the element spacing in Rx is d_R and the element spacing in Tx is Nd_R.

3) Figure-3: CDM waveform transmit scheme.

The transmitting scheme is illustrated in Figure-3 with two transmitters. It can be extended to more than two transmitters easily. In this example, both transmitters use the same PRI of T seconds. In CDM transmission, the two transmit antennas are triggered simultaneously to transmit same waveforms that are phase coded with respect to pulse index using coding scheme such as Hadamard code. In Figure-3 (a) the waveform transmit scheme is illustrated with a general number of K+1 pulses in each of the L subframes that form a whole frame of time duration LT. In each subframe, there are K-1 pulses are coded with phase code of [1;1] before a normal Hadamard coding of two pulses is applied to the K-th and K+1-th pulses. In this figure, the symbol '+' stands for the code of 1 and symbol '–' stands for the code of 0. The first K-1 pulses are named complementary pulses and the K-th pulse is named the main pulse.

In Figure-3 (b), we illustrate the general waveform transmit method with three pulses in each subframe. The first pulse index is associated with a phase code of [1; 1], the second pulse index with [1; 1] and the third pulse index with [1; 0]. Each sub-frame consists of three pulse indices. There are overall L such repeating sub-frames that form the whole frame of the total duration of LT.

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 scheme in Figure-3. By the time the first pulse is transmitted from the antenna array, the receiving antenna array starts to receive signal reflected back from the environment as in step 401. The signal impinging on the receiving antenna array will go through the whole receiver chain to radar memory for data storage and processing.

Once the received signal is collected, the signal processing step starts. The first processing is range compression, step 402, that is usually accomplished by fast Fourier transform 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 of step 403 will be carried out for every range bin, or range cell, on the range-compressed data. In particular, the Doppler processing will be performed 3 times, i.e., for each pulse index in Figure-3. After that there are 3 Range-Doppler (RD) maps generated at each receiver. Based on all the RD maps, RD detection can be performed in step

404 through methods such as conventional constant false alarm rate (CFAR). Detection provides the information about target on its range and Doppler (velocity). Since there is ambiguity issue in the Doppler domain due to the MIMO operation, Doppler ambiguity resolution is conducted in step 405. Then, based the range and Doppler information of each target, data in the spatial domain corresponding to the virtual antenna array can be formed and angle estimation, step 406, can be conducted. After the angle information is obtained, a step of point cloud generation 407 can be carried out by computing the Cartesian coordinate of each target using the range and angle information.

5) Figure-5: Doppler ambiguity resolution

We illustrate the method of Doppler ambiguity resolution based on the waveform scheme in Figure-3 (b). The processing of Doppler ambiguity resolution is illustrated in Figure-5. At each Receiver channel, step 500 is conducted to perform range and Doppler processing for Pulse index-1 which gives rise to RD map P1R1, meaning Pulse index-1 and Receiver-1. Step 502 performs similar range and Doppler processing for Pulse index-2 and RD map P2R1 is obtained. Step 504 performs similar range and Doppler processing for Pulse index-3 and RD map P3R1 is obtained. Step 506 selects the indices of the targets detected during the step of CFAR detection on the RD map. Let us assume that there are Q targets detected and for the Q-th target its range and Doppler index are (r_q, d_q). Step 508 computes the phase difference between the data from P2R1 and P1R1 for each detected target, let us say, m-th target at the corresponding range-Doppler index (r_q, d_q). The same processing steps from 500 to 508 are carried out for all the receiving channels. Finally, step 508 makes use of all the phases to resolve the ambiguity. In particular, the phase difference between successive pulses is determined by the equation below:

$$\phi = \frac{2\pi 2vT}{3\lambda} \tag{1}$$

where v is the velocity of target and λ is the wavelength. Thus based on the phase difference, the unambiguous velocity can be estimated. The reason to use multiple receivers is to have a better estimation of the phase difference from more measurement channels. This can be achieved by such method as averaging processing.

With the obtained unambiguous Doppler velocity estimation, phase decoding can be performed for the data from P2R1 and P3R1 after P3R1 is phase compensated according to the phase contribution by the Doppler velocity.

The main differences from prior-arts are as follows
i) we design a very efficient waveform scheduling scheme that has no requirement on array configuration and chipset arrangement; ii) the Doppler ambiguity resolution is strictly in the Doppler processing domain without dependence on the angle estimation; iii) the Doppler ambiguity resolution method is efficient, involving only FFT processing and basic arithmetic calculations.
And regarding such differences, on why a person skilled in this field would not think of making the same differences is as below:
The mainstream works in this field lie in the fields of TDM-FMCW applications by solving the Doppler ambiguity resolution with other information in the spatial domain. The intrinsic property of MIMO radar and CDM waveform design are not fully exploited.

About whether it is possible to change or replace any of the components by equivalent components without changing the invention is as below:

1) In Figure-2, the transmit and receive array design can be changed according to requirements of practical applications.
2) In Figure-3, the CDM waveform scheduling scheme can be modified in such ways as changing the number of pulses from 3 to larger number.
3) In Figure-5, when the transmitting scheme is changed, the Doppler ambiguity resolution needs to change accordingly in order to make us of all the information.
4) In Figure-5, the phase difference computation can be replaced by spectrum analysis techniques such as MUSIC, FFT when the number of pulses is larger than 3.
5) In Figure-1, the waveform generator can be changed to generate other type of waveforms. In this case the mixer and receiver could be changed accordingly.

Claims

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

1. An efficient method for achieving Doppler ambiguity resolution in CDM MIMO radar, consisting of:
   1) A method of designing transmit waveforms at M transmitters working in CDM mode.
   2) A method of signal processing for Doppler ambiguity resolution by exploiting the phase information embedded into the received signal at one or multiple receivers according to the waveform design method.
2. The method of claim 1, where the transmit waveform can be designed as follows:
   1) one whole frame consisting of multiple subframes,
   2) in each subframe, consecutive K pulses transmitted at all the transmitters using the same coding, consisting of the first K-1 pulses as the complementary pulse and the K-th pulse as the main pulse, M-1 more pulses transmitted at all the transmitters with different coding in such a way that the pulses with indices of K, K+1,…, K+M-1 are transmitted in CDM scheme.
   3) all the pulses having the same PRI
3. The method of claim 1, where the signal processing for Doppler ambiguity resolution can be achieved as follows:
   1) Range and Doppler processing for the main pulses and the complementary pulses across all the subframes at one or multiple receivers to generate the RD map of the main pulses and complementary pulses separately
   2) target detection at the RD map of the main pulses by making use of RD maps available
   3) associate the target detected at RD map of the main pulses to the target at the RD map of the complementary pulses at each receiver through the index of the range and Doppler bins
   4) phase difference computation by comparing the phase of the targets detected from the RD map of the consecutive complementary pulses.
   5) Doppler ambiguity resolution by making use of the all the phase difference information from the complementary pulses from all the receivers

4. The method of claim 3, where the Doppler ambiguity resolution can be achieved 1) by solving the velocity through the equation (1) relating the phase difference and the complementary pulse PRI, 2) or by normal processing of the complementary pulses through Fourier transforms, 3) or by super-resolution spectrum estimation methods, 4) in addition, with possible additional information from target tracking and neighboring frames
5. A MIMO radar system for achieving Doppler ambiguity resolution for CDM MIMO radar, consisting of:
   1) A system of transmitting the transmit waveforms at multiple transmitters working in CDM mode.
   2) A system of signal processing for Doppler ambiguity resolution by exploiting the phase information embedded into the received signal at one or multiple receivers according to the waveform transmitted.

6. The system of claim 5, where the transmit waveform can be scheduled in one way as follows:
   1) one whole frame consisting of multiple subframes,
   2) in each subframe, consecutive K pulses transmitted at all the transmitters using the same coding, consisting of the first K-1 pulses as the complementary pulse and the K-th pulse as the main pulse, M-1 more pulses transmitted at all the transmitters with different coding in such a way that the pulses with indices of K, K+1,…, K+M-1 are transmitted in CDM scheme.
   3) all the pulses having the same PRI

7. The system of claim 5, where the signal processing for Doppler ambiguity resolution can be achieved in one method as follows:
   1) Range and Doppler processing for the main pulses and the complementary pulses across all the subframes at one or multiple receivers to generate the RD map of the main pulses and complementary pulses separately
   2) target detection at the RD map of the main pulses by making use of all the RD maps available
   3) associate the target detected at the RD map of the main pulses to the target at the RD map of the complementary pulses at each receiver
   4) phase difference computation by comparing the target detected from the RD map of the consecutive complementary pulses.
   5) ambiguity resolution by making use of the all the phase difference information from the complementary pulses from all the receivers
8. The system of claim 7, where the Doppler ambiguity resolution can be achieved 1) by solving the velocity through the equation (1) relating the phase difference and the complementary pulse PRI, 2) or by normal processing of the complementary pulses through Fourier transforms, 3) or by super-resolution spectrum estimation methods, 4) in addition, with possible additional information from target tracking and neighboring frames