Title: System and Method for Efficient Doppler Ambiguity Resolution in Time Domain Multiplexing - Frequency Modulation Continuous Wave (TDM-FMCW) Radar

FMCW radar has wide applications in both civil and military operations. Multiple input multiple output (MIMO) radar with TDM-FMCW is the mainstream radar system adopted in automotive vehicles nowadays. One common problem about applying MIMO TDM-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 and complicated algorithm for Doppler ambiguity resolution in TDM FMCW MIMO radar.

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

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 100, to generate FMCW waveform with specified configurations, transmitter radio frequency (RF) front-end 101, to modulate the generated waveform to dedicated RF frequency with desired power. The transmitting channels may operate in certain mode such as TDM. Each transmitting channel is connected to one transmit antenna, component 102, through the transmitter 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 in the receive antenna array 103, via receiving front-end 104. Receiving front-end 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 105, that mixes the receiving RF signal with a copy of transmitting waveform, followed by baseband receiver 106 and receiver digital front-end 107.

Baseband receiver 106 may include bandpass filter, low noise amplifier, analog-to-digital converter (ADC). Digital front-end 107 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 is written into memory 108 and processed in the signal processing unit 109. 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 110 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 common MIMO radar configuration, the element spacing in Rx is d_R and the element spacing in Tx is Nd_R.

3) Figure-3: TDM transmitting scheme.

~~Instead of requiring specific array configuration or different Pulse Repetition Interval (PRI) waveforms, the method in this patent uses one constant PRI as illustrated in Figure-3. Although the example is with two transmitters, it can be extended to more than two transmitters easily. The first transmitter transmits *K* pulses followed by the second transmitter transmitting one pulse. This is one sub-frame with total duration of *T* seconds. In this example, both transmitters use the same PRI of *T/(K+1)* seconds. There are overall *L* such repeating sub-frames that form one whole frame. *K* can be a number larger than one but is much smaller than *L*.~~

Instead of requiring specific array configuration or complicated waveforms of different PRI waveforms for Doppler ambiguity resolution, two efficient waveform scheduling schemes are proposed in this patent to extend the Doppler ambiguity range with efficient algorithms. One method is first proposed in this patent that uses one constant PRI as illustrated in Figure-3 (a). Although the example is with two transmitters, it can be extended to more than two transmitters easily. The first transmitter transmits *K* pulses followed by the second transmitter transmitting one pulse. The K-th pulse at the first transmitter is called the main pulse and the other K-1 pulses are called complementary pulse. The main pulse at the first transmitter and the pulse transmitted at the second transmitter form the conventional TDM transmitting scheme. The K+1 pulses is one sub-frame with total duration of *T* seconds. In this example, both transmitters use the same PRI of *T/(K+1)* seconds. There are overall *L* such repeating sub-frames that form one whole frame. *K* can be a number larger than one but is much smaller than *L*. In theory, the Doppler ambiguity is limited by the subframe duration of T with the MIMO operation, which will be extended to T/(K+1).

As a variant of the method in Figure-3 (a), the scheme depicted in Figure-3 (b) illustrates a different waveform scheduling with different PRIs in Tx-1. In the drawing, in each subframe, Tx-1 transmits a pulse P3, i.e., the main pulse, with a duration of T_1, after transmitting two consecutive pulses P1 and P2, i.e., the complementary pulse, with a duration of T_2. T_2 can be a fraction of T_1 and the bandwidth within T2 can be a fraction of the bandwidth within T1. The fraction of time can be same to or different from the fraction of frequency. However, the unambiguous range of P1 and P2 should be no smaller than that of P3. In each subframe, TDM scheme is applied to Tx-1 and Tx-2. There are overall *L* repeating subframes in one frame.

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 TDM scheme in Figure-3. By the time the first pulse is transmitted from the first antenna, 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 processing step 402, that is usually accomplished by fast Fourier transform operation. Range processing 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 *K* times for transmitter-1 and one time for transmitter-2 at each receiver. After that there are *K*+1 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 of 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 on 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 can be carried out by computing the Cartesian coordinate of each target using the range and angle information.

5) Figure-5: Doppler ambiguity resolution

~~The processing of Doppler ambiguity resolution is illustrated in Figure-6.~~

~~Suppose K=2, at each Receiver channel, step 500 is conducted to perform range and Doppler processing for Pulse-1 of Transmiter-1. RD map P1R1, meaning Pulse-1 and Receiver-1 is obtained. Step 502 performs similar range and Doppler processing for Pulse-2 of Transmiter-1. RD map P2R1 is obtained. Step 504 selects the indices of the targeted detected during the step of CFAR detection on the RD map. Let us assume that there are M targets detected and for the m-th target its range and Doppler indices are (r_m, d_m). Step 506 compute the phase difference between the data from P2R1 and P1R1 for each detected target. For example, the phase difference for the m-th target is obtained by comparing the phase of data (r_m, d_m) in P2R1 and that of data (r_m, d_m) in P1R1. The same processing steps from 500 to 506 are carried out for all the receiving channels. Finally, step 508 makes use of all the phases at all the receivers to resolve the ambiguity. In particular, the phase difference between successive pulses is determined by the equation below:~~

$$\phi = \frac{2\pi 2vT}{\lambda(K+1)} \quad (1)$$

~~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.~~

The processing of Doppler ambiguity resolution is illustrated in Figure-5 (a), (b).

In Figure-5 (a) the Doppler ambiguity resolution method is designed for the waveform scheduling scheme in Figure-3 (a). Suppose K=2, at each receiver channel, step 500 is conducted to perform range and Doppler processing for Pulse-1 of Transmiter-1. RD map P1R1, meaning Pulse-1 and Receiver-1 is obtained. Step 502 performs similar range and Doppler processing for Pulse-2 of Transmiter-1. RD map P2R1 is obtained. Step 504 selects the indices of the targeted detected during the step of CFAR detection on the RD map. Let us assume that there are M targets detected and for the m-th target its range and Doppler indices are (r_m, d_m). Step 506 compute the phase difference between the data from P2R1 and P1R1 for each detected target. For example, the phase difference for the m-th target is obtained by comparing the phase of data (r_m, d_m) in P2R1 and that of data (r_m, d_m) in P1R1. The same processing steps from 500 to 506 are carried out for all the receiving channels. Finally, step 508 makes use of all the phases at all the receivers to resolve the ambiguity. In particular, the phase difference between successive pulses is determined by the equation below:

$$\phi = \frac{2\pi 2vT}{\lambda(K+1)} \quad (1)$$

where v is the velocity of target and λ is the wavelength. Thus based on the phase difference, the unambiguous velocity can be estimated and extended (K+1) times as compared to that of MIMO radar. The benefit of using 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 of the phase difference from different receivers. Besides the ambiguity resolution based on the phase difference comparison, spectrum estimation using multiple complementary pulses at the multiple receivers can be achieved through normal processing like Fourier transform and super-resolution method. Meanwhile, information from tracking and neighboring frames can also be used to improve ambiguity resolution.

In Figure-5 (b) the Doppler ambiguity resolution method is designed for the waveform scheduling scheme in Figure-3 (b). At each receiver channel, step 510 is conducted to perform range and

Doppler processing for Pulse-1,2 of Transmitter-1. RD maps P1R1 and P2R1, meaning Pulse-1,2 and Receiver-1 are obtained. Step 5012 performs similar range and Doppler processing for Pulse-3 of Transmiter-1. RD map P3R1 is obtained. Step 514 selects the indices of the targets detected during the step of CFAR detection on the RD map and associates the targets from RD map P3R1 with those from RD map P1R1 and P2R1. Let us assume that there are M targets detected from RD map P3R1 and for the m-th target its range and Doppler indices are (r_m, d_m). In association, the target at RD map P1R1 and P2R1 with Doppler index d_m and range index that is closest to r_m is associated the m-th target at RD map P3R1. In the case that there are more than one closest indices, the one with higher signal amplitude can be chosen. Step 516 computes the phase difference between the data from P2R1 and P1R1 for each detected target. For example, the phase difference for the m-th target is obtained by comparing the phase of data in P2R1 and that of data in P1R1. The same processing steps from 510 to 516 are carried out for all the receiving channels. Finally, step 518 makes use of all the phases at all the receivers to resolve the ambiguity. In particular, the phase difference between successive pulses is determined by the equation below:

$$\phi = \frac{2\pi 2vT_2}{\lambda} \quad (2)$$

where v is the velocity of target and λ is the wavelength. Thus based on the phase difference, the unambiguous velocity can be estimated and extended T/T2 times as compared to that of MIMO radar. The benefit of using 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 of the phase difference from different receivers. Besides the ambiguity resolution based on the phase difference comparison, spectrum estimation using multiple complementary pulses at the multiple receivers can be achieved through normal processing like Fourier transform and super-resolution method. Meanwhile, information from tracking and neighboring frames can also be used to improve ambiguity resolution.

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 (a), the TDM waveform scheduling scheme can be modified in such ways as i) changing the value of K, ii) adopt the pulsing scheme of transmitter-1 at different transmitters with different value of K; In Figure-3 (b), the number of pulses of duration T2 can be more than 2 and the pulsing scheme at transmitter-1 can be adopted by other transmitters.
3) In Figure-5, when the transmitting scheme is changed, the Doppler ambiguity resolution needs to change accordingly in order to make use of all the information from all the transmitters.
4) In Figure-5, the phase difference computation can be replaced spectrum analysis techniques such as MUSIC, FFT when the number of pulses K is larger than 2.
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.

The invention is intended for TDM FMCW MIMO radar used on automotive vehicles. It is possible to be applied to any TDM MIMO radar in other fields like airborne radar, spaceborne radar, sonar, and any kind of such active or passive sensors in any applications.

And regarding why a person skilled in this field would not think of making the same differences is because the mainstream works in this field focus on the doppler ambiguity resolution either by making use of other information in the spatial domain or by staggered PRF methods. However, the intrinsic property of MIMO radar and TDM waveform design are not fully exploited.

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 adaptions without departing from the scope of this invention defined in the following claims.

1. An efficient method for achieving Doppler ambiguity resolution for TDM MIMO radar, consisting of:
   1) A method of designing the transmit waveforms at multiple transmitters working in TDM 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.
2. The method of claim 1, where the transmit waveform can be designed in one method as follows:
   1) one whole frame consisting of multiple subframes,
   2) in each subframe, consecutive K pulses transmitted at one or multiple transmitters, consisting of the first K-1 pulses as the complementary pulse and the K-th pulse as the main pulse, one pulse transmitted at the rest of the transmitters.
   3) all the pulses having the same PRI
3. The method of claim 1, where the transmit waveform can be designed in the other method as follows:
   1) one whole frame consisting of multiple subframes,
   2) in each subframe, consecutive K-1 pulses transmitted at one or multiple transmitters, consisting of the first K-1 pulses as the complementary pulse and the K-th pulse as the main pulse, one pulse the same as the main pulse transmitted at the rest of the transmitters.
   3) the complementary pulses having the same PRI which is different from, in particular, smaller than that of the main pulse
4. The method of claim 1, 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 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 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

5. The method of claim 4, 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

6. The method of claim 1, where the signal processing for Doppler ambiguity resolution can be achieved in the other 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 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 range and Doppler bins
   4) phase difference computation by comparing the target detected from the RD map of the consecutive complementary pulses.
   5) velocity estimation by making use of all the phase difference information from the complementary pulses from all the receivers.
7. The method of claim 6, where the Doppler ambiguity resolution can be achieved 1) by solving the velocity through the equation (2) 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
8. A MIMO radar system for achieving Doppler ambiguity resolution for TDM MIMO radar, consisting of:
   1) A system of transmitting the transmit waveforms at multiple transmitters working in TDM 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.
9. The system of claim 8, 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 one or multiple transmitters, consisting of the first K-1 pulses as the complementary pulse and the K-th pulse as the main pulse, one pulse transmitted at the rest of the transmitters.
   3) all the pulses having the same PRI
10. The system of claim 8, where the transmit waveform can be scheduled in the other method as follows:
    1) one whole frame consisting of multiple subframes,
    2) in each subframe, consecutive of K-1 pulses transmitted at one or multiple transmitters, consisting of the first K-1 pulses as the complementary pulse and the K-th pulse as the main pulse, one pulse the same as the main pulse transmitted at the rest of the transmitters.
    3) the complementary pulses having the same PRI which is different from, in particular, smaller than that of the main pulse.
11. The system of claim 8, 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

12. The system of claim 11, 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
13. The system of claim 8, where the signal processing for Doppler ambiguity resolution can be achieved in the other 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 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
    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
14. The method of claim 13, where the Doppler ambiguity resolution can be achieved 1) by solving the velocity through the equation (2) 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