Title: Antenna Array Design and Processing for Super-resolution Imaging Radar

High angular resolution is desired in radar system because it can reveal more feature about target and can thus provide better information for subsequent processing and decision-making. However, high resolution in general requires larger antenna array aperture and more antenna elements and channels. This requirement becomes exaggerated when the radar is designed for 3D applications that estimate both azimuth and elevation. This imposes strict constraint to practical applications where the array form factor is limited by space and cost. For example, automotive radar needs to be designed with compact form factor and low cost so that it can be commercially accessible for mass production. The conflicting nature of requirement on high resolution and requirement on low cost and compact form factor makes it a challenging problem for array design and DOA estimation.

One common approach to compromise the two requirements is multiple input multiple output (MIMO) radar that is able to form a virtual array of NM elements by using N transmit (receive) elements and M receive(transmit) elements. When this concept is applied to the 2D array design, significant reduction in the number of physical antenna elements as well as the physical array size can be achieved. As most of existing arts show, 2D MIMO radar can have dense virtual 2D array on which the good angular estimation is based. Meanwhile, the signal processing method on the 2D virtual antenna array still requires expensive 2D DOA estimation. More importantly, even with 2D MIMO radar, the resulting dense array can only provide limited improvement to resolution performance since the total number of elements are limited by cost and size. Another method of achieving 2D angular resolution with less antenna element is the conventional Watterson array which uses two branches to estimate the azimuth and elevation separately by phase comparison. However, this conventional array design cannot meet the high-resolution requirement and cannot handle multiple targets efficiently. In terms of DOA estimation signal processing, although there are many different DOA estimation techniques, the most efficient is the matched filter, i.e., delay-and-sum beamformer implemented using fast Fourier transform (FFT). The application of FFT implies that the array should be uniformly spaced. This requirement again put strict constraint on the design of the low complex 2D array. As a result, the existing state-of-the-art array design applying FFT has dense uniform structure. In summary, there are limitations in the state-of-the-art array design and DOA estimation methods.

The main problem solved in this invention is to improve the resolution of the antenna array in MIMO radar while keeping the complexity of antenna array and signal processing reduced. In our invention, we designed the MIMO radar array jointly with the efficient signal processing algorithms. Thus, our invention is able to operate with sparse array that has much better angular resolution and smaller number of antenna elements than the dense arrays in the existing inventions.

The major difficulty is how to design an array consisting of both uniform sparse array and uniform dense array and at the same time make use of both sparse array and dense array to achieve high resolution with efficient computation. We overcome this difficult by coming up with a new array configuration, i.e., hybrid array, and signal processing algorithm for degree of angle estimation tailored to this new array configuration. In short, we jointly design the array configuration and the signal processing algorithm so that high resolution and high accuracy of the array can be obtained with less antenna elements and lower computational complexity.

Detailed description of each component of our invention, e.g. functions of each component, and interaction between respective components are as below:

1) Figure-1: radar system architecture

The radar system 001 for which the antenna array is designed has a waveform generator 100 that generates waveforms such as continuous waveforms and pulse radar waveforms. Meanwhile, waveforms generated for different transmitters are orthogonal to each other in order to exploit the benefit of MIMO radar. The orthogonality can be achieved in many ways such as time division multiplexing (TDM), and code division multiplexing (CDM). Our patent is not confined to the specific use of the type of orthogonal waveforms. The waveform undergoes the transmitter circuit 102 before being transmitted from transmit antenna array 104. In the MIMO radar operation, each transmit antenna transmits its own waveform that is orthogonal to the waveforms to be transmitted by other transmitters. The geometry of transmit array can be 1D array or 2D array of desirable array configuration. After being reflected from target, the radar signals are received at the receive antenna array 106 that is connected to the receiver circuit 108. The geometry of receive array can be 1D array or 2D array of desirable array configuration. In fact, each receive antenna array receives a combination of echo signals due to all the transmitted signals. After that, receiver baseband 110 samples the radar signal into digital domain for signal processing. The radar system is controlled by a radar control and processing unit 112 that performs radar signal processing to fulfil the radar functionalities such as range processing, Doppler processing, DOA estimation, target detection, and advanced perception based on point cloud in data processing. The data processing for perception may include target classification, tracking, segmentation, etc. The radar system 001 may be connected to other devices or sensor network control & processing system 114 so that the radar information generated from the signal processing can be applied to advanced functions.

The focus of this patent is the invention of novel antenna array design that can achieve high resolution with low complexity.

2) Figure-2: Dense ULA and its MIMO array configuration with four Tx antennas and six Rx antennas

MIMO radar concept is widely adopted to increase the array resolution with reduced number of physical elements. Here we illustrate the conventional MIMO array configuration.

We consider first a four-Tx, six-Rx configuration. The conventional dense ULA of 24 elements is illustrated in Figure-2 (a), which can be obtained from the 4-Tx, 6-Rx MIMO radar as illustrated in Figure-2(b). In this figure, the Rx elements are spaced with d, which is half wavelength. The resulting virtual array is also with inter-element spacing of d. From Figure-2, we can see that with MIMO radar concept, a larger antenna array aperture can be achieved with smaller number of elements when we design dense antenna array with half wavelength inter-element spacing. When the inter-element spacing is larger than half wavelength, the array aperture can be extended. However, there will be ambiguity issue due to the high sidelobe in this case.

3) Figure-3: Hybrid array design with MIMO configuration, four Tx antennas and six Rx antennas

Now we illustrate the idea of designing hybrid regular array in order to improve the resolution of conventional MIMO radar with dense array. The virtual hybrid array consists of sparse uniform linear array and dense uniform linear array that result from specially configured Tx array and Rx array as illustrated in Figure-3. Taking four Tx elements and six Rx elements for example. The distance between Tx element is dT=4d, i.e., twice of wavelength and the distance between first three Rx elements is dR=16d, i.e., eight times of wavelength. The rest three Rx elements are spaced by d. With this configuration, we can achieve a hybrid array of 24 elements with aperture size of 47d in Figure-3(b), which is about twice the aperture size of 23d resulted from 24-element dense ULA in Figure-2. The enlarged aperture size can improve the resolution of the array by twice. Meanwhile, the hybrid array consists of a sparse ULA of 12 elements with spacing of 4d and a dense ULA of 16 elements with spacing of d. The large sparse ULA can be used for improved resolution and dense ULA can be used for ambiguity resolution. The general hybrid array design consisting of one sparse ULA subarray-1 and dense ULA subarray-2 is illustrated in Figure-3 (c).

The array design can be generalized to the case of N transmitters and M receivers. Suppose M is larger than N. One way to generalize the design is as follows. We first design a sparse ULA using the N transmitters with a spacing of kd, k=1,2,…, M-1, then we take k receivers to form a dense ULA with spacing of d and M-k+1elements to form a sparse ULA with spacing of kNd. This will form the hybrid array consisting of a sparse ULA and a dense ULA with total aperture of dkN(M-k)+d(k-1)k+d. The balance between the sparsity and the aperture size can be achieved through the selection of k.

4) Figure-4: Hybrid array design for 2D radar

When applying the design method illustrated in Figure-3, 2D array can be designed. To reduce the number of elements in the 2D plane, we design the cross-array along y-axis and z-axis separately so that both azimuth and elevation can be estimated with less number of elements. In y-axis, there are two subarrays, i.e., subarray-A.1 and subarray-A.2. Subarray-A.1 is the sparse ULA and Subarray-A.2 is the dense ULA as illustrated in Figure-3. Likewise, along z-axis, Subarray-E.1 is the sparse ULA and Subarray-E.2 is the dense ULA. Besides those hybrid arrays along y-axis and z-axis, there is one irregular subarray formed through the Tx on y-axis (z-axis) and Rx on z-axis (y-axis), which can assist the target detection in different stages.

5) Figure-5: General signal processing flowchart

The general signal processing flowchart 05 referring to automotive radar signal processing is illustrated in Figure-5. This processing flow 05 can be modified to suit different function and purpose with specific applications. The raw data received at each receiver element undergoes range compression 500 first followed by Doppler compression 502. Then, target detection 504 based on thresholding can be applied to detect the potential targets in the range-Doppler domain. Common method of detection is the constant false alarm rate (CFAR) detection with

ordered-statistics (OS) method for noise level estimation. After that, virtual array data can be formed at step 506 for each detected target by concatenating the data from each Tx-Rx pair. With this virtual array data, DOA estimation 508 can be applied, which will be presented separately. After DOA estimation, point cloud 510 can be formed for each detected target in the range-Doppler domain. The point cloud can further be used in advanced perception processing 512 such as tracking, classification, occupancy grid mapping, et cetera.

6) Figure-6: DOA estimation for 1D hybrid array

The DOA estimation system 06 in the 1D array case is illustrated in Figure-6. In the first step 600, the DOA estimation processing is applied on the subarray-1, referring to Figure-3. Subarray-1 is the sparse ULA part of the array along the y-axis or z-axis. The DOA estimation method can be conventional delay-and-sum (DAS) beamformer which can be efficiently implemented using fast Fourier transform (FFT). Other super-resolution methods such as Capon, MUSIC and ESPRIT can also be applied. Although the subarray-1 is capable of higher resolution, there is ambiguity issue due to the sparsity in the array. In the second step 602, DOA estimation is applied on the subarray-2, which is the dense ULA part of the hybrid 1D array. Similar DOA estimation method as applied in step 600 can be applied. Subarray-2 has lower resolution but without ambiguity issue. After that detection 604 is performed on the DOA spectrum from the two subarrays. Detection method can be threshold based method or source number detection based methods. After each target is detected, the ambiguity issue in A can be resolved by comparing the DOA results from the two subarrays in the step of ambiguity resolution 606. Furthermore, Doppler and velocity information from the ego-vehicle and target can be used to assist the DOA estimation.

7) Figure-11: DOA estimation for 2D hybrid array

The DOA estimation system 07 for 2D array is illustrated in Figure-7. In the 2D DOA estimation, we take a sequential DOA estimation approach which divides the two-dimensional estimation problem into two one-dimensional estimation problems with reduced complexity. First, azimuth is estimated in 700 using elements on the subarray-y. The azimuth estimation is in fact a 1D DOA estimation problem that can be solved using the DOA estimation method described in system 6. Then detection is performed. The detection 702 is in fact included in the 1D DOA estimation in the azimuth estimation. We keep it here to stress that the DOA estimation is jointly performed with detection. With each azimuth estimation, elevation estimation on subarray-z 704 is conducted and the 2D DOA estimation is completed. The system 7 only illustrated one possible way of the general sequential DOA estimation method. Other form of design can be easily generated by changing the steps in the system. For example, we can start by processing the elevation domain on subarray-z followed by detection and azimuth estimation. Furthermore, Doppler and velocity information from the ego-vehicle and target can be used to assist the DOA estimation.

In our invention, we present a joint array design and signal processing method so that not only the cost of the array is reduced, but also the signal processing is efficient in computation and suitable for multiple target in one range-Doppler cell. The resolution can be improved by twice with this design as compared to dense array design

Regarding why a person skilled in this field would not think of making invention is as mentioned below:
The current array design methods never jointly consider both array design and signal processing. Instead, the current array design still focuses on the design of antenna array that is suitable for the conventional DOA estimation methods. Moreover, since sparse array has ambiguity problems in practical application, sparse array design is not as popular as dense array design in practice. Meanwhile, combining both sparse array and dense array is not considered in the existing works.

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

1) The hybrid array design illustrated in Figures 3,4 can be achieved via different antenna configuration designs, for example, different number of Tx and Rx, different splitting of Tx and Rx, different element spacing, etc.

2) In the DOA estimation processing steps, although we illustrate the DOA estimation starting with azimuth, it can start with elevation estimation followed by azimuth estimation.

3) In the 1D DOA estimation, instead of using the two subarrays, the whole array can be used for DOA estimation in many cases with different DOA estimation method like MF.

The essential components of your invention, i.e. which steps or which units are indispensable in order for your invention to function are as follows
1) In the radar system 001, all the components in the architect are essential to the system. However, there can be various practical forms for each component. For example, the waveform generator can be either FMCW waveform generator or a pulsed waveform generator.
2) The methods of hybrid array design for 1D MIMO radar and 2D MIMO radar, as illustrated in Figure-3 and Figure-4 are essential components of this invention. However, the design concepts can be applied to arrays with a different number of elements and configurations.
3) The DOA estimation method for 1D and 2D array as described in Figure-6 and Figure-7 are essential steps. In particular, the ambiguity resolution step followed by the DOA spectrum computation on each of the subarray is one of the key steps in this invention.

The invention can be applied to MIMO radar system for vehicles. The invention can also be used in other fields such as conventional phased array radar and MIMO radar in the airborne, spaceborne, and ground-based and ship-based applications. Moreover, this invention can also be applied to general active or passive sensors with sensor arrays for improved angular resolution.

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. A method for achieving super-resolution imaging with MIMO radar of a number of transmitters and receivers, consisting of:
   1) A method of designing the transmit array and receive array that can generate a desirable virtual hybrid array for improved resolution, consisting of, besides other array configurations, sparse uniform linear arrays and dense uniform linear arrays.
   2) A method of high-resolution array processing on the hybrid array designed by processing the signals on both the sparse uniform linear arrays for high resolution but with possible ambiguity and the dense uniform linear arrays for low resolution but without ambiguity.
2. The method of claim 1, where the virtual hybrid array is in one case designed as a 1D array with N transmitters and M receivers in the following manner:
   1) a sparse ULA was designed using the N transmitters with element spacing of kd, k=1,2,…, M-1,
   2) k receivers are used to form a dense ULA with element spacing of d and M-k+1elements to form a sparse ULA with element spacing of kNd
   3) this will form the hybrid array consisting of a sparse ULA and a dense ULA with total aperture of $dkN(M-k)+d(k-1)k+d$.
   4) the balance between the sparsity and the aperture size can be adjusted through the selection of k.
3. The method of claim 1, where the virtual hybrid array is in the other case designed as a 2D array with N transmitters and M receivers in the following manner:
   1) Among those N transmitters and M receivers, N_a transmitters are for azimuth and N_b=N-N_a+1 are for elevation, M_a for azimuth and M_b (M_b=M-M_a+1) for elevation;
   2) the antenna array configuration for azimuth, i.e., antenna array along the horizontal direction can be achieved through a similar method as those in claim-2 through a balancing factor k_a.
   3) the antenna array configuration for elevation, i.e., antenna array along vertical direction can be achieved through a similar method as those in claim-2 through a balancing factor k_a.
   4) the numbers N_a , N_b , M_a , M_b , k_a , k_b can be chosen in such a way that the resolution along azimuth and elevation can be met.
4. The method of claim 1, where the array processing for super-resolution can be achieved on the 1D array through the following steps:
   1) super-resolution DOA processing on the sparse ULA with a large antenna array aperture, generating a first set of DOA estimation and source number detection, which can be accomplished through many algorithms, thanks to the uniform structure of the array
   2) super-resolution or normal processing on the dense ULA with a small antenna array aperture, generating a second set of DOA estimation and source number detection
   3) a final DOA estimation can be made by utilizing the first set of DOA estimation and source number detection and the second set of DOA estimation and source

number detection, where only unambiguous DOA estimates of super-resolution remain.

5. The method of claim 1, where the array processing for super-resolution can be achieved on the 2D array through the following steps:
   1) super-resolution DOA processing on elevation array (azimuth array) will be carried out to achieve super-resolution estimation of elevation (azimuth) first, following the method as in claim-4.
   2) super-resolution DOA processing on azimuth array (elevation array) will be carried out to achieve super-resolution estimation of azimuth (elevation), following the method as in claim-4
   3) a final DOA estimation can be made by utilizing both the elevation estimation and azimuth estimation from the 1D array to achieve final DOA estimation.
6. A MIMO radar system for achieving sup-resolution imaging with a limited number of transmitters and receivers, consisting of:
   1) a system of achieving a virtual hybrid array for improved resolution, that consists of sparse uniform linear arrays and dense uniform linear arrays.
   2) A system of high-resolution array processing on the hybrid array by processing the signals on both the sparse uniform linear arrays for high resolution but with ambiguity and the dense uniform linear arrays for low resolution but without ambiguity.
7. The system of claim 6, where the virtual hybrid array is in one case realized as a 1D array with N transmitters and M receivers in the following manner:
   1) a sparse ULA was designed using the N transmitters with element spacing of kd, k=1,2,…, M-1,
   2) k receivers are used to form a dense ULA with element spacing of d and M-k+1elements to form a sparse ULA with element spacing of kNd
   3) this will form the hybrid array consisting of a sparse ULA and a dense ULA with total aperture of $dkN(M-k)+d(k-1)k+d$.
   4) the balance between the sparsity and the aperture size can be adjusted through the selection of k
8. The system of claim 6, where the virtual hybrid array is in the other case realized as a 2D array with N transmitters and M receivers in the following manner:
   1) Among those N transmitters and M receivers, N_a transmitters are for azimuth and N_b=N-N_a+1 are for elevation, M_a for azimuth and M_b (M_b=M-M_a+1) for elevation;
   2) the antenna array configuration for azimuth, i.e., antenna array along the horizontal direction can be achieved through a similar method as those in claim-2 through a balancing factor k_a.
   3) the antenna array configuration for elevation, i.e., antenna array along vertical direction can be achieved through a similar method as those in claim-2 through a balancing factor k_a.
   4) the numbers N_a , N_b , M_a , M_b , k_a , k_b can be chosen in such a way that the resolution along azimuth and elevation can be met.
9. The system of claim 6, where the array processing system for super-resolution on the 1D array consists of the following steps/subsystems:
   1) super-resolution DOA processing on the sparse ULA with a large antenna array aperture, generating a first set of DOA estimation and source number detection, which can be accomplished through many algorithms such as MUSIC, thanks to the uniform structure of the array
   2) super-resolution or normal processing on the dense ULA with a small antenna array aperture, generating a second set of DOA estimation and source number detection

3) a final DOA estimation can be made by utilizing the first set of DOA estimation and source number detection and the second set of DOA estimation and source number detection, where only unambiguous DOA estimates of super-resolution remain

10. The system of claim 6, where the array processing system for super-resolution on the 2D array consists of the following steps/subsystems
    1) super-resolution DOA processing on elevation array (azimuth array) will be carried out to achieve super-resolution estimation of elevation (azimuth) first, following the method as in claim-9.
    2) super-resolution DOA processing on azimuth array (elevation array) will be carried out to achieve super-resolution estimation of azimuth (elevation), following the method as in claim-9
    3) a final DOA estimation can be made by utilizing both the elevation estimation and azimuth estimation from the 1D array to achieve final DOA estimation