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

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). This invention 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).

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.

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, ESPRIT, etc 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 any threshold based methods or source number detection based methods or alike ones. 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.

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.