

US Patent & Trademark Office

Patent Public Search | Text View

United States Patent Application Publication

20250264573

Kind Code

A1

Publication Date

August 21, 2025

Inventor(s)

Moradi; Hassan Daniel

RADAR SYSTEM WITH WAVELENGTH INDEPENDENT ANTENNA ARRAY

Abstract

A radar system comprises a physical radar array comprising a plurality of physical transmit antennas, each configured to transmit a respective signal having a wavelength λ . The physical radar array further comprises a plurality of physical receive antennas, each configured to receive each of the respective signals. The radar system further comprises a neural network configured to receive data from the physical radar array and generate data corresponding to an emulated array of antennas, wherein a defined distance between each antenna of the emulated array of antennas is $\lambda/2$.

Inventors: Moradi; Hassan Daniel (San Diego, CA)

Applicant: MURATA MANUFACTURING CO., LTD. (Kyoto, JP)

Family ID: 1000008575030

Assignee: MURATA MANUFACTURING CO., LTD. (Kyoto, JP)

Appl. No.: 19/172482

Filed: April 07, 2025

Related U.S. Application Data

parent US continuation 18891798 20240920 parent-grant-document US 12298427 child US 19172482

us-provisional-application US 63556002 20240221

Publication Classification

Int. Cl.: G01S7/03 (20060101)

Background/Summary

CROSS REFERENCES TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 18/891,798, for “RADAR SYSTEM WITH WAVELENGTH INDEPENDENT ANTENNA ARRAY,” filed Sep. 20, 2024, which is related to concurrently filed and commonly assigned U.S. patent application Ser. No. 18/891,432, for “RADAR SYSTEM WITH MACHINE LEARNING ENHANCED ANTENNA ARRAY,” filed Sep. 20, 2024, both applications of which claim priority to U.S. Provisional Patent Application Ser. No. 63/556,002, for “RADAR SYSTEM WITH MACHINE LEARNING-ENHANCED ANTENNA ARRAY” filed Feb. 21, 2024, all of which are hereby incorporated by reference in their entirety for all purposes.

FIELD

[0002] The described embodiments relate generally to radar systems, such as arrays that employ one or more transmitters and one or more receivers. More particularly, the present embodiments relate to multiple input and multiple output (MIMO) radar systems.

BACKGROUND OF THE INVENTION

[0003] Radar provides the ability to detect objects in challenging scenarios (e.g., snow, rain, low or no lighting, etc.). Radar can be used to provide range, speed, and angle data for objects and can have myriad uses including collision avoidance (e.g., for a vehicle) and target detection (e.g., detection of a drone from a ground-based station). Vehicular-based radar systems may have many uses including parking assist, blind spot monitoring, lane change assist, automatic cruise control and automatic emergency braking.

[0004] One type of radar system that employs multiple transmitters and receivers, also called a multiple input, multiple output (MIMO) radar configuration, can be used to determine angular information for an object so it can be positioned in space relative to the antennas. With traditional radar systems, the angular resolution of a radar system is directly linked to the quantity of antennas used, in line with the Nyquist-Shannon limitation. Thus, to improve the angular resolution of such radar systems the number of antennas needs to be increased which commensurately increases the system cost, weight, and complexity.

[0005] Some MIMO radar systems employ methods to create virtual antenna arrays such that a given MIMO radar system having a fixed number of physical antennas can have improved angular resolution. For example, if a MIMO radar system has 3 “physical” transmit antennas and 4 “physical” receive antennas, a 12-element “virtual” antenna array can be created where the virtual antennas are generated via digital signal processing of the received signals. However, if one or more of the physical antennas do not have consistent $\lambda/2$ spacing between adjacent antennas, the 12-element virtual antenna may have “gaps” (e.g., a spacing larger $\lambda/2$) that result in the array having non-uniform phase which is detrimental to angle processing. New radar systems are needed that can provide uniform phase for physical antenna arrays having one or more spaces between adjacent antennas that are not $\lambda/2$.

SUMMARY OF THE INVENTION

[0006] In some embodiments a radar system comprises a physical radar array comprising a plurality of physical transmit antennas, each configured to transmit a respective signal having a wavelength λ . The physical radar array further comprises a plurality of physical receive antennas, each configured to receive each of the respective signals. The radar system further comprises a neural network configured to receive data from the physical radar array and generate data

corresponding to an emulated array of antennas, wherein a defined distance between each antenna of the emulated array of antennas is $\lambda/2$. In various embodiments the neural network operates on a processor that is configured to generate data corresponding to a virtual antenna array having a defined distance between each virtual antenna that is inconsistent, and wherein the neural network uses the generated data corresponding to the virtual antenna array to generate the data corresponding to the emulated array of antennas.

[0007] In some embodiments the neural network is trained via machine learning. In various embodiments at least two adjacent antennas of the plurality of physical receive antennas are spaced apart by a distance that is a non-integer, or integer multiple of $\lambda/2$. In some embodiments at least two adjacent antennas of the plurality of physical transmit antennas are spaced apart by a distance greater than $\lambda/2$. In various embodiments at least two adjacent antennas of the plurality of physical transmit antennas are spaced apart by a distance less than $\lambda/2$. In some embodiments at least two adjacent antennas of the plurality of physical receive antennas are spaced apart by a distance greater than $\lambda/2$. In various embodiments at least two adjacent antennas of the plurality of physical receive antennas are spaced apart by a distance less than $\lambda/2$.

[0008] In some embodiments a radar system comprises a physical antenna array comprising a plurality of physical transmit antennas, each configured to transmit a respective signal having a wavelength λ , and a plurality of physical receive antennas, each configured to receive each of the respective signals. The physical antenna array further comprises a processor coupled to the physical antenna array and arranged to generate data for a virtual antenna array using data received from the physical antenna array, and generate, using a neural network, data for an emulated array of antennas wherein a defined distance between each antenna of the emulated array of antennas is $\lambda/2$, and wherein the neural network uses the data for the virtual antenna array. In various embodiments the virtual antenna array has a defined distance between each virtual antenna that is inconsistent. In some embodiments the neural network is trained via machine learning. In various embodiments at least two adjacent antennas of the plurality of physical transmit antennas are spaced apart by a distance greater than $\lambda/2$.

[0009] In some embodiments at least two adjacent antennas of the plurality of physical transmit antennas are spaced apart by a distance less than $\lambda/2$. In various embodiments at least two adjacent antennas of the plurality of physical receive antennas are spaced apart by a distance greater than $\lambda/2$. In some embodiments at least two adjacent antennas of the plurality of physical receive antennas are spaced apart by a distance less than $\lambda/2$.

[0010] In some embodiments a method of operating a radar system comprises generating data from a physical antenna array, wherein the physical antenna array comprises a plurality of physical transmit antennas, each configured to transmit a respective signal having a wavelength λ , and a plurality of physical receive antennas, each configured to receive each of the respective signals. The method further comprises generating, using a neural network, data for an emulated array of antennas wherein a defined distance between each antenna of the emulated array of antennas is $\lambda/2$.

[0011] In some embodiments the neural network operates on a processor that is configured to generate data corresponding to a virtual antenna array having a defined distance between each virtual antenna that is inconsistent. In various embodiments the data corresponding to the virtual antenna array is used by the neural network to generate the data corresponding to the emulated array of antennas. In some embodiments the neural network is trained via machine learning. In various embodiments at least two adjacent antennas of the plurality of virtual receive antennas are spaced apart by a distance that is not $\lambda/2$.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIG. 1A is a simplified diagram of a radar system with non-standard (sparse, uniform or non-uniform) spacing between physical antenna elements, according to some aspects of the present disclosure.

[0013] FIG. 1B is an illustration of an example array of “virtual” antennas that can be created via physical antennas and a processor according to some aspects of the present disclosure.

[0014] FIG. 1C is an illustration of an example array of “virtual” antennas with gaps filled in with virtual antenna elements, according to some aspects of the present disclosure.

[0015] FIG. 2 is an example block diagram of how a radar system may work, according to embodiments of the present disclosure.

[0016] FIG. 3 is an illustration of a simplified model of one embodiment of a generation of antennas inside a neural network model, according to some aspects of the present disclosure.

[0017] FIG. 4 is an illustration of a high-level depiction of a machine learning-based neural network model, according to embodiments of the present disclosure.

[0018] FIG. 5 is an illustration of example steps associated with training a machine learning model, according to embodiments of the present disclosure.

[0019] FIG. 6 is a flow chart for a simplified example process for generating training data for a machine learning model, according to embodiments of the present disclosure.

[0020] FIG. 7 is an illustration of an architecture for integrating a generated model into a hardware-accelerated architecture based on a Field Programmable Gate Array (FPGA) according to some aspects of the present disclosure.

[0021] FIG. 8 is a block diagram of an example processor that may be used to operate a radar system having an array of physical antennas to generate an array of virtual antennas with generated antennas to fill gaps within the array of virtual antennas, according to embodiments of the present disclosure.

[0022] FIG. 9 is a simplified diagram of a radar system that determines target information using a physical receive antenna array having at least one physical antenna (e.g., can be either transmitter or receiver) with wavelength independent spacing, according to embodiments of the disclosure.

[0023] FIG. 10 illustrates a simplified diagram of a physical radar system **1000**, according to embodiments of the disclosure.

[0024] FIG. 11 is a simplified diagram of a physical radar system **1100** having non- $\lambda/2$ -based spacing between one or more physical transmit and/or one or more receive antennas, according to some aspects of the present disclosure.

[0025] FIG. 12 is a simplified system diagram of two example modes of an algorithm that can be used by a processor to generate output data, according to some aspects of the present disclosure.

DETAILED DESCRIPTION

[0026] A multiple input multiple output (MIMO) radar configuration employs multiple physical transmit antennas and receive antennas that are used to generate a virtual antenna array which can be used to calculate angular information for an object. However, if each of the physical antennas does not have “ $\lambda/2$ -based spacing” between adjacent antennas, the resulting virtual array will have one or more gaps causing non-uniform phase that either prevents angular calculations from being performed or degrades the resolution of the angular calculations. The present invention uses a neural network to supplement the data generated by the physical antennas, providing the virtual array with uniform phase so the angular calculations can be performed with the requisite resolution.

[0027] In a first embodiment, the present invention uses data from the physical transmit and receive antennas to generate a virtual antenna array, however because one or more of the physical transmit and/or receive antennas does not have “ $\lambda/2$ -based spacing” the resulting virtual antenna array has one or more gaps (e.g., one or more spaces between virtual antennas that are integer multiples of $\lambda/2$ where the integer is greater than 1). More specifically, “ $\lambda/2$ -based spacing” of the physical

antennas is when the direct generation of a virtual antenna array from the physical antennas results in consistent $\lambda/2$ spacing between each virtual antenna. This embodiment employs a neural network to generate data for one or more supplemental antennas that are used to “fill in” the one or more gaps so the resulting supplemented virtual antenna array has a consistent $\lambda/2$ spacing, and uniform phase. The system uses data from both the virtual antenna array and from the neural network (e.g., the one or more supplemental antennas) to calculate angular information for the radar system.

[0028] In a second embodiment, the present invention similarly uses data from the physical transmit and receive antennas to generate data for a virtual array that includes one or more gaps (e.g., one or more missing virtual antennas). However, in this embodiment the one or more gaps in between the physical transmit and/or receive antennas may or may not be an integer multiple of $\lambda/2$, therefore this embodiment can be used for one or more physical antennas that have wavelength independent (e.g., any) spacing. Similar to the embodiment above, the system provides the data from the virtual array to a neural network. A further distinction from the embodiment above is that in this embodiment instead of the neural network only generating data for the missing “supplemented” antennas this neural network generates data for every antenna of an emulated array that has a plurality of virtual antennas all with uniform $\lambda/2$ spacing. The system uses the data from the neural network to calculate angular information for the radar system.

[0029] The neural network can be trained via machine learning with data from the physical and/or virtual antennas to fill in the gaps that cause phase discontinuity, providing an antenna array with improved and/or uniform angular resolution. Thus, conventional radar systems can have improved angular resolution and/or improved uniformity of angular resolution with minimal increased system cost, weight, or complexity. These and other embodiments will be described in more detail below.

Neural Network Enhanced Antenna Array

[0030] FIG. 1A illustrates a simplified diagram of a radar system **100** with non-“ $\lambda/2$ -based spacing” (sparse or unequal) spacing between one or more physical antenna elements. As shown in FIG. 1A, in this embodiment there are two physical transmit antennas Tx1 **105a** and Tx2 **105b** that each transmit signals at a wavelength λ and that are separated by d_4 . There are also four physical receive antennas where Rx1 **110a** is separated from Rx2 **110b** by d_1 , Rx3 **110c** separated from Rx2 by d_2 and Rx4 **110d** is separated from Rx3 by d_3 . Distributed antenna arrays having non-“ $\lambda/2$ -based spacing” (e.g., sparsity, irregular or inconsistent spacing) can be used on the physical transmitter antennas **105**, the physical receiver antennas **110** or both.

[0031] More specifically, in a traditional radar system that has “ $\lambda/2$ -based spacing” for example, $d_1=\lambda/2$, $d_2=\lambda/2$, $d_3=\lambda/2$ and $d_4=\lambda/2$ such that each virtual antenna of the resulting virtual antenna array is spaced apart at consistent $\lambda/2$ intervals. In contrast, in one example embodiment in which the physical receiver antennas **105** have non-“ $\lambda/2$ -based spacing”, $d_1=\lambda/2$, $d_2=\lambda$, $d_3=\lambda/2$ and $d_4=2\lambda$ while in other example embodiment the physical transmitter antennas **105** may have non-“ $\lambda/2$ -based spacing”, for example, $d_4=4\lambda$ when d_1 through $d_3=\lambda/2$. In this embodiment the non-“ $\lambda/2$ -based spacing” of the physical transmit **105** and/or receive **110** antennas results in a virtual antenna array having one or more “gaps” (a space between adjacent virtual antennas that is an integer multiple of $\lambda/2$ where the integer is greater than 1). In some embodiments one or more of d_1 - d_4 is an integer multiple of $\lambda/2$ including the integers 2, 3, 4, 5, etc. and may exclude the integer 1.

[0032] Each physical transmit and receive antenna, **105**, **110**, respectively, is connected to a processor **120** that controls each antenna and may more specifically control the transmission operations of the transmit antennas and the received data from the receive antennas. Processor **120** may be any suitable processing system including but not limited to a radio frequency (RF) system-on-chip (SOC), a local and/or remote computing system or a combination of computing systems. Although radar system **100** depicts six physical antennas with a particular spacing (e.g., d_1 - d_4) between each antenna, one of skill in the art having the benefit of this disclosure will appreciate that this invention is not limited to this embodiment and that any suitable number of physical transmit and receive antennas can be used and the spacing therebetween may be any suitable

distance.

[0033] FIG. 1B illustrates an example virtual antenna array **115** that can be created from a combination of the physical transmit antennas **105** and the physical receive antennas **110** via digital signal processing performed by the processor **120** shown in FIG. 1A in its general form. When multiple physical transmit and receive antennas are co-located, they can act together to form what is commonly known as a virtual antenna array **115**. The virtual antenna array **115** is not a set of physical antennas, rather it is a mathematically equivalent construct that describes the behavior of the antenna array. The number of virtual elements in a traditional planar virtual antenna array having “N” physical transmit antennas and “M” physical receive antennas is the product of N and M, however if any of the physical antennas have non-“ $\lambda/2$ -based spacing” the number of antenna positions (all having $\lambda/2$ -based spacing) in the virtual array may be greater than the product of N and M, as described in more detail below

[0034] As shown in FIG. 1B radar system **100** may employ digital signal processing to create the virtual antenna array **115** of eight virtual receive antennas (**125a-125h**) from the signals sent to and/or received from the two physical transmit antennas Tx1 **105a**, Tx2 **105b** and the four physical receive antennas Rx1 **110a**, Rx2 **110b**, Rx3 **110c**, Rx4 **110d**. As further shown in FIG. 1B, one or more missing virtual antennas **130a**, **130b** may form “gaps” (spaces between adjacent virtual antennas that are greater than $\lambda/2$, in this case λ) in the virtual antenna array **115** and thus the virtual antenna array may not have uniform phase consistency. The combination of the virtual antennas **125a-125h** and the missing virtual antennas **130a-130b** each have a consistent defined distance “d” between them where $d=\lambda/2$. The virtual antenna array **115** has e.g., sparsity, irregular or inconsistent spacing between virtual antennas **125a** because of the missing virtual antennas **130** (e.g., antennas that are missing at $\lambda/2$ spacing). For example, the space between virtual antenna **125a** and **125b** is d ($\lambda/2$) whereas the space between virtual antenna **125b** and **125c** is 2d (λ). In some embodiments the one or more missing virtual antennas **130** may be generated when one or more of the physical transmit and/or receive antennas have non-“ $\lambda/2$ -based spacing”.

[0035] FIG. 1C illustrates the example virtual antenna array **115** shown in FIG. 1B, with missing virtual antennas **130a-130b** filled in with supplemental virtual antennas **135a-135b** forming a supplemented virtual antenna array **140**. The supplemented virtual antenna array **140** includes ten virtual antenna elements regularly spaced at a distance d (where $d=\lambda/2$), providing a virtual array of antennas with uniform angular resolution and phase consistency. More specifically, processor **120** (see FIG. 1A) may employ a neural network, machine learning process or other suitable algorithm to generate data for each supplemental virtual antenna **135** such that processor **120** can detect objects uniformly across all 10 antenna elements. Processor **120** may use data from the physical transmit antennas **105** (see FIG. 1A) and the physical receive antennas **110** to generate data for the supplemental virtual antennas **135**. As shown in FIG. 1C, the number of virtual antennas for the supplemented virtual array **140** is the product of M and N (two times four) plus the number of supplemental virtual antennas (in this case there are two) so in this example there are ten virtual antennas. As appreciated by a person of ordinary skill in the art having the benefit of this disclosure processor **120** may include one or more processors that work in conjunction with each other. In one example embodiment a first processor is an RF ASIC that communicates with the physical antennas, a second process is used for data transfer and a third processor is used for the neural network processing.

[0036] The neural network can be trained based on a machine learning model, including Deep Neural Networks (DNN), convolutional neural network (CNN) or any other suitable type of training, some of which can be based on a neural network. In some embodiments the neural network may undergo training to understand patterns and correlations within the available radar data, enabling the network to estimate the signals for the supplemental virtual antennas **135** that are missing in the virtual array and send corresponding data to processor **120**. In some embodiments the neural network can produce data for supplemental antennas **135** while in further embodiments

the neural network can additionally produce data for each virtual antenna **125** so the processor produces data for each antenna of the supplemented virtual antenna array **140**. In various embodiments the neural network may be integrated into processor **120** and/or may form a portion of a system-on-a-chip. In some embodiments d , which is a spacing between each element of the supplemented virtual array **115**, is $\lambda/2$.

[0037] As appreciated by one of ordinary skill in the art having the benefit of this disclosure, in some embodiments, when the field of view of the system is greater than or less than 180 degrees, the optimal spacing between each antenna of the supplemented virtual array **140** may be greater than or less than $\lambda/2$ and may be referred to more generally as a “predetermined distance”. For example, in one embodiment a desired field of view of the supplemented virtual array **140** is 120 degrees and therefore the optimal predetermined distance between each antenna of the supplemented virtual antenna array is $\lambda/3$. In various embodiments the predetermined distance may be $\lambda/2$ while in other embodiments the predetermined distance may be greater or less than $\lambda/2$.

[0038] In some embodiments transmit antennas **105** may be arranged in a two-dimensional array providing the radar system **100** with a two-dimensional virtual antenna that provides data for both azimuth and elevation dimensions. For example, radar system **100** may use a transmit antenna array similar to transmit antenna **1105** shown in FIG. **11** and described in greater detail below.

[0039] FIG. **2** is an example block diagram of how radar system **100** shown in FIG. **1A** may work, according to embodiments of the disclosure. As shown in FIG. **2**, raw data from the radar array (e.g., from processor **120**, receive antennas **110** and/or transmit antennas **105**) enters range processing **205** where ranges of the targets are processed. Data is transferred from range processing to a doppler processing **210** before slicing **215** takes place. The sliced data is transferred to a Constant False Alarm Rate (CFAR) processing **220** which may be used to detect target returns against a background of noise, clutter, and interference. The results of the CFAR analysis may then be used to generate supplemental virtual antenna elements **135** (see FIG. **1C**) via a trained generative neural network **225**. Data from the supplemental virtual antenna elements **135** (see FIG. **1C**), from the virtual antenna elements **125** (see FIG. **1C**) and optionally from the physical antenna elements **105**, **110** (see FIG. **1A**) is transferred to angle processing **230**, from which angle information is derived.

[0040] FIG. **3** illustrates a simplified model **300** of one embodiment of the generation of a supplemental virtual antennas using a neural network model. This generator network may be responsible for generating data for the missing virtual antennas (e.g., supplemental virtual antennas). The training process allows the generator to improve over time and produce more realistic samples. As shown in FIG. **3** the sparse input signal may be part of a sampled continuous signal. Note that the samples are defined in a space dimension, which are the data received from antennas. The generated samples by the neural network correspond to the signals of the missing antennas in angle domain of the radar. These signals can be alternatively used along with the signals from original receivers for angle processing. Angle processing data may be used to generate angle information for the object(s).

[0041] The integration of a neural network with sparse antennas may be used to transform the radar system from a discrete-time low-resolution signal to a high-resolution signal within the network architecture. In some embodiments the network may be based on a Tensorflow Processing Units (TPU) or other suitable approach that utilizes distributed antennas in conjunction with the neural network.

[0042] FIG. **4** illustrates a high-level depiction of a machine learning-based neural network model **400**, according to embodiments of the invention. As shown in FIG. **4**, the neural network can be used to generate the data for supplemental antennas using the trained model and may be based on the locations of the antennas. In some embodiments the system may generate supplemental antenna elements.

[0043] FIG. **5** illustrates example steps associated with a method of training a machine learning

model **500**, according to embodiments of the disclosure. As shown in FIG. 5, the training may apply in the angle domain if the focus is on improved angular resolution, however, other embodiments may employ different suitable training algorithms. In some embodiments, the deep learning network, or any other suitable neural network model, is capable of learning and capturing patterns within the underlying data. In one example a dataset comprising 10,000 instances is generated, e.g., test scenarios, that represent typical test scenarios. This dataset may consist of both real and imaginary data, enabling the deep learning network to learn and model the patterns effectively.

[0044] Datasets may be divided into three subsets: training, validation, and test. The division may be used to assess the accuracy of the trained model by comparing its predictions to actual data and determining the level of agreement between them. In order to have data available for evaluation, a portion of the dataset may be set aside before the training process begins. In one example 20% of the data is reserved for validation, 20% is used for testing, and the remainder of 60% is used to train the model.

[0045] A person of skill in the art, with the benefit of this disclosure, will appreciate that, in other embodiments, the machine learning model **500** may have variations, modifications and alternatives that are within the scope of this disclosure. For example, the machine learning model **500** describes several functions including DNN, TinyML Keras, Tensorflow, however this disclosure is not limited these disclosed functions and other suitable functions can be used in addition to or in place of the disclosed function. In one example, a CNN model may be used in place of the DNN model. Further, the order of the steps disclosed in the machine learning model **500** may be changed.

[0046] FIG. 6 illustrates an example of a simplified process **600** for generating training data for the machine learning model, according to embodiments of the disclosure. Other suitable training processes may be used. As shown in FIG. 6, real-world field data may be used to train the model. The data used for training the neural networks may include three types of radar input, which are outlined below: [0047] Theoretical data: Preliminary radar data, typically system generated and used in simulations for algorithm development. [0048] Real-world field data: Radar data gathered from selected scenarios (e.g., a pedestrian). [0049] Hybrid data: Creating numerous synthetic scenarios using a subset of real-world measurements that effectively replicate hundreds of challenging scenarios of interest.

[0050] A training data set may be created from the real-world field data as the baseline and then adjustments can be made to the phase, amplitude, and duplications, including normalization. The model's ability to effectively learn from the data and achieve accurate detection performance in radar applications is evaluated during the training. This evaluation may be carried out by calculating, for example, both a loss metric and an error metric: [0051] Loss Metric: This is the output of the loss function which may be mean squared error, which is expressed as a positive number. Generally, the smaller the loss value, the better. [0052] Mean Absolute Error (MAE) Metric: This is the mean absolute error of the training data. It shows the average difference between the network's output regression and the expected values from the training data.

[0053] The trained model may utilize signals from the physical sparse antennas as input and generate a set of additional and new virtual antennas as output. This specific problem falls under the category of regression, where the model aims to predict continuous phase values based on the given input. To develop the model, any suitable neural network architecture may be used that consists of layers of interconnected neurons that aim to learn patterns and relationships within the training radar data to make accurate estimations.

[0054] FIG. 7 illustrates an architecture **700** of integrating the generated model into a hardware-accelerated architecture based on a FPGA. As shown in FIG. 7, the commands and data are transferred through the PS interface using the AXIS bus. Upon reception, these commands are decoded and directed to one of the following functions: [0055] Write Weight Memory: Data on the bus is written into a specific location in Weight Memory space. [0056] Write Input Memory: Data

on the bus is written onto a specified location in Input Memory space. [0057] Fill Weight FIFO's: A set of weights is read from weight memory into the weight FIFO's. [0058] Drain Weight FIFO's: A set of weights currently held in the weight FIFOs is loaded into the systolic array. [0059] Matrix Multiply: A set of inputs is piped into the systolic array and multiplied with the set of weights currently held in the array. [0060] Read Output Memory: A specified word from memory is read to the host.

[0061] The architecture may utilize a weight stationary systolic array, which operates by loading a set of weights once and reusing them for multiple operations. This array may be fully pipelined and can perform a 16×16 matrix multiplication in 32 cycles. The systolic array consists of multiple processing elements (PEs) that contain a small amount of memory and control logic, along with a single multiply-accumulate data path. The execution of a complete matrix multiplication starts from the top left corner of the systolic array and progresses diagonally downward in a pipelined fashion.

[0062] FIG. 8 is a block diagram **800** of an example processor **120** (see FIG. 1A) that may be used to operate a radar system having an array of physical antennas to generate an array of virtual antennas with continuous phase, according to embodiments of the disclosure. Processor **120** may be one or more semiconductor devices including but not limited to a system on a chip (SOC), a multi-chip module, a field programmable gate array (FPGA) or other suitable device. In some embodiments, processor **120** may include a computer-readable medium (memory) **802**, a processing system **804**, an Input/Output (I/O) subsystem **806**, wireless circuitry **808**, and audio circuitry **810** including speaker **850** and microphone **852**. These components may be coupled by one or more communication buses or signal lines **803**. Processor **120** can encompass any suitable processing device and/or portable electronic device, including a handheld computer, a tablet computer, a remote control unit for a drone, a mobile phone, laptop computer, tablet device, media player, a wearable device, personal digital assistant (PDA), a multi-function device, a mobile phone, a portable gaming device, a car display unit, or the like, including a combination of two or more of these items.

[0063] The processor **120** can be a system on chip (SOC) which may be an RF device with an embedded processor or can be any other suitable processor in accordance with some embodiments. The touch screen optionally displays one or more graphics within user interface (UI). In some embodiments, a user is enabled to select one or more of the graphics by making a gesture on the graphics, for example, with one or more fingers or one or more styluses. In some embodiments, selection of one or more graphics occurs when the user breaks contact with the one or more graphics. In some embodiments, the gesture optionally includes one or more taps, one or more swipes (from left to right, right to left, upward and/or downward) and/or a rolling of a finger (from right to left, left to right, upward and/or downward) that has made contact with processor **120**. In some implementations or circumstances, inadvertent contact with a graphic does not select the graphic. For example, a swipe gesture that sweeps over an application icon optionally does not select the corresponding application when the gesture corresponding to selection is a tap. Processor **120** can optionally also include one or more physical buttons, such as "home" or menu button. As menu button is, optionally, used to navigate to any application in a set of applications that are, optionally executed on the processor **120**. Alternatively, in some embodiments, the menu button is implemented as a soft key in a graphical user interface displayed on touch screen.

[0064] The processor **120** can incorporate a display **854**. The display **854** can be a LCD, OLED, AMOLED, Super AMOLED, TFT, IPS, or TFT-LCD that typically can be found a computing device. The display **854** may be a touch screen display of a computing device.

[0065] In one embodiment, processor **120** includes touch screen, menu button, push button for powering the device on/off and locking the device, volume adjustment button(s), Subscriber Identity Module (SIM) card slot, head set jack, and docking/charging external port. Push button is, optionally, used to turn the power on/off on the device by depressing the button and holding the

button in the depressed state for a predefined time interval; to lock the device by depressing the button and releasing the button before the predefined time interval has elapsed; and/or to unlock the device or initiate an unlock process. In an alternative embodiment, processor **120** also accepts verbal input for activation or deactivation of some functions through microphone. Processor **120** also, optionally, includes one or more contact intensity sensors for detecting intensity of contacts on touch screen and/or one or more tactile output generators for generating tactile outputs for a user of processor **120**.

[0066] In one illustrative configuration, processor **120** may include at least one computer-readable medium (memory) **802** and one or more processing units (or processor(s)) **818**. Processor(s) **818** may be implemented as appropriate in hardware, software, or combinations thereof. Computer-executable instruction or firmware implementations of processor(s) **818** may include computer-executable instructions written in any suitable programming language to perform the various functions described.

[0067] Computer-readable medium (memory) **802** may store program instructions that are loadable and executable on processor(s) **818**, as well as data generated during the execution of these programs. Depending on the configuration and type of processor **120**, memory **802** may be volatile (such as random access memory (RAM)) and/or non-volatile (such as read-only memory (ROM), flash memory, etc.). Processor **120** can have one or more memories. Processor **120** may also include additional removable storage and/or non-removable storage including, but not limited to, magnetic storage, optical disks, and/or tape storage. The disk drives and their associated non-transitory computer-readable media may provide non-volatile storage of computer-readable instructions, data structures, program modules, and other data for the devices. In some implementations, memory **802** may include multiple different types of memory, such as static random access memory (SRAM), dynamic random access memory (DRAM), or ROM. While the volatile memory described herein may be referred to as RAM, any volatile memory that would not maintain data stored therein once unplugged from a host and/or power would be appropriate.

[0068] Memory **802** and additional storage, both removable and non-removable, are all examples of non-transitory computer-readable storage media. For example, non-transitory computer readable storage media may include volatile or non-volatile, removable or non-removable media implemented in any method or technology for storage of information such as computer-readable instructions, data structures, program modules, or other data. Memory **802** and additional storage are both examples of non-transitory computer storage media. Additional types of computer storage media that may be present in processor **120** may include, but are not limited to, phase-change RAM (PRAM), SRAM, DRAM, RAM, ROM, electrically erasable programmable read-only memory (EEPROM), flash memory or other memory technology, compact disc read-only memory (CD-ROM), digital video disc (DVD) or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to store the desired information and that can be accessed by processor **120**. Combinations of any of the above should also be included within the scope of non-transitory computer-readable storage media. Based on the disclosure and teachings provided herein, a person of ordinary skill in the art can appreciate other ways and/or methods to implement the various embodiments. However, as noted above, computer-readable storage media does not include transitory media such as carrier waves or the like.

[0069] Alternatively, computer-readable communication media may include computer-readable instructions, program modules, or other data transmitted within a data signal, such as a carrier wave, or other transmission. However, as used herein, computer-readable storage media does not include computer-readable communication media.

[0070] Processor **120** may also contain communications connection(s) **808** that allow processor **120** to communicate with a data store, another device or server, user terminals and/or other devices via one or more networks. Such networks may include any one or a combination of many different

types of networks, such as cable networks, the Internet, wireless networks, cellular networks, satellite networks, other private and/or public networks, or any combination thereof. Processor **120** may also include I/O device(s) **806**, such as a touch input device, a keyboard, a mouse, a pen, a voice input device, a display, a speaker, a printer, etc.

[0071] It should be apparent that the architecture shown in FIG. **8** is only one example of an architecture for processor **120**, and that processor **120** can have more or fewer components than shown, or a different configuration of components. The various components shown in FIG. **8** can be implemented in hardware, software, or a combination of both hardware and software, including one or more signal processing and/or application specific integrated circuits.

[0072] Wireless circuitry **808** is used to send and receive information over a wireless link or network to one or more other devices' conventional circuitry such as an antenna system, an RF transceiver, one or more amplifiers, a tuner, one or more oscillators, a digital signal processor, a CODEC chipset, memory, etc. Wireless circuitry **808** can use various protocols, e.g., as described herein. For example, wireless circuitry **808** can have one component for one wireless protocol (e.g., Bluetooth®) and a separate component for another wireless protocol (e.g., UWB). Different antennas can be used for the different protocols.

[0073] Wireless circuitry **808** is coupled to processing system **804** via peripherals interface **816**. Interface **816** can include conventional components for establishing and maintaining communication between peripherals and processing system **804**. Voice and data information received by wireless circuitry **808** (e.g., in speech recognition or voice command applications) is sent to one or more processors **818** via peripherals interface **816**. One or more processors **818** are configurable to process various data formats for one or more application programs **834** stored on computer-readable medium (memory) **802**.

[0074] Peripherals interface **816** couple the input and output peripherals of the device to processor(s) **818** and computer-readable medium **802**. One or more processors **818** communicate with computer-readable medium **802** via a controller **820**. Computer-readable medium **802** can be any device or medium that can store code and/or data for use by one or more processors **818**. Medium **802** can include a memory hierarchy, including cache, main memory, and secondary memory.

[0075] Processor **120** also includes a power system **842** for powering the various hardware components. Power system **842** can include a power management system, one or more power sources (e.g., battery, alternating current (AC)), a recharging system, a power failure detection circuit, a power converter or inverter, a power status indicator (e.g., a light emitting diode (LED)) and any other components typically associated with the generation, management, and distribution of power in mobile devices.

[0076] In some embodiments, processor **120** includes a camera **844**. In some embodiments, processor **120** includes sensors **846**. Sensors **846** can include accelerometers, compasses, gyroscopes, pressure sensors, audio sensors, light sensors, barometers, and the like. Sensors **846** can be used to sense location aspects, such as auditory or light signatures of a location.

[0077] In some embodiments, processor **120** can include a GPS receiver, sometimes referred to as a GPS unit **848**. A mobile device can use a satellite navigation system, such as the Global Positioning System (GPS), to obtain position information, timing information, altitude, or other navigation information, including for one or more objects detected by the radar system. During operation, the GPS unit can receive signals from GPS satellites orbiting the Earth. The GPS unit analyzes the signals to make a transit time and distance estimation. The GPS unit can determine the current position (current location) of the mobile device. Based on these estimations, the mobile device can determine a location fix, altitude, and/or current speed. A location fix can be geographical coordinates such as latitudinal and longitudinal information.

[0078] One or more processors **818** run various software components stored in medium **802** to perform various functions for processor **120**. In some embodiments, the software components

include an operating system **822**, a communication module (or set of instructions) **824**, a location module (or set of instructions) **826**, a bounding path **828** that is used as part of ranging operation described herein, and other applications (or set of instructions) **834**.

[0079] Operating system **822** can be any suitable operating system, including iOS, Mac OS, Darwin, RTXC, LINUX, UNIX, OS X, WINDOWS, or an embedded operating system such as VxWorks. The operating system can include various procedures, sets of instructions, software components and/or drivers for controlling and managing general system tasks (e.g., memory management, storage device control, power management, etc.) and facilitates communication between various hardware and software components. An operating system **822** is system software that manages computer hardware and software resources and provides common services for computer programs. For example, the operating system **822** can manage the interaction between the user interface module and one or more user application(s). The various embodiments further can be implemented in a wide variety of operating environments, which in some cases can include one or more user computers, devices or processing devices which can be used to operate any of a number of applications. User or client devices can include any of a number of general purpose personal computers, such as desktop or laptop computers running a standard operating system, as well as cellular, wireless and handheld devices running mobile software and capable of supporting a number of networking and messaging protocols. Such a system also can include a number of workstations running any of a variety of commercially-available operating systems and other known applications for purposes such as development and database management. These devices also can include other electronic devices, such as dummy terminals, thin-clients, gaming systems and other devices capable of communicating via a network.

[0080] Communication module **824** facilitates communication with other devices over one or more external ports **836** or via wireless circuitry **808** and includes various software components for handling data received from wireless circuitry **808** and/or external port **836**. External port **836** (e.g., USB, FireWire, Lightning connector, 60-pin connector, etc.) is adapted for coupling directly to other devices or indirectly over a network (e.g., the Internet, wireless LAN, etc.).

[0081] Location/motion module **826** can assist in determining the current position (e.g., coordinates or other geographic location identifiers) and motion of processor **120** and/or one or more object detected by the radar system. Modern positioning systems include satellite based positioning systems, such as Global Positioning System (GPS), cellular network positioning based on “cell IDs,” and Wi-Fi positioning technology based on a Wi-Fi networks. GPS also relies on the visibility of multiple satellites to determine a position estimate, which may not be visible (or have weak signals) indoors or in “urban canyons.” In some embodiments, location/motion module **826** receives data from GPS unit **848** and analyzes the signals to determine the current position of the mobile device. In some embodiments, location/motion module **826** can determine a current location using Wi-Fi or cellular location technology. For example, the location of the mobile device can be estimated using knowledge of nearby cell sites and/or Wi-Fi access points with knowledge also of their locations. Information identifying the Wi-Fi or cellular transmitter is received at wireless circuitry **808** and is passed to location/motion module **826**. In some embodiments, the location module receives the one or more transmitter IDs. In some embodiments, a sequence of transmitter IDs can be compared with a reference database (e.g., Cell ID database, Wi-Fi reference database) that maps or correlates the transmitter IDs to position coordinates of corresponding transmitters, and computes estimated position coordinates for processor **120** based on the position coordinates of the corresponding transmitters. Regardless of the specific location technology used, location/motion module **826** receives information from which a location fix can be derived, interprets that information, and returns location information, such as geographic coordinates, latitude/longitude, or other location fix data.

[0082] The neural network module **828** can be employed with sparse antennas and used to generate a new radar data with continuous phase from a discrete-time physically sparse signal configuration

within the network architecture. In some embodiments the network may be based on a Tensorflow Processing Units (TPU) approach that utilizes sparse antennas in conjunction with the neural network. The neural network can be trained based on machine learning model based on perception, including Deep Neural Networks (DNN) and convolutional neural network (CNN). In some embodiments the neural network may undergo training to understand patterns and correlations within the available radar data, enabling the network to estimate the signals for the generated virtual antennas.

[0083] The one or more applications programs **834** on the mobile device can include any applications installed on the processor **120**, including without limitation, a browser, address book, contact list, email, instant messaging, word processing, keyboard emulation, widgets, JAVA-enabled applications, encryption, digital rights management, voice recognition, voice replication, a music player (which plays back recorded music stored in one or more files, such as MP3 or AAC files), etc.

[0084] There may be other modules or sets of instructions (not shown), such as a graphics module, a time module, etc. For example, the graphics module can include various conventional software components for rendering, animating, and displaying graphical objects (including without limitation text, web pages, icons, digital images, animations and the like) on a display surface. In another example, a timer module can be a software timer. The timer module can also be implemented in hardware. The timer module can maintain various timers for any number of events.

[0085] The I/O subsystem **806** can be coupled to a display system (not shown), which can be a touch-sensitive display. The display system displays visual output to the user in a GUI. The visual output can include text, graphics, video, and any combination thereof. Some or all of the visual output can correspond to user-interface objects. A display can use LED (light emitting diode), LCD (liquid crystal display) technology, or LPD (light emitting polymer display) technology, although other display technologies can be used in other embodiments.

[0086] In some embodiments, I/O subsystem **806** can include a display and user input devices such as a keyboard, mouse, and/or track pad. In some embodiments, I/O subsystem **806** can include a touch-sensitive display. A touch-sensitive display can also accept input from the user based on haptic and/or tactile contact. In some embodiments, a touch-sensitive display forms a touch-sensitive surface that accepts user input. The touch-sensitive display/surface (along with any associated modules and/or sets of instructions in medium **802**) detects contact (and any movement or release of the contact) on the touch-sensitive display and converts the detected contact into interaction with user-interface objects, such as one or more soft keys, that are displayed on the touch screen when the contact occurs. In some embodiments, a point of contact between the touch-sensitive display and the user corresponds to one or more digits of the user. The user can make contact with the touch-sensitive display using any suitable object or appendage, such as a stylus, pen, finger, and so forth. A touch-sensitive display surface can detect contact and any movement or release thereof using any suitable touch sensitivity technologies, including capacitive, resistive, infrared, and surface acoustic wave technologies, as well as other proximity sensor arrays or other elements for determining one or more points of contact with the touch-sensitive display.

[0087] Further, the I/O subsystem can be coupled to one or more other physical control devices (not shown), such as pushbuttons, keys, switches, rocker buttons, dials, slider switches, sticks, LEDs, etc., for controlling or performing various functions, such as power control, speaker volume control, ring tone loudness, keyboard input, scrolling, hold, menu, screen lock, clearing and ending communications and the like. In some embodiments, in addition to the touch screen, processor **120** can include a touchpad (not shown) for activating or deactivating particular functions. In some embodiments, the touchpad is a touch-sensitive area of the device that, unlike the touch screen, does not display visual output. The touchpad can be a touch-sensitive surface that is separate from the touch-sensitive display or an extension of the touch-sensitive surface formed by the touch-sensitive display.

[0088] In some embodiments, some or all of the operations described herein can be performed using an application executing on the user's device. Circuits, logic modules, processors, and/or other components may be configured to perform various operations described herein. Those skilled in the art can appreciate that, depending on implementation, such configuration can be accomplished through design, setup, interconnection, and/or programming of the particular components and that, again depending on implementation, a configured component might or might not be reconfigurable for a different operation. For example, a programmable processor can be configured by providing suitable executable code; a dedicated logic circuit can be configured by suitably connecting logic gates and other circuit elements; and so on.

[0089] Most embodiments utilize at least one network that would be familiar to those skilled in the art for supporting communications using any of a variety of commercially-available protocols, such as TCP/IP, OSI, FTP, UPnP, NFS, CIFS, and AppleTalk. The network can be, for example, a local area network, a wide-area network, a virtual private network, the Internet, an intranet, an extranet, a public switched telephone network, an infrared network, a wireless network, and any combination thereof.

[0090] In embodiments utilizing a network server, the network server can run any of a variety of server or mid-tier applications, including HTTP servers, FTP servers, CGI servers, data servers, Java servers, and business application servers. The server(s) also may be capable of executing programs or scripts in response requests from user devices, such as by executing one or more applications that may be implemented as one or more scripts or programs written in any programming language, such as Java®, C, C # or C++, or any scripting language, such as Perl, Python or TCL, as well as combinations thereof. The server(s) may also include database servers, including without limitation those commercially available from Oracle®, Microsoft®, Sybase®, and IBM®.

[0091] Such programs may also be encoded and transmitted using carrier signals adapted for transmission via wired, optical, and/or wireless networks conforming to a variety of protocols, including the Internet. As such, a computer readable medium according to an embodiment of the present invention may be created using a data signal encoded with such programs. Computer readable media encoded with the program code may be packaged with a compatible device or provided separately from other devices (e.g., via Internet download). Any such computer readable medium may reside on or within a single computer product (e.g., a hard drive, a CD, or an entire computer system), and may be present on or within different computer products within a system or network. A computer system may include a monitor, printer, or other suitable display for providing any of the results mentioned herein to a user.

[0092] The environment can include a variety of data stores and other memory and storage media as discussed above. These can reside in a variety of locations, such as on a storage medium local to (and/or resident in) one or more of the computers or remote from any or all of the computers across the network. In a particular set of embodiments, the information may reside in a storage-area network (SAN) familiar to those skilled in the art. Similarly, any necessary files for performing the functions attributed to the computers, servers or other network devices may be stored locally and/or remotely, as appropriate. Where a system includes computerized devices, each such device can include hardware elements that may be electrically coupled via a bus, the elements including, for example, at least one central processing unit (CPU), at least one input device (e.g., a mouse, keyboard, controller, touch screen or keypad), and at least one output device (e.g., a display device, printer, or speaker). Such a system may also include one or more storage devices, such as disk drives, optical storage devices, and solid-state storage devices such as RAM or ROM, as well as removable media devices, memory cards, flash cards, etc.

[0093] Such devices also can include a computer-readable storage media reader, a communications device (e.g., a modem, a network card (wireless or wired), an infrared communication device, etc.), and working memory as described above. The computer-readable storage media reader can be

connected with, or configured to receive, a non-transitory computer-readable storage medium, representing remote, local, fixed, and/or removable storage devices as well as storage media for temporarily and/or more permanently containing, storing, transmitting, and retrieving computer-readable information. The system and various devices also typically can include a number of software applications, modules, services or other elements located within at least one working memory device, including an operating system and application programs, such as a client application or browser. It should be appreciated that alternate embodiments may have numerous variations from that described above. For example, customized hardware might also be used and/or particular elements might be implemented in hardware, software (including portable software, such as applets) or both. Further, connection to other devices such as network input/output devices may be employed.

[0094] Any of the software components or functions described in this application may be implemented as software code to be executed by a processor using any suitable computer language such as, for example, Java, C, C++, C #, Objective-C, Swift, or scripting language such as Perl or Python using, for example, conventional or object-oriented techniques. The software code may be stored as a series of instructions or commands on a computer readable medium for storage and/or transmission. A suitable non-transitory computer readable medium can include random access memory (RAM), a read only memory (ROM), a magnetic medium such as a hard-drive or a floppy disk, or an optical medium, such as a compact disk (CD) or DVD (digital versatile disk), flash memory, and the like. The computer readable medium may be any combination of such storage or transmission devices.

[0095] Computer programs incorporating various features of the present disclosure may be encoded on various computer readable storage media; suitable media include magnetic disk or tape, optical storage media, such as compact disk (CD) or DVD (digital versatile disk), flash memory, and the like. Computer readable storage media encoded with the program code may be packaged with a compatible device or provided separately from other devices. In addition, program code may be encoded and transmitted via wired optical, and/or wireless networks conforming to a variety of protocols, including the Internet, thereby allowing distribution, e.g., via Internet download. Any such computer readable medium may reside on or within a single computer product (e.g., a solid state drive, a hard drive, a CD, or an entire computer system), and may be present on or within different computer products within a system or network. A computer system may include a monitor, printer, or other suitable display for providing any of the results mentioned herein to a user.

Antenna Array with Wavelength Independent Spacing

[0096] FIG. 9 illustrates a simplified diagram of a radar system **900** that determines information for objects using a physical receive antenna array having at least one antenna with wavelength independent spacing, according to embodiments of the disclosure. Radar system **900** is similar to radar system **100** and generates data for a virtual array that includes one or more gaps (e.g., one or more missing virtual antennas due to the wavelength independent spacing of the physical receive antennas). However, in radar system **900**, instead of the neural network generating data for the missing virtual antennas, radar system **900** generates data for each antenna of an emulated antenna array where each antenna has uniform $\lambda/2$ spacing. The system uses data for the emulated antenna to calculate angular information for the radar system.

[0097] More specifically, in radar system **100** described above, the virtual antenna array **115** may have one or more gaps that integer multiples of $\lambda/2$ where the integer is greater than one, and wherein the one or more gaps are filled in with supplemental antenna elements generated by a neural network to provide the system with data from a supplemented array of virtual antenna elements having a consistent $\lambda/2$ spacing. In contrast, in some of the embodiments described below, one or more of the physical antennas may be spaced apart from an adjacent antenna by any distance which may be unrelated to the wavelength λ of the transmit antennas (e.g., wavelength independent). For example, one or more of the physical antennas may be spaced apart from an

adjacent physical antenna by, for example, $1.3\lambda/2$, $0.8\lambda/2$, λ , 0.6λ , 2λ , 10 millimeters etc., including non-integer values of $\lambda/2$. A neural network converts data from the physical antennas to data for an emulated antenna array having a consistent $\lambda/2$ spacing which is used for the angular calculations. The array of regularly spaced antennas provides a continuous signal phase across the emulated array and enables the field of view (FOV) to remain at $\pm 90^\circ$.

[0098] In some embodiments the spacing between each physical receive antenna **940** of the radar is greater than $\lambda/2$ (e.g., $1.2\lambda/2$) and the radar system has an unaffected FOV (e.g., $\pm 90^\circ$) and improved angular resolution as compared to a radar system that has consistent $\lambda/2$ spacing. In another embodiment the spacing between each physical receive antenna **940** is less than $\lambda/2$ (e.g., $0.6\lambda/2$) and the radar system has an unaffected FOV and reduced resolution as compared to a radar array that has consistent $\lambda/2$ spacing, which is in contrast to a traditional radar system (e.g., no neural network) which would not be efficiently operational with antennas at a spacing of less than $\lambda/2$. Thus, the present disclosure enables radar systems having receive antennas at wavelength independent spacing.

[0099] As described herein, wavelength independent spacing is when one or more of the distances between adjacent physical receive and/or transmit antennas is not $\lambda/2$ -based, which is the traditional “wavelength dependent” spacing between physical antennas. More specifically, the radar systems disclosed herein can use any suitable spacing between physical antenna elements and therefore can be considered “wavelength independent” spacing as defined herein. Further, even though some distances between adjacent antennas are described herein using the term λ , (e.g., $1.3\lambda/2$) the use of λ does not mean the distance between the antennas is “wavelength dependent”, in particular, when used with a non-integer value of λ or when any spacing between physical antennas is not $\lambda/2$ -based spacing. Rather, the use of λ in such ways herein is merely one way to describe the spacing between antennas as related to a transmission wavelength of the physical transmit antennas.

[0100] In some embodiments radar system **900** may use wavelength independent spacing of antenna elements to improve the angular resolution of a radar system without sacrificing the FOV while in further embodiments the angular resolution and FOV may be able to be tuned to specific use cases that e.g., need a narrower field of view and increased angular resolution in only a portion of the field, etc. In some embodiments this methodology can eliminate a dependency between angular resolution and unambiguous field of view constraints, which in conventional systems are both dependent on antenna spacings. The angular resolution enhancement can be a software dependent enhancement and can be carried out under spacing that is uniform, semi-uniform or nonlinear/nonuniform. The methodology can apply to MIMO or any other suitable type of radar systems. In further embodiments the transmit antennas can also, or alternatively, have elevation and/or azimuth wavelength independent spacings and the machine learning model can be trained to generate data from an emulated array of receive antennas having consistent and uniform $\lambda/2$ spacing in the elevation and azimuth dimensions. These and other features of radar systems having wavelength-independent antenna spacings will be described in more detail below.

[0101] As shown in FIG. **9**, radar system **900** includes a physical radar array **905** that may generate data that a processor may use to generate an optional virtual antenna array **920**. A neural network **910** may use data from the virtual antenna array **920** and/or the physical radar array **905** to generate data for an emulated antenna array **925** having an array of virtual receive antennas **920** (e.g., virtual receivers) uniformly spaced at a distance of $\lambda/2$. The radar system **900** may be or include any of the components, features, or characteristics of any of the radar systems previously described in the present disclosure.

[0102] The physical radar system **905** can include a plurality of physical transmit antennas **935**. Each of the physical transmit antennas **935** can transmit a respective signal having a wavelength of λ . The physical transmit antennas **935** can be spaced apart from each other forming a 1-dimensional, 2-dimensional or other suitable geometry array, as described in more detail below (see

e.g., FIG. 11). The physical radar system **905** can further include a plurality of physical receive antennas **940**. The number of physical receive antennas **940** in the physical radar system **905** may be the same as or may differ from the number of physical transmit antennas **935**. While two physical transmit antennas **935** and four physical receive antennas **940** are depicted in FIG. 9, the physical radar system **905** can include any suitable number of physical transmit antennas and receive antennas. Each physical receive antenna **940** can receive each of the respective signals transmitted from each of the physical transmit antennas **935**. The physical receive antennas **940** can be spaced apart from each adjacent physical receive antenna by a predetermined spacing, one of which may not be $\lambda/2$ (e.g., wavelength independent). This results the spacing between virtual antenna elements to not uniformly be $\lambda/2$ -based spacing. More specifically, in some embodiments the spacing between two adjacent virtual receive antennas may be for example $1.3\lambda/2$, $0.8\lambda/2$, λ , 0.6λ , 2λ , 5 millimeters etc., including non-integer values (e.g., a wavelength independent value). The spacing between one or more physical transmit antennas **935** may also or may alternatively not be $\lambda/2$ (e.g., may be wavelength independent). In some embodiments, at least two physical receive antennas **940** and/or at least two physical transmit antennas **935** can be spaced apart by a distance that can be a wavelength independent value.

[0103] Optionally, radar system **900** may employ a processor (e.g., processor **110** in FIG. 1A) to generate a virtual antenna array **920** that can be created from a combination of the physical transmit antennas **935** and the physical receive antennas **940**. When multiple transmit and receive antennas are co-located, they can act together to form what is commonly known as a virtual antenna array. The virtual antenna array **920** is not a set of physical antennas, rather it is a mathematically equivalent construct that describes the behavior of the antenna array.

[0104] The radar system **900** may employ digital signal processing to create the virtual antenna array **920** of virtual receive antennas from parameters of the physical transmit antennas **935** and the physical receive antennas **940**. The parameters can include which transmit antenna is transmitting, a timing and/or phase of such transmission, the transmit wavelength, a number of and geometric arrangement of the physical transmit antennas **935**, a number of and geometric arrangement of the physical receive antennas **940**, the size and shape of each antenna, etc. The geometric arrangement can include spacings between each adjacent antenna.

[0105] The virtual antenna array **920** includes a plurality of virtual antennas spaced apart at a defined distance “d” that is $\lambda/2$ and one or more missing virtual antennas (designated as “X”) may form “gaps” in the virtual antenna array **920**. The gaps may be any integer multiple of $\lambda/2$ where the integer is greater than one. Because of the gaps, the virtual antenna array **920** may not have uniform phase consistency. More specifically, the virtual antenna array **920** has e.g., sparsity, irregular or inconsistent spacing between virtual antennas. This may be due to one or more of the physical transmit **935** and/or physical receive **940** antennas having a spacing between adjacent antennas that is not $\lambda/2$. In some embodiments the radar system **900** may not generate data for the virtual antenna array **920** and may use data directly from the physical antennas to generate data for the emulated antenna array **925**.

[0106] Radar system **900** also includes a trained neural network **910**. The neural network **910** may be or include any of the aspects, features, or characteristics of any of the neural networks previously described in the present disclosure. For example, the trained neural network **910** may be trained by training data formed from process **600** described above.

[0107] The trained neural network **910** can use data generated for the virtual antenna array **920** to generate data for an emulated antenna array **925**. Optionally, the processor may not generate data for the virtual antenna array **920** and may directly generate the data for the emulated antenna array from the physical radar array **905**. The neural network may generate a complete set of emulated antennas with no gaps or sparsity, where a defined distance “d” between each antenna of the emulated antenna array is $\lambda/2$. More specifically, any gaps or missing antennas that result due to non- $\lambda/2$ spacing in the physical radar array **905** are accommodated for by the neural network which

generates data for a consistently spaced set of emulated antennas enabling angular calculations to be performed. The properties of the output data **930** depends on the training pattern applied to the neural network **910**. The $\lambda/2$ spacing of the antennas in the emulated virtual array **925** can enable a maximized FOV e.g., $\pm 90^\circ$ for the radar system **900**. The angular resolution and the unambiguous FOV of the uniformly spaced emulated antennas **925** may be enhanced in comparison to a FOV of the physical receive antennas **940** in the physical radar system **905**. While ten emulated antennas **925** are depicted in FIG. **9**, the array of uniformly spaced virtual antennas **920** can include any suitable number of virtual antennas. The number of virtual antennas **920** can be greater than, equal to, or less than the number of physical receive antennas **940** or physical transmitter antennas **935**. Additionally, the number of virtual antennas **920** can be greater than, equal to, or less than the multiplication of the number of physical receive antennas **940** and the number of physical transmit antennas **935**.

[0108] The output data **930** is produced from the uniformly spaced emulated antenna array **925**. The output data **930** can include static and/or dynamic data associated with target objects that are sensed by the physical radar system **905**. The static and/or dynamic data can include object's position, velocity, acceleration, etc. relative to an origin. The object can be either single or multiple having different locations, velocities, or shapes, etc. The origin can be a stationary point or a moving point, such as a fixed point on a moving vehicle that includes the physical radar system **905**. The output data **930** can correspond to data associated with the physical radar system **905**, such as data received by the physical receive antennas **940** and physical transmit antennas **935** of the physical radar system **905**. The uniformly spaced virtual receive antennas **920** can produce output data **930** consistent with an enhanced unambiguous field of view in comparison to the field of view of the virtual antennas **945** of the physical radar system **905**. The output data **930** can provide an angular resolution that is equivalent to or improved over the angular resolution of the virtual antennas **945**.

[0109] In further embodiments, radar system **900** may operate similar to radar system **100** in which all antennas of the physical radar system have $\lambda/2$ spacing but in which there may be one or more gaps between adjacent antennas that is an integer multiple of $\lambda/2$ (e.g., where the integer is 2 or greater), however as compared to radar system **100** in which the neural network filled in the missing antennas, in this embodiment the neural network generates data for an complete emulated array of antennas, all with $\lambda/2$ spacing.

[0110] As appreciated by one of ordinary skill in the art having the benefit of this disclosure, in some embodiments, when the field of view of the radar system is greater than or less than 180 degrees, the optimal spacing between each antenna of the emulated array **925** of antennas may be greater than or less than $\lambda/2$ and may be referred to more generally as a "predetermined distance". For example, in one embodiment a desired field of view of the emulated array **925** is 120 degrees and therefore the optimal predetermined spacing between each antenna of the emulated antenna array is $\lambda/3$. Therefore, some embodiments may generate, using a neural network, data for an emulated array of antennas having a predetermined distance between each antenna of the emulated array of antennas. In various embodiments the predetermined distance may be $\lambda/2$ while in other embodiments the predetermined distance may be greater or less than $\lambda/2$.

[0111] FIG. **10** illustrates a simplified diagram of a traditional physical radar system **1000**, according to embodiments of the disclosure. As shown in FIG. **10**, several performance parameters of a traditional physical radar system **1000** are based on the wavelength dependent spacing d of receive antennas (e.g., $\lambda/2$), whereas embodiments of the current disclosure are not so limited, as described in more detail below. The total number of virtual antennas in FIG. **10** is 2, which is calculated by multiplying 1 transmit with 2 receive antennas. Generally, a minimum of two virtual antennas is needed to facilitate angle processing.

[0112] Two common performance parameters of radar systems are angular resolution and FOV, both dependent on the virtual and physical antenna spacing. Angular resolution can be a minimum

angle between two different objects (ideally with same velocity and same range), in which the objects can be distinguished by a radar. Such angle resolution can be bounded by radar hardware and is traditionally dependent on a number of physical antennas used in the radar. A high radar resolution requirement traditionally leads to a larger size of hardware, additional circuitry, and increased costs. Further, traditional radar can suffer from poor angular resolution when designed under hardware constraints such as limiting the size of the receive antenna array. The FOV is the angular field that the radar can detect a target, e.g., $\pm 90^\circ$ and dependent on the spacing between antenna elements, but can be affected by ambiguity which happens at the edges of the FOV when traditional receive antennas are spaced apart at distances greater than $\lambda/2$. For traditional radar systems an optimal antenna spacing where phase ambiguity is minimal and field of view and angular resolution are maximized, is when each receiver is spaced apart from adjacent receivers by one-half of the radar wavelength, e.g., $\lambda/2$.

[0113] Under a conventional MIMO radar configuration, a target can be identified through several rounds of Discrete Fourier Transform (DFT) calculations, mostly for estimation of range, velocity, or angle. Under certain embodiments, they are commonly known as Fast Fourier Transform (FFT), velocity FFT, and angle FFT. Super resolution methods can use alternative techniques to populate angular information. Angle estimation can have a particular impact on accurate localization as the angle can be very sensitive to measurement inaccuracies about a location of the object. Even a small error in the angle estimation may cause a sizable estimation inaccuracy about the angle of the object.

[0114] Traditional radar systems typically design the physical receive antenna array based on the Nyquist criterion which requires a sampling rate to be at least twice the signal's maximum frequency to accurately sample a signal. In the context of Digital Signal Processing (DSP)-based angle processing for radar, the Nyquist criterion translates to spatial sampling in an antenna domain. In the angle domain, each virtual antenna element from a total of N elements, can act as a sample of data. An antenna spacing can be designed based on a maximum FOV requested at a time of radar design. By spacing antennas at approximately $\lambda/2$ intervals, the field of view of the radar will be widest at $\pm 90^\circ$ and the radar system can adequately sample the spatial domain, reducing spatial aliasing and mitigating phase ambiguities. The maximum field of view that can be serviced, an unambiguous zone for angle measurement, specifies the optimal antenna spacing by the criterion depicted in FIG. 10, subject to $d \sin \theta < \lambda/2$, yielding equation (1):

$$[00001] \theta_{\max} = \sin^{-1}(\frac{\lambda}{2d}) \quad (1)$$

where d is antenna spacing and $\theta_{\text{sub.max}}$ indicates an unambiguous field of view. Anything out of this FOV can create measurement ambiguity for the radar system. Antennas spaced at

$$[00002] d = \frac{\lambda}{2}$$

intervals maintain a widest FOV under a phase coherence across an array, which is $\pm 90^\circ$. Such coherence can be important for coherent signal processing in MIMO radar systems, enabling accurate target detection with adequate angular information. A development of traditional signal processing towards angular information relies on antenna spacing requirements. From equation (1), antenna spacing cannot be smaller than $\lambda/2$. Furthermore, an antenna spacing of greater than $\lambda/2$ will limit the FOV. The term “ $\lambda/2$ -based spacing” used in this invention, refers to the cases where equation (1) is applicable, even though the spacing may be $\lambda/2$ or greater.

[0115] Although a larger antenna spacing can result in a smaller FOV, the larger spacing can also result in improved detection precision. Note that radar angular resolution is dependent on the total number of virtual antenna elements and spacings between the elements. A larger antenna spacing d will result in improved angular resolution according to equation (2):

$$[00003] \theta_{\text{res}} = \frac{\lambda}{Nd \cos \theta} \quad (2)$$

where θ is an angle of detected object relative to the radar, making radar angular resolution dependent on angle, and varying from object to object. A larger spacing thus improves resolution

(smaller $\theta_{\text{sub.res}}$), but at an expense of limiting the FOV. For $\theta=0$ and $d=\lambda/2$, the angular resolution is $2/N$, as previously stated.

[0116] In contrast, some of the radar systems disclosed herein do not adhere to traditional $\lambda/2$ -based antenna spacing standards. For such systems, a FOV-dependent antenna spacing can be eliminated and equations (1) and (2) no longer apply. Antenna spacing in the radar systems disclosed herein can be smaller or larger than $\lambda/2$, without necessarily reducing the FOV. The antenna spacing can be independent of λ and cover a 180° FOV. An effective FOV for the radar systems may be independent of the antenna spacing. Some embodiments may have physical antennas that do not use $\lambda/2$ -based spacing and may have a FOV of less than 180° .

[0117] In some embodiments, an angle processing methodology based on a neural network enables the radar system to operate. The neural network can deliver enhanced radar imaging characterized by a different angular resolution than traditional DSP processing which is limited by the Nyquist criterion. A number of physical or virtual antennas and spacing between antennas can depend on the application, specific use cases, and a target performance of a neural network design, among other factors.

[0118] FIG. 11 is a simplified diagram of a physical radar system 1100 having non- $\lambda/2$ spacing between one or more physical transmit and/or one or more receive antennas, according to some aspects of the present disclosure. Radar system 1100 may be or include any of the components, features, or characteristics of any of the radar systems previously described in the present disclosure. More specifically, physical radar system 1100 may be used in radar system 100 or 900 to provide both azimuth and elevation data. As shown in FIG. 11, the radar system 1100 includes three physical transmit antennas 1105 where Tx1 1105a and Tx2 1105b are separated in a horizontal direction by d_5 and separated in a vertical direction by d_7 and where Tx2 1105b and Tx3 1105c are separated in the horizontal direction by d_6 and in the vertical direction by d_8 . In some embodiments at least one of distances d_1 - d_8 are not equal to $\lambda/2$ (e.g., may be a integer multiple of $\lambda/2$ where the integer is not 1) and/or may be wavelength independent (e.g., a non-integer multiple of $\lambda/2$). The third physical transmit antenna TxM 1105c indicates that the radar system can include M total physical transmit antennas. While M is three in FIG. 11, M can have any suitable value.

[0119] Additionally, the radar system 1100 depicted in FIG. 11 includes five physical receive antennas where Rx1 1110a is separated from Rx2 1110b by d_1 , Rx3 1110c separated from Rx2 1110b by d_2 and Rx4 1110d is separated from Rx3 1110c by d_3 . The fifth physical receive antenna RxN 1110e is separated from Rx4 1110d by d_4 and indicates that the radar system can include N total physical receive antennas. While N is five in FIG. 11, N can be any suitable value, including M. In some embodiments at least one of d_1 - d_4 are not equal to $\lambda/2$.

[0120] In some embodiments d_5 and d_6 are related to d_1 - d_4 . For example, in one embodiment d_1 - d_6 have similar distances, e.g., $1.2\lambda/2$. In another embodiment d_1 - d_8 have similar distances, e.g., $1.3\lambda/2$. In further embodiments only one of d_1 - d_8 may not be $\lambda/2$. These and other permutations are within the scope of this disclosure, some of which are described in more detail below.

[0121] In general, spacings between physical receive antennas 1110 of the radar system 1100 can be defined as $d_{\text{sub}.i}$ and spacings between the physical transmit antennas 1105 can be defined as $d_{\text{sub}.j}$. Each of the physical receive antenna spacings can be described by an expression

$$[00004] d_i = a_i(\tau),$$

whereas the physical transmit antenna spacing components can be defined in a similar manner:

$$[00005] d_k = b_k(\tau) \text{ and } d_j = b_j(\tau).$$

The transmit antenna spacing components can be horizontal components or vertical components. The horizontal components $d_{\text{sub}.k}$ can be useful for determining azimuthal angular data for an object, whereas the vertical components $d_{\text{sub}.j}$ can assist in determining elevation angular data. The radar system 1100 can include several types of arrangements, such as (note: this is not an exhaustive list of all permutations which are within the scope of this disclosure): [0122] Completely uniform wavelength independent spacing: (every nonzero $a_{\text{sub}.i}$ =every nonzero

b.sub.k=every nonzero b.sub.j, where a.sub.i, b.sub.k, b.sub.j are all non-integer values) [0123] Partially uniform wavelength independent spacing: (every nonzero a.sub.i=every other nonzero a.sub.i; where a.sub.i is a non-integer value OR every nonzero b.sub.k=every other nonzero b.sub.k; where b.sub.k is a non-integer value OR every nonzero b.sub.j=every other nonzero b.sub.j; where b.sub.j is a non-integer value) [0124] Completely irregular wavelength independent spacing: (every nonzero a.sub.i≠every other nonzero a.sub.i; where a.sub.i is a non-integer value AND every nonzero b.sub.k≠every other nonzero b.sub.k; where b.sub.k is a non-integer value AND every nonzero b.sub.j≠every other nonzero b.sub.j; where b.sub.j is a non-integer value) [0125] Partially irregular wavelength independent spacing: (every nonzero a.sub.i=every other nonzero a.sub.i; where a.sub.i is a non-integer value OR every nonzero b.sub.k=every other nonzero b.sub.k; where b.sub.k is a non-integer value OR every nonzero b.sub.j=every other nonzero b.sub.j; where b.sub.j is a non-integer value) [0126] Mostly wavelength dependent spacing: (only one a.sub.i is a non-integer value OR only one b.sub.k is a non-integer value OR only one b.sub.j is a non-integer value)

[0127] Each physical transmit antenna **1105** and receive antenna **1110** is connected to a processor **1120** that controls each antenna and may more specifically control the transmission operations of the transmit antennas and the received data from the receive antennas. The processor **1120** may be or include any of the components, features, or characteristics of any of the processors previously described in the present disclosure. Processor **1120** may be any suitable processing system including but not limited to a system on a chip (SOC), a local and/or remote computing system or a combination of computing systems. The processor **1120** can include a machine learning model. The machine learning model can receive data from and associated with the radar system **100** to produce a virtual array of receive antennas that can produce output that is consistent with an array of physical receive antennas all with $\lambda/2$ spacing.

[0128] FIG. **12** is a simplified system diagram **1200** of two example modes of an algorithm that can be used by processor **1120** in FIG. **11** to generate output data, according to some aspects of the present disclosure. The algorithm can be a trained machine learning model or neural network that may be or include any of the components, features, or characteristics of any of the machine learning models previously described in the present disclosure. The neural network can receive non-uniform, non-linear data from a physical radar system and generate either raw data or radar point cloud data.

[0129] The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. It will, however, be evident that various modifications and changes may be made thereunto without departing from the broader spirit and scope of the disclosure as set forth in the claims.

[0130] Other variations are within the spirit of the present disclosure. Thus, while the disclosed techniques are susceptible to various modifications and alternative constructions, certain illustrated embodiments thereof are shown in the drawings and have been described above in detail. It should be understood, however, that there is no intention to limit the disclosure to the specific form or forms disclosed, but on the contrary, the intention is to cover all modifications, alternative constructions and equivalents falling within the spirit and scope of the disclosure, as defined in the appended claims.

[0131] The use of the terms “a” and “an” and “the” and similar referents in the context of describing the disclosed embodiments (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms “comprising,” “having,” “including,” and “containing” are to be construed as open-ended terms (i.e., meaning “including, but not limited to,”) unless otherwise noted. The term “connected” is to be construed as partly or wholly contained within, attached to, or joined together, even if there is something intervening. The phrase “based on” should be understood to be open-ended, and not limiting in any way, and is intended to be interpreted or

otherwise read as “based at least in part on,” where appropriate. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., “such as”) provided herein, is intended merely to better illuminate embodiments of the disclosure and does not pose a limitation on the scope of the disclosure unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the disclosure.

[0132] Disjunctive language such as the phrase “at least one of X, Y, or Z,” unless specifically stated otherwise, is otherwise understood within the context as used in general to present that an item, term, etc., may be either X, Y, or Z, or any combination thereof (e.g., X, Y, and/or Z). Thus, such disjunctive language is not generally intended to, and should not, imply that certain embodiments require at least one of X, at least one of Y, or at least one of Z to each be present. Additionally, conjunctive language such as the phrase “at least one of X, Y, and Z,” unless specifically stated otherwise, should also be understood to mean X, Y, Z, or any combination thereof, including “X, Y, and/or Z.”

[0133] Preferred embodiments of this disclosure are described herein, including the best mode known to the inventors for carrying out the disclosure. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the disclosure to be practiced otherwise than as specifically described herein. Accordingly, this disclosure includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the disclosure unless otherwise indicated herein or otherwise clearly contradicted by context.

[0134] All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

Claims

1. A radar system comprising: a physical radar array comprising: a plurality of physical transmit antennas; and a plurality of physical receive antennas; and a neural network arranged to receive data from the physical radar array and generate data corresponding to an emulated array of antennas, wherein a defined distance between each antenna of the emulated array of antennas is equal.
2. The radar system of claim 1, wherein a defined distance between each antenna of the emulated array of antennas is $\lambda/2$.
3. The radar system of claim 1, wherein a distance between each physical receive antenna of the plurality of physical receive antennas is inconsistent.
4. The radar system of claim 1, further comprising a processor coupled to the physical radar array and arranged to generate data corresponding to a virtual antenna array, wherein the data received by the neural network includes the data corresponding to the virtual antenna array.
5. The radar system of claim 1, wherein the plurality of physical transmit antennas are arranged in both a horizontal direction and in a vertical direction.
6. The radar system of claim 1, wherein the generated data corresponding to the emulated array of antennas includes data for a two-dimensional emulated array of antennas.
7. The radar system of claim 1, wherein the neural network generates both horizontal and azimuth

data corresponding to the emulated array of antennas.

8. The radar system of claim 6, wherein a horizontal distance and an azimuth distance between each antenna of the emulated array of antennas is $\lambda/2$.

9. A radar system comprising: a physical antenna array comprising: a plurality of physical transmit antennas; and a plurality of physical receive antennas; and a processor coupled to the physical antenna array and arranged to: generate data for a virtual antenna array using data received from the physical antenna array; and generate, using a neural network, data for an emulated array of antennas, wherein the neural network uses the generated data for the virtual antenna array.

10. The radar system of claim 9, wherein the generated data for the virtual antenna array corresponds to virtual antennas having an inconsistent spacing between adjacent antennas.

11. The radar system of claim 9, wherein a defined distance between each antenna of the emulated array of antennas is equal.

12. The radar system of claim 9, wherein a defined distance between each antenna of the emulated array of antennas is $\lambda/2$.

13. The radar system of claim 9, wherein a distance between each physical receive antenna of the plurality of physical receive antennas is inconsistent.

14. The radar system of claim 9, wherein the plurality of physical transmit antennas are arranged in both a horizontal direction and in a vertical direction.

15. The radar system of claim 9 wherein the generated data for the emulated array of antennas includes data for a two-dimensional emulated array of antennas.

16. The radar system of claim 9, wherein the neural network generates both horizontal and azimuth data for the emulated array of antennas.

17. The radar system of claim 16, wherein a horizontal distance and an azimuth distance between each adjacent antenna of the emulated array of antennas is $\lambda/2$.

18. A method of operating a radar system, the method comprising: generating first data from a physical antenna array, wherein the physical antenna array comprises: a plurality of physical transmit antennas; and a plurality of physical receive antennas; and generating, using a neural network, second data for an emulated array of antennas wherein the neural network uses the first data.

19. The radar system of claim 18, wherein a defined distance between each antenna of the emulated array of antennas is equal.

20. The radar system of claim 18, wherein the neural network generates both horizontal and azimuth data for the emulated array of antennas.
