Displaced Radar Imaging System with Multiple Asynchronous Radar Sensors

Detailed description of each component of the invention and how the invention works to achieve the advantages over the existing technology.

This invention solved the problem of improving the automotive radar imaging quality by making use of multiple asynchronous individual radars mounted on different part of the same vehicle. Particularly, the problems of synchronization and distributed aperture imaging are solved though first a non-coherent imaging system in the raw data domain and second a coherent imaging system with automatic synchronization.

Due to the constraints on the bandwidth, radar image frame rate and radar form factor, the resolution of real aperture automotive radar imaging is limited in range, angle and Doppler frequency. This makes it difficult to achieve high resolution radar images with the conventional automotive radars. Although there are approaches to achieving enhanced radar imaging by using distributed MIMO radar configuration, those methods do not exploit the benefit of the existing automotive radar and requires supporting systems for synchronization between those separated transmitters and receivers. This invention, instead, designs the improved distributed radar imaging system based on the existing automotive radars. In this invention, different from a conventional distributed MIMO radar, the automotive displaced radar sensors operate independently and are only coarsely time synchronized through use of standards such as IEEE 1588 generic precision time protocol (gPTP). Each radar being independent, our received signal depends only on the local timing of each sensor thereby circumventing the need of fine time-synchronization within each sensor. We also assume that the vehicle manufacturing and radar mounting can be controlled with high position accuracy, which is much smaller than range resolution cell. Thus, the impact of the error of radar position on imaging is ignored in this invention. Hence, the error we are considering in this invention is due to the synchronization between radar sensors.

1) Figure-1: Distributed radar system on vehicle
   Figure-1 illustrated the distributed radar system on a vehicle 001, which consists of multiple individual radars 002 located at different positions on the vehicle. Those individual radars form the distributed radar system 003. The distributed radar systems might take different forms as compared to the one illustrated. For example, it may consist more individual radar sets that are mounted on the vehicle on different places in different configuration.
2) Figure-2: System diagram of individual radar system
   The individual radar system 002 has a waveform generator 200 that generates waveforms such as continuous waveforms and pulse radar waveforms. Meanwhile, waveforms generated for different transmitters are orthogonal to each other to exploit the benefit of MIMO radar and its versions. The orthogonality can be achieved in many ways such as time division multiplexing (TDM), and code division multiplexing (CDM). Our patent is not confined to the specific use of the type of orthogonal waveforms. The waveform undergoes the transmitter circuit 202 before being transmitted from transmit antenna array 204. In the MIMO radar operation, each transmit antenna transmits its own waveform that is orthogonal to the waveforms transmitted by other transmitters. After being reflected from target, the radar signals are

received at the receive antenna array 206 that is connected to the receiver circuit 208. Each receive antenna array receives a combination of echo signals due to the transmitted signals of all the transmitters. After that, receiver baseband 210 converts the analog radar signal into digital domain for signal processing. The radar system is controlled by a Radar Control, Storage and Processing unit 212 that performs signal processing to fulfil the radar functionalities such as range processing, Doppler processing, DOA estimation, detection, and even advanced perception based on data processing. The radar system 002 may be connected to other devices or sensor network control & central processing unit 320 so that the radar information generated can be applied to advanced functions. In this patent, the enhanced imaging function is conducted at the central processing unit 320.

3) Figure-3: Distributed radar system
The distributed radar system 003 consists of multiple individual radar 002. Those individual radars 002 are connected to Sensor Network Control & Central Processing Unit 320. The Sensor Network Control & Central Processing Unit 320 has the following functions. First, it provides the coordination among the individual radars 002 in the same distributed radar system. The coordination may include but is not limited to such functions as synchronization through the networking synchronization protocol, radar waveform and system configuration for operation in different situations. Second, it provides information from other driving sensors 360 and motion sensors 340 to radar systems. Motion sensors 340 may include IMU, GPS, etc. while other driving sensors 360 may include camera, Lidar and ultra-sound devices. The information may include but is not limited to the motion information of car such as its velocity, orientation, position, the information about the environment such as the image and position of targets and infrastructures. Third, it carries out the central processing that depends on different radars and sensors. For example, the improved non-coherent and coherent imaging is based in the central processing unit of 320. Fourth, it takes the outputs from each individual radar and other sensors for advanced processing and applications. For example, it can make use of the radar sensing outputs and outputs from Lidar and cameras to assist automotive driving functions. In this invention, the distributed radar imaging system carries out the improved imaginary recovery at the central processing unit of 320 by making use of data from multiple individual radar 002. Last it interfaces with the advanced driving assistance systems (ADAS) and other applications 380 to coordinate between the driving and the sensor functioning.

4) Figure-4: Distributed radar imaging system diagram
The distributed radar imaging system 004 consists of multiple of individual radars 002. On the same vehicle, there may be multiple of distributed radar imaging systems 004, each of which may consist of different set of individual radars. Each distributed radar imaging system is a subsystem of the distributed radar system 003. For illustration, we consider the distributed radar imaging system 004 consists of Radar-1, Radar-2, and Radar-K_1. Those radars are coordinated through the function of radar coordination 410 which is realized in the Sensor Network Control & Central Processing Unit 320. The multiple distributed radars need to be roughly synchronized in time and the waveform configuration needs to be coordinated so that each radar can work independently while not interfering with other radar units. The radar imaging processing system 420 processes the data from each radar of the distributed radar imaging system 004 to generate enhanced radar imaginary with the aid of motion information 430 obtained from motion sensor 340. The radar imaging processing system 420 is realized in the Central Processing Unit of system 340. The output of radar imaging processing is the enhanced radar image that is sent to ADAS for driving applications 380.

5) Figure-5: Distributed radar imaging processing system
The imaging processing system 005 takes the raw data 510 of individual radar 002, which undergoes the preprocessing 520 before non-coherent imaging 530. The preprocessing 520 may include those processing like filtering, and down sampling. Non-coherent imaging 530 takes both the radar raw data and the information from motion sensor to recover the enhanced image of interested area in the radar field of view (FOV). If improved resolution 540 is wanted after non-coherent imaging, then the system goes for the coherent imaging 550.
6) Figure-6: Non-coherent imaging processing system
The non-coherent imaging processing system 006 conducts non-coherent imaging function by making use of the raw data collected from the distributed radars. The imaging system employs compressive sensing approach that exploits sparsity in the environment. Firstly, based on the radar configuration 630 and vehicle motion information 640, the dictionary generation 650 is conducted and the dictionary is latter used by compressive sensing imaging algorithm. Raw data 610, after preprocessing 620 is processed by image recovery algorithm 660 that produces enhanced image of higher accuracy. The image recovery algorithm is sparsity-driven and in the framework of compressive sensing. Candidate algorithms like L1-Norm and Orthogonal matching pursuit can be used. The key in this invention is the formulation of the block sparsity recovery problem for the imaging. The formulation is given as follows.
We consider a distributed radar imaging system consisting of Q individual radars that are roughly synchronization in the frame level. The synchronization error at the *q*-th radar with respect to the first radar set is σ_q, which is zero for the first radar set itself and less than the time duration of one frame. That means that the operation of individual radar is aligned within the same frame time. Each radar is a frequency modulated continuous wave (FMCW) radar that has *N* transmitters and *M* receivers. The position the *q*-th radar is denoted by $\boldsymbol{p}_{T,n}^{q}$ for its *n*-th transmit antenna and $\boldsymbol{p}_{R,m}^{q}$for its *m*-th receive antenna, respectively. The radars are moving at a velocity of $\boldsymbol{v}$ on the vehicle. The Doppler velocity of the target at the *q*-th radar is thus $v_q = v^H \boldsymbol{p}_{t,q}$, where $\boldsymbol{p}_{t,q}$ is the direction vector between the target and the *q*-th radar, defined as

$$\boldsymbol{p}_{t,q} = (\boldsymbol{p}_t - \boldsymbol{p}_{T,1}^{q})/\|\boldsymbol{p}_t - \boldsymbol{p}_{T,1}^{q}\| \quad (1)$$

Each transmitter transmits at center frequency of f_c^q *K* pulses of pulse repetition interval of T_r and the waveform bandwidth and duration as well as the sampling frequency are properly configured that results into frequency modulation rate of B_r and *Ns* samples per pulse. Consider a target located at $\boldsymbol{p}_t$ with reflection coefficient of α, the received signal at the *m*-th receiver of the *q*-the radar due to the *l*-th sample in the *k*-th pulse from the *n*-th transmitter of the same radar is given by:

$$y_{qmnkl} = \alpha_q e^{-\frac{j2\pi f_c^q g_{qmn}}{c}} e^{-j2\pi\left(\frac{2f_c^q v_q}{c}+\frac{B_r g_{qmn}}{c}\right)lT_s} e^{-\frac{j2\pi 2 f_c^q v_q T_r}{c}(n-1+(k-1)N)} \quad (2)$$

where $\alpha_q = \alpha c_q$, and $c_q = e^{-\frac{j2\pi f_c^q 2v_q}{c}\sigma_q}$, g_{qmn} is the bistatic range defined as:

$$g_{qmn} = \|p_t - p_{T,n}^{q}\| + \|p_t - p_{R,m}^{q}\| \quad (3)$$

We denote $h(\boldsymbol{p}_t) = [h_{11111}, \cdots, h_{QMNKL}]$, with h_{qmnkl} defined as

$$h_{qmnkl} = e^{-\frac{j2\pi f_c^q g_{qmn}}{c}} e^{-j2\pi\left(\frac{2f_c^q v_q}{c}+\frac{B_r g_{qmn}}{c}\right)lT_s} e^{-\frac{j2\pi 2 f_c^q v_q T_r}{c}(n-1+(k-1)N)} \quad (4)$$

Defining $\boldsymbol{\alpha} = [\alpha_1; \cdots; \alpha_Q]$, then the signal received at all the radars can be written as:

$$\boldsymbol{y}_{nc} = (\boldsymbol{\alpha} \otimes I_{MNKL\times 1}) \odot \boldsymbol{h}(\boldsymbol{p}_t) \quad (5)$$

We can rewrite (5) as:

$$\boldsymbol{y}_{nc} = vec\{[\boldsymbol{h}_1(\boldsymbol{p}_t), \cdots, \boldsymbol{h}_Q(\boldsymbol{p}_t)]\mathbf{A}\} = (\mathbf{I}_Q \otimes \mathbf{H})vec\{\mathbf{A}\} \quad (6)$$
$$= (\mathbf{I}_Q \otimes \mathbf{H})\mathbf{S}\boldsymbol{\alpha} = \mathbf{H_s}(\boldsymbol{p_t})\boldsymbol{\alpha}$$

where $\boldsymbol{I}_Q$ is the identity matrix of dimension Q, $\boldsymbol{h}_q(\boldsymbol{p}_t)$ is the vector containing the rows corresponding to the q-th radar in $\boldsymbol{h}(\boldsymbol{p}_t)$, $\mathbf{S}$ is the selection matrix that makes $vec\{\mathbf{A}\} = \mathbf{S}\boldsymbol{\alpha}$ with $vec\{\mathbf{M}\}$ standing for the operation of stacking the column of $\mathbf{M}$ into a single column vector, and $\mathbf{H} = [\boldsymbol{h}_1(\boldsymbol{p}_t), \cdots, \boldsymbol{h}_Q(\boldsymbol{p}_t)]$.

Suppose that the field of view of interest can be divided into multiple set of $\Phi_{\mathrm{p}} = [x_p, y_p], p = 1, \cdots, P$, and the position of the target reside on one particular $\Phi_{\mathrm{p_t}}$, then the signal model can be written in the compressive sensing framework as:

$$\boldsymbol{y}_{nc} = [\mathbf{H}_s(\Phi_1), \cdots, \mathbf{H}_s(\Phi_P)]\boldsymbol{b}=\mathbf{B}\mathbf{b} \quad (7)$$

where $\mathbf{B}$ is the basis matrix or dictionary matrix, and $\mathbf{b}$ contains the reflection coefficient of targets. In particular, $\boldsymbol{b}$=[$\boldsymbol{b}_1$;…;$\boldsymbol{b}_P$] is block-wise sparse vector with $\boldsymbol{b}_p$=0 if there is no target at Φ_p. With (7), the non-coherent imaging is formulated as a block-sparsity recovery problem that can be solved by compressive sensing algorithms such as OMP.

In order to reduce the complexity, (7) can be modified further to the following form:

$$\boldsymbol{r}_{nc} = \mathbf{G}\boldsymbol{y}_{nc} = \mathbf{G}\mathbf{B}\boldsymbol{b} = \mathbf{F}\boldsymbol{b} \quad (8)$$

where the measurement matrix $\mathbf{G}$ is used to compress the measurement of $\boldsymbol{y}_{\mathrm{nc}}$ into a smaller set of samples. Measurement matrix can be chosen as Gaussian random matrix or random matrix of Bernoulli distribution. The compressive sensing algorithm can be applied to (8) to recover the image. With the formulation of (8) significant complexity reduction can be achieved. For example, the dimension of $\boldsymbol{r}_{\mathrm{nc}}$ can be only 10% of that of $\boldsymbol{y}_{\mathrm{nc}}$. In Figure-9, we show the superiority of the proposed method, i.e., block sparsity image recovery on a distributed system of 3 radars. We provide as comparison the imaging result of only one sensor.

7) Figure-7: Coherent imaging processing system

The coherent imaging processing system 007 is built on top of the non-coherent imaging system. The coherent image system performs automatic synchronization 740 on non-coherent image 730. The automatic synchronization 740 estimates the time synchronization error between the different radar sets. With the synchronization information estimation, dictionary generation 770 is performed with radar configuration 750 and motion information 760. In this case the signal model for the same target used in the non-coherent imaging formulation is written as:

$$\boldsymbol{y}_c = \alpha(\boldsymbol{c_q} \otimes I_{MNKL\times 1}) \odot \boldsymbol{h}(\boldsymbol{p}_t) = \alpha\boldsymbol{h}^c(\boldsymbol{p}_t) \quad (9)$$

where $\boldsymbol{c}_q = [c_1; \cdots; c_Q]$,. From the noncoherent image, after the automatic synchronization, the time synchronization estimates are used to generate the dictionary in the following form

$$\boldsymbol{y}_c = [\boldsymbol{h}^c(\Phi_1), \cdots, \boldsymbol{h}^c(\Phi_P)]\boldsymbol{b_c} = \mathbf{B}_c\boldsymbol{b_c} \quad (10)$$

From (10) coherent imaging can be carried out using compressive sensing method. In particular, the coherent image recovery algorithm 780 processes the radar raw data 710 after preprocessing 720 to generate the enhanced image. The coherent image recovery algorithm takes the form of compressive processing methods such as L1-Norm and OMP. Figure-10 demonstrates the improved performance of the coherent imaging as compared to the non-coherent imaging in the case of multiple closely spaced scatters.

8) Figure-8: Automatic synchronization

The automatic synchronization starts with choosing the strongest target 830 from the noncoherent image 810. Then target coefficient estimates 850 at all individual radars are obtained. In particular, those estimates can be written in the following form:

$$\hat{\alpha}_q = \alpha c_q \tag{11}$$

Thus, comparing the phase of target coefficient estimate from the q-th radar with respect to the 1st radar will reveal the synchronization error. Multiple strong targets can be used to improve the synchronization accuracy based on the method designed above.

Claims

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

1. A distributed radar system, comprising:
    a. Multiple asynchronous radar sensors
    b. Other sensors such as motion sensor and other imaging sensor such as Lidar and camera
    c. A sensor network and control unit that process all the data and information from all the sensors to provide information for driving applications
    d. Processing methods, in particular, an imaging method by using all the data from the distribute radar sensors
2. The method of claim 1, wherein a distributed radar imaging system consisting of:
    a) multiple radar sensors;
    b) a radar coordination components and ego car motion sensor
    c) imaging methods
3. The method of claim 2, wherein
    a) each radar sensor is capable of working independently and is preferably of FMCW MIMO radar configuration although other radar mode can also be applicable;
    b) each radar sensor has its own transmitter and receiver well synchronized;
    c) All the radar sensors are asynchronous with time offset smaller than the frame period;
4. The method of claim 2, wherein:
    a) the signal model at each receiver is defined in (1);
    b) the signal model for all the receivers from all the radars is defined as (5);
5. The method of claim 2, wherein an imaging method based on the multiple asynchronous radar sensors are designed including a noncoherent imaging method and a coherent imaging method;
6. The method of claim 4, a noncoherent imaging method based on the data is formulated in (7) as a block-wise sparse signal recovery problem;
7. The method of claim 5, wherein the noncoherent imaging method consists of :
    a) dictionary generation based on radar system configuration and car motion information
    b) preprocessing such as compressive sampling of the radar data from all the radar sensors
    c) image recovery based on the sparsity-exploitation method
8. The method of claim 7, wherein the sparse signal recovery problem is solved through compressive sensing, as indicated in (8) although other method can be applied to solve this problem.
9. The method of claim 5, wherein a coherent imaging system by exploiting the radar configuration and array configuration, as well as the synchronization;
10. The method of claim 9, wherein the coherent imaging is expressed in (10) and solved by compressive sensing method.
11. The method of claim 7, the synchronization is conducted from the noncoherent image by phase comparison as illustrated in (11).