Novel Synthetic Phased-Array Antenna Systems for Wide-view Concertos Platforms

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Abstract—Active Synthetic Phased-Array Antenna Sensors will significantly enhance the RF performance for various synchronized platforms. It is built on the idea of systematically integrating and interfacing Phased-Array Antenna manifolds to retrieve various sensor information. This approach essentially overcomes the inflexibility of employing passive stand-alone single-aperture phased-array sensor as its performance degrades from systems eclipse due to its scan limit. It is a form of concerted RF sensors, designed to provide extended coverage i.e. wide field of view to compensate for the performance loss suffered from using the passive singly-aperture phased-array RF sensors. The design for these sensors is flexible that they can be reconfigured easily for broad range of RF applications. In addition, these sensors can be integrated on various moving and/or stationary platforms with state of the art computing capability coupled with interface connectivity to improve the survivability and reliability of the RF sensors. These systems are especially adaptable to mobile structures such as robotics and the like for modern RF radar, communication and remote sensing operating at extreme weather condition.

Keywords—Reconfigurable and survivable sensor systems; Cost effective and reliable phased array

I. Introduction

Great interests generated in the field of all weather-proof RF systems to deal with ever-increasing performance requirements imposed on wireless communication and multi-purpose radar systems. There are numerous ideas developed to achieve high RF performance for sensors mounted on mobile platforms. The present work is built on previous study on Integrated inter-and intra connected Collaborated Aperture Radar System (i3CARS) [1]. The merit of the new design is that it is capable of elegantly treating wide and diversified wide-field-of-view RF signals; this would result in significant improvement in RF gain budget. Because of the spatial separation of these sensors, also these sensors are in general incoherent and dispersive; therefore the synchronization of these sensors for synthetic phased-array operation can be primary design challenge to deal with. With the advancement of modern digital signal processing technology, rapid software and material science research, the synchronized synthetic phased array are starting to bloom in various types of sensors other than RF field; i.e. non-invasive ultra-sound probes for medical applications and others [2].

II. Description of the Design Concept

A general account of the phased-array antenna beam steering systems is summarized in [3]. The design principle of the synthetic phased array antenna for different generic wide field-of-view platforms i.e. UAV, robotic mobile platforms and the others is described as shown in Fig. 1.

![Fig.1 Different generic wide-view Concertos Platforms where RF signals can be combined coherently to achieve optimal results](image)

Essentially it is a “super-resolution” high-speed beam switching/scanning network manifold to multiplexing transmit/receive signals. The operation may be easily unfolded in terms of a prototype unit where the transmitter and the receiver will be coherently combined for achieving the optimal performance for RF wireless communication and all-purpose radar imaging and sensing application.

In addition, these sensors can be integrated on various moving and/or stationary platforms with state of the art computing capability coupled with interface connectivity to improve the survivability and reliability of the RF sensors. These systems are especially adaptable to mobile structures such as robotics.
and the like for high-performance RF radar and communication capability. Furthermore, these novel phased array systems can be employed to allow long-distance interferometers to obtain super-resolution RF image in the baseline defined plane. These RF images can be generated by using wireless stations (multiple transmitter/receiver sets) for signal reconstruction through a system of highly collaborated networks. Very importantly, the development of digital orthogonal waveforms provides an momentum for the system to achieve an optimal channel capacity at the expanse and the cost of frequency spectrum re-use and others. Software radio technology [4] is now readily available, because of the rapid improvement since the end of last century in high-speed signal processors.

### III. DESIGN CONSIDERATION AND DISCUSSION

Typical two-dimensional beam scanning characteristics without structure coupling are available in open literature [3, 5] for singly aperture phased-array as shown in Fig. 2.

Multi-platform synthetic phased array systems can therefore be employed to circumvent the undesirable side-lobe degradation and the associated scan losses caused by the singly aperture phased-array (referred to Fig.2). The enhanced performance of the systems can be further achieved by precision field calibration and measurement to take into account the platform interference and other perturbation. Beam steering modules can be designed to incorporate both the strip-mode and spot-mode of operation to meet the necessary mission requirement. Over-head cost function of the spot-mode is more expensive but yields far more better resolution. The system is reconfigurable and therefore cost effective.

SAR raw maps of geo-terrain and location of general interest may be combined from two near-by CARS placed and mounted securely on the UAVs (assuming two totally different and distinct routes of flight). The resulting raw image can be brought to sharp-focus by coherent summation of the raw images with appropriate processing skills. Fig.3 illustrates the robustness of the new technique of Synthetic Phased-Array applied for wide-view Concertos Platforms.

### IV. IMPLEMENTATION METHODOLOGY & CONSIDERATION

**ACTIVE PHASED-ARRAY ANTENNA DESIGN**

The use of Electronic-Steer-Array (phased array) for the traditionally old-fashioned RF-based antenna makes it convenient to re-align and boost up its scan-volume. This widens its applications substantially, and pushes for higher RF performance edges.

One may start from a short account on this innovative transportable and re-configurable millimeter wave scanning/imaging radar designed for wide-view landscape imaging and continue the discussion to highlight on its potential application to modern MSAR/MSAL(Multi-Purpose-Synthetic-Aperture-Radar/Lidar) sensors.

The design principle and special features for Holographic Phased-Array Antenna Systems are described in Fig. 4. Essentially, it is a mechanically scanned device equipped with electronic radar switching beams. The theory of the operations are very plain and simple. The phased-array antenna acts as a smart sensing device with returning signal highly convoluted electromagnetically. The scanner electronically rotates to one side, where a single reflective object is targeted. When the target comes within the range, its return path will be much...
longer and brings in a longer phase delay. This reaches a minimum as the scanner is directly above the target and increases more thereafter. It is near-field in nature for the 3-D wide-view landscape imaging scanner, the holographic image algorithm (3-D image reconstruction) will bring all these dispersive data to a focus point at the location of the reflective object. These highly non-coherent returns appear as the well-known “range walk” phenomena [6, 7]. In the same way, the Holography-based Phased-Array Antenna Imaging Systems may be easily employed in other platforms (e.g. air-borne platforms) for advanced MSAR (Multi-purpose Synthetic Aperture Radar).

In Fig. 4 the Holographic Phased Array Antenna is described. (Note that it is a Sub-array Approach – the primary drive is ease in implementation and particularly convenient for later stage fast problem diagnosis and failure detection and the sequent panel replacement.)

With proper digital signal processing techniques [8], the quality images of the wide-view landscape may be obtained. The processing essentially involves different kind of noise removal techniques as described in Fig.5. In addition, various other modern signal enhancement filtering techniques can be applied for the image retrieval e.g. the edge detection filter and motion compensation filter can be employed to facilitate target tracking and identification. Signal processing is a key for transforming the raw pixel images to fine graphical display.

The applications are not radar spectral limited, same principle may be adapted for Lidar (for Light Detection and Ranging), which uses concertos lasers to scan a wide-view geo-area, including concealed terrain. Placed on a flying plane and/or UAV, the laser continually sending signals toward the geo-terrain beneath, such that a large number penetrates via the wide-view scope of area even between the concealed/natural or man-made obstacles, and reflected back with high-fidelity to the transmitter/receiver unit with all the relevant information (signal and noise included). High-tech and high-speed signal processors then are employed to analyzing the Lidar returns to retrieve the data for 3-D images development and further synthesis and analyses. In essence, this can be extended to multi-spectral imaging to fuse/combining all-spectrum data for proper analyses and further manipulation.

![Fig. 4 Holographic Active Phased Array Antenna](image)

![Fig. 5 Typical noise removal filtering techniques](image)

**V. THEORETICAL BACKGROUND**

A short note of the Analytical development work will make it easier for the readers to understand the theory involved. To start with, we need a valid linear model to circumvent the difficulty in extending the conventional locally plane-waves approach to the problem. So far, no non-linear model had been attempted. We tried a compromise by introducing spherical waves to generalize the wave phenomena of the signals for the receivers and the transmitters to satisfy both the near-field and far-field propagation boundary conditions. Of course, the application of the principal of superposition will be used through-out the syntheses of the solution for multiple robotics data manipulation. All the other residue factors can be attributed to the statistical noise where SNR (signal-to-noise) will be of primary interest and Gaussian noise terms are dealt accordingly within the discipline of radio and wireless communications. Truly non-linear solutions are not yet available for the time being and hopeful one day can be unfolded for the wireless radar/antenna sensor applications.
Basic equations to reconstruct 3-D image from a 2-D aperture

If \( S(X,Y,\omega) \) is the receiver response at discrete frequency \( \omega \) due to a reflectivity function of the target \( G(X,Y,Z) \) and assume that \( G(X,Y,Z) \) at \( X,Y,Z \) in object space is the best estimate existed, then it may be reconstructed as a 3-D image by taking Inverse Fourier transform as follows:

\[
G(X,Y,Z) = \left\{ \text{FT}_3 \right\}^{-1} \left[ \text{FT}_2 \{ S(X,Y,\omega) \} \exp\left(-\frac{4\pi^2k^2}{2\omega} X^2 + Y^2\right) \right]^{1/2} \quad (1)
\]

Note: for FT(Fourier Transform), \( X,Y,\omega \) are at discrete samples and where \( f \) is the swept between the designated operating frequency bandwidth \( B \) from \( f - B/2 \) to \( f + B/2 \).

This technology is based on unfocused (diverging) beam imagery, and all focusing is done numerically using synthetic aperture/(holographic)techniques. The process can be illustrated for graphical representation as shown in Fig 6 and Fig 7. Particularly Fig 7 is very important for the understanding of the reasoning where super-resolution can be guaranteed when proper and correct retrieval techniques are applied. This involves very good estimation of the initial boundary conditions, different noise parameters can also be applied to simulate the real scenario of the extreme weather condition involved. Therefore, statistical parameters of the radio propagation factors are very important for the accurate retrieval of the signals intended. Different non-linear filtering techniques can be applied. This explains also why active phased array systems are preferred. Manifold data structures can be readily obtained, because multiple beams can be utilized to capture more information data that can be overlooked and skipped by the passive sensor aperture. The cheap version of passive phased array just cannot do the job no matter how large the aperture can be deployed. Bigger the passive sensor aperture just a waste of resources for diminishing returns. This is a very important lesson to learn from the past space programs. A heavily concentration on the streamlined design philosophy particularly the system interface architecture may not be the real answer to the diminishing returns of the quality target images.

A real understanding of the physics involved is a very important resource for the sensor-systems-engineers who bear the responsibility of the success of the sensor mission.

VI. 2D AND 3D “HJ INVERSE IMAGE FILTER” DESIGN

For simplicity 2D case is elaborated.

2D case- discrete frequency

\[
s(x, y) = \text{out-of-focus - measured data} \quad (2)
\]

\[
f(x, y) = \text{in-focus image – original image} \quad (3)
\]

\[
h(x, y) = \text{point-spread defocusing function} \quad (4)
\]

\[
n(x, y) = \text{Gaussian white noise} \quad (5)
\]

They are related by

\[
s(x, y) = f(x, y) * h(x, y) + n(x, y) \quad (6)
\]

where \((x, y)\) is the coordinate in image space.

Assuming that \( h(x, y) * g(x, y) \approx 1 \),

Then

\[
f(x,y) = [s(x,y)-n(x,y)] * g(x,y) \quad (7)
\]

g\((x,y)\) can be approximated by a two-dimensional Gaussian function given by

\[
\frac{1}{(2\pi\sigma^2)} \exp\left[-\frac{(x^2 + y^2)}{(2\sigma^2)}\right] \quad (8)
\]

where \(\sigma\) is the shaping parameter.

Note that the asterisk is the convolution operator. Eqt (8) can be extended to other form where effects due to quadratic phase correction can be incorporated.

Eqt. (7) is the recipe for the innovative “HJ inverse filter” that can be applied to retrieve the image data at high speed i.e. taking the image raw data at different orientations as a first step and then perform a data fusion procedure to bypass regular back & forth FFTs (Fast FOURIER TRANSFORMS).

There is a trade-off between the accuracy and the time factor involved, This gives quick turn-out of the image data for
initial assessment of the image data to determine if the retrieved data is useful or not, merely for quick examination. The irrelevant data can be sorted out easily. It is a time saving filter that bypassing the conventional iterations of FFT transformation (forward and backward).

**EXAMPLE 1 : HJ INVERSE FILTER ON DISCRETE FREQUENCY**

Refer to Fig 8: Computer Simulation (standard graphic display mode) for fast image output by data fusion using HJ filter

Remark: Results generated from superposed filtered output (combined images from different available orientations)

![M-47 Tanks](image)

**FIG 8 DATA FUSION AT DISCRETE FREQUENCIES FOR DIFFERENT ORIENTATION: BYPASS BACK & FORTH FFTS**

Example 2: Moving Target identification routines
More sophisticated data processing involved:
Clutter removals and motion compensations

![Complex Target Detection/Classification](image)

**VII. REMARKS**

Hubble Space Telescope (HST), first conceived in 70’s, subsequently developed in 80’s and 90’s, and plateaued in early 2010’s, serves as a fore runner for the envisioned synthetic phased-array technology on synchronized robotics-like platform.

Pertinent information on the HST technology and its fascinating development history can be surveyed through open literature and NASA website on HST.

HST, comprised of hybrid sensors on its focal plane, is a low altitude orbiting/moving (exo-atmosphere) system to make up for the multi-beaming deficiency.

Though, HST a receive-only passive (strip-mode) imaging system, its systems performance in terms of wide instantaneous field-of view, sequential imaging capability, and rapid area-of-interest update rate is exceedingly good.

In hind-sight, the imaging systems of HST could have been adapted to the radio-frequency by augmenting a state-of-art RF receive beam-former to the CCD (Charge-coupled device) for parallel RF signal processing in a time-sharing synchronized fashion.

It is highly recommended future space mission should consider employing active phased array aperture for enhanced performance i.e. better resolution and more efficient data processing routines to combat with more stringing design restriction on the mission payload.

**VIII. CONCLUSION**

To circumvent the problems encountered by the conventional sequential imaging- single aperture radar/antenna, a new active phased- array mounted on multiple mobile sensor platform for wide-view application is proposed. Its design philosophy, operation condition and capability are detailed.

Merely increasing the aperture size of the passive array can never match up with the active phased-array for Wide-view Concertos Platforms.

Coupled the advancement in modern digital imaging filtering breakthrough and platform improvement via material science research, this active phased-array can be deployed for various sensor mission for extreme operating condition endo- & exo-atmospheric robotics exercises.

High resolution 3D manifold data structures can be readily obtained, because multiple beams of the active phased-array can be utilized to capture more information than that of the conventional passive counterpart.

The Integrated connected Collaborated Aperture Radar System on wide-view concertos platforms, will boost RF performance of wireless communication systems and radar sensors (Fig 10)
This innovative technique of phased array mounted on moving platform with super-speed computing soft-wares and stream-lined system interfacing architecture, is especially suitable to robotics generics such as UAVs and other similar platforms for advanced RF communication applications and multi-function radar imaging and target classification.

Novel Synthetic Phased-Array Antenna Systems for Wide-view Concertos Platforms may be implemented with well coordinating system interface routines.

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