IJIREEICE

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

nCORETech

LBS College of Engineering, Kasaragod

Vol. 3, Special Issue 1, February 2016

A Review of Advances in Synthetic Aperture Sonar Imaging Algorithms

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Abstract: Synthetic aperture techniques use coherent addition over many pings to create an aperture whose extent can be increased with range to maintain a constant along-track resolution. This paper is a review, dealing the past works in, and the recent status of, active Synthetic Aperture Sonar (SAS), covering the early developments in SAS. By constructing the SAS, it can eliminate the huge hardware requirement. A new image recovery method is proposed using the compressive sensing. The proposed method deals with a reconstruction of SAS image using the sparse recovery method. The number of samples for recovery is low when using Compressive Sensing.

Keywords: Signal processing, Synthetic Aperture Sonar, Compressed sensing, Sparse recovery, Review, SAS.

I. INTRODUCTION

Sonar uses to navigate or detect objects on or under the surface of the water. Based on the Imaging technology there are three types SONAR's they are Real Aperture Sonar, Side Scan Sonar and Synthetic Aperture Sonar. Active Synthetic Aperture Sonar is a type of side scan sonar used to producing a more faithful, optical-like image of the sea floor. In standard side-looking sonar, each ping echo return is processed independently and the main problem with the image is that the along-track resolution (sometimes called azimuth resolution) becomes poorer as the range increases. Synthetic aperture techniques use coherent addition over many pings to create an aperture whose extent can be increased with range to maintain a constant along-track resolution. Advantages of Synthetic Aperture Sonar (SAS) are

1) Lower frequency of operation
2) Higher detection range for same resolution
3) Range and frequency independent Resolution.

In SAS the image is not created by line-by-line picture of the sea floor, Instead SAS pings several times and then records the echoes on a hard drive for post-processing [1]. SAS has Frequency range of 50 kHz to 200 kHz, Resolution of a pixel size of 1 inch by 1 inch and Depth range of 10 to 6,000 meters. SAS is used to automatic detection and classification of objects. In order to keep the narration and the formulas as concise as possible a few simplifying assumptions are made:

- The sensor trajectory is a straight line.
- The start and stop approximation is adopted, it means transmission and reception of a pulse at the same position without the sensor movement.
- Since we are only interested in the phase aberrations of the processor transfer function the influences of the finite pulse bandwidth, and the antenna patterns are not considered.
- Constants are freely discarded or abbreviated [3].

The rest of the paper is organized as follows. In Section II, we are narrating the challenges in synthetic aperture sonar. Section III, we present the current state of the art related to historical developments in the field of SAS. In Section IV, we discuss the various methods of algorithms for reconstruction of SAS Image. In Section V we propose the work that is intended as the first author's project and in Section VI we discuss its applications. Finally Section VII summarizes this paper with some concluding remarks.

II. CHALLENGES IN SYNTHETIC APERTURE SONAR

There are many challenges in SAS than its radar counterpart. The practical possibility of SAS is restricted by many factors. Primary factor that cause the implementation of SAS is speed of sound in water. It is very low compared to the Electro Magnetic waves through the atmosphere. So it restricts speedy data acquisition using SAS. The other factors that are challenges in implementation of SAS are

DOI 10.17148/IJIREEICE

- Platform Stability- Unmanned under water vehicles (UUV) are best platform choice for SAS. Its roll, pitch & yaw along with surge and heave motions due to ocean currents and internal waves makes motion compensation a challenging task.
- Mapping Rate versus Resolution– In order to achieve high resolution micro-navigation is required. The movement of platform at higher speeds increase the mapping rate at the cost of resolution.
- Reverberation – Clutter from biological and other unwanted objects makes the identification of desired objects is difficult.
- Speckle- The variance in image pixel level occurred due to constructive & destructive interference between individual scatterers in a geometric cell resolution.
- Multipath Propagation & Ocean Environment - Shadow image quality (fidelity and contrast) is affected due to multipath arrival, spatial coherence across the array is degraded. In SAS temporal coherence ping is also affected, variation in sound speed with depth degrades image.

III. STATE OF THE ART

The developments in the field of Synthetic Aperture Sonar begin as early from 1969. In 1969, Walsh coined Acoustic mapping apparatus for SAS [9]. Cutrona presented a review paper in 1975 stating the important parameters of SAS are identified and quantified [10]. Gilmour modeled Synthetic aperture side-looking sonar system in 1978 and he clearly specified the introduction of a hydrophone array in the along track direction [11]. In 1983, Gough shows an Experimental SAS using air acoustics is a scaled replica of sonar in water and it is named as Kiwi-SAS. Grating-lobe artifacts in the processed image cause the problem for this type of Sonar [12]. Douglas, Higgins, Logging and Christ off worked or a SAS with single transmitter in 1990 [13]. In the same year Eichel presented a Phase correction system for automatic focusing of synthetic aperture radar [14]. Hawkins described a second wide bandwidth SAS is currently at University of Canterbury in the year 1996 and also University of Canterbury had evolved KiwiSAS II [15]. In 1998 Alliant Techsystems developed Sona tech multiple receiver system [16]. From 2001 to 2004 Gough, Hayes, Callow and Miller worked on fast Fourier domain image reconstruction algorithms and the efficiency of the motion compensation algorithms [17]. In 2001 Hanssen used SAS for interferometric systems, the final stage in the SAS processing flow is bathymetry estimation using interferometry. Callow presented a Paper (2003) on after image formation; blind correction for residual errors (known as autofocus) in the image can be performed. In 2005 Delft university of technology used SAS to verify the efficiencies of image reconstruction algorithms and MOCOMP techniques [20], [21]. In 2009 Brynmor J. Davis Peter T. Gough published a paper in Modeling Surface Multipath Effects in Synthetic Aperture Sonar and become commercially available [19]. In 2011 Wachowski, Azimi-Sadjadi used a coherence analysis framework to generate synthetic aperture sonar like images that display acoustic colour information [18].

In 2013 Josiah Jideani and Andrew Wilkinson synthetic aperture sonar (SAS) tomography in air was carried out using the compressive sampling technique to obtain 3D focusing of SAS data. In 2015 Marston formulates the stripmap gradient expression in conjunction with a computationally efficient imaging approach [23]. During the year 2015 David P. Williams proposed a new unsupervised algorithm for the detection of underwater targets in synthetic aperture sonar (SAS) imagery is proposed. The method capitalizes on the high quality SAS imagery whose high resolution permits many pixels on target. One particularly novel component of the method also detects sand ripples and estimates their orientation. The overall algorithm is made fast by employing a cascaded architecture and by exploiting integral-image representations [22].

IV. SAS IMAGE PROCESSING ALGORITHMS

Synthetic aperture image reconstruction is an inverse problem to create reconstruction of an image of the sea floor reflectivity. Here we are using Stop and Hop approximation for synthesizing the aperture of the SAS. The echo data received will be in the time series form. It contains the information of the scene. Storing the time series data for a fixed number of hops and reconstructing the image from these time series data. The Simplest SAS reconstruction algorithm is the correlation algorithm. This algorithm correlates the echo data against a simple model for the data that would have been received for each image pixel and records the peak value. This process is time-consuming pixel-by-pixel cross correlation. The other useful Image recovery algorithms are Spatial-temporal domain and fast-correlation processing, Range-Doppler algorithm, wave number domain algorithm, chirp scaling algorithm, Accelerated chirp scaling and Back Projection Algorithm.

A. Spatial-Temporal Matched Filter

Initial synthetic aperture processors used spatial-temporal domain processing. Early airborne SAR systems pulse compressed the echoes in the receiver before recording them onto film. The range resolution of these systems was such that the range curvature was so small it did not need to be accounted for. To determine each pixel value in the output image, the corresponding pixel location is found in the raw pulse compressed data. The data along the locus scribed out by the PSF for that point is multiplied by the complex conjugate of the PSF phase and the result is integrated. Since the recorded data is sampled on a rectangular grid, and the locus is a continuously varying function in both t and u, this inversion scheme requires interpolation from the sampled data surrounding the exact position of the locus in t and u. The result of all this processing is the value for a single image pixel and the whole process must be repeated for every image pixel. Clearly this is time consuming. Spatial-temporal algorithm is Very slow process in the time domain and only marginally faster in the frequency domain [8].

B. Range-Doppler Algorithm

Range-Doppler Algorithm was developed by Wu, at the Jet Propulsion Laboratories, in 1976. The range-Doppler algorithm performs fast correlation in the along-track direction and uses time-domain interpolation to extend the focus depth. The correlation could be obtained as a frequency domain fast convolution in the azimuth direction (i.e., in Doppler wavenumber), with a time domain convolution operation in the range dimension to handle the range migration, hence the name range-Doppler[8]. In Range-Doppler Algorithm, it starts by changing the echo data into the range-Doppler domain by taking a one dimensional Fourier Transform in the along-track direction. A coordinate transformation and phase correction is then applied to remove the curvature so that the data point spread invariant. The diffraction-limited image can be revealed by 1-D along-track inverse Fourier transform. If we use wide beam width, then it requires an additional secondary range compression step.

C. Wave Number Domain or ω-K Algorithm

Wave number or ω-k domain algorithm is 2-D Fourier transform of the echo data into the wave-number domain. The wavenumber algorithm relies on inverting the effect of the imaging system by the use of a coordinate transformation in the spatial-frequency domain. Followed by a co-ordinate mapping and a phase and amplitude correction. The reconstructed image results from an inverse 2-D Fourier transform. The technique is often termed wavenumber interpolation because the coordinate transform is implemented using wavenumber domain interpolation [8]. The sidelobe level of the reconstructed image is reduced by the wave-number data. The raw data, a real modulated function, is usually demodulated to complex baseband to minimize data storage and shifted to the desired middle of the object/image plane, and the wavenumber data is demodulated to simplify interpolation [24].

D. Chirp Scaling Algorithm

Interpolation step Avoided by using a sequence of 2-D phase multiplications and 2-D FFTs to reconstruct an image. Input echo data needs to be in the form of an uncompressed chirp with a duty period longer than the expected spread of time migration. The first step in the chirp scaling algorithm is to spatial Fourier transform the raw data into the range-Doppler domain. To be time efficient, the chirp-scaling algorithm needs pre-computing of three full-sized complex arrays in addition to the input data array and the output image array.

E. Fast Chirp Scaling Algorithm

The efficiency can be improved dramatically with the inclusion of a preliminary range compression step. The full temporal support of the transmitted range chirp is not required. The chirp length required by chirp scaling multiplier only needs to be long enough to support the shift of the chirps phase center to that of the reference range. Generally the scene centre is chosen as the reference range so that the shift of the phase center is never particularly large. Bulk range curvature is performed during a later phase multiply.

F. Back Projection Algorithm

This is done by back propagating the received signal via each pixel in the scene to be imaged and into the transmitter. It operates by back-projecting the echoes for each ping over spherical arcs of all possible contributing points. Then range filtering step to obtain the reconstructed image.

V. PROPOSED COMPRESSED SENSING BASED ALGORITHM

In the proposed project we are trying to recover SAS image from time series echo using the compressive sensing (CS) algorithms. The disadvantages of existing algorithms are 1) the range resolution is limited by the bandwidth of transmitted signal. 2) Large No. of samples are required and result in extra burden to the system. 3) Imaging shows serious side lobe interference problem. Increased denoising and high range resolution SAS Imaging is obtained by compressed sensing algorithm. In Compressed sensing (CS) the reconstruction of sparse signal using far fewer samples or measurements than Nyquist rate. The pre-condition of exact recovery by CS is that the signal is sparse or compressible in some domain such as time, space and frequency. For seafloor if the main scattering targets distribute in a sparse way, then Number of dominant scatterers is much smaller than the Number of overall samples. In such case, SAS echo can be regarded as sparse signal. The algorithms used in recovery of image will be greedy algorithms such as Orthogonal Matching Pursiut(OMP) or convex optimization algorithms such as Basis pursiut(BP) etc. Perform sampling of x (image) through projections onto random bases and reconstruct the signal at the receiver with full knowledge of the random bases.

VI. APPLICATIONS

SAS is the only technology that can provide a solution where large area coverage and very high resolution is needed at the same time. Synthetic Aperture Sonar has wide applications in the unmanned underwater vehicles. Since the SAS system using less hardware space, it appropriate method of sonar imaging in small ships, unmanned vehicles and submarines. It has increased applications sea floor mapping, mine detection and under water survey. SAS is a suitable technology in searching for wrecks and other objects of historic interest. When searching for small objects over very large areas, SAS is an excellent tool. External inspection of underwater constructions such as pipelines is an important task. The objective of these inspections is to detect burial, exposure, free spans and buckling of the pipeline, as well as possible damages due to trawling, anchoring and debris near the pipeline. SAS may be well suited technology for some of these tasks. The sparse recovery algorithm of SAS can used in Interferometric SAS.

VII. CONCLUSION

The Synthetic Aperture Sonar and its various Imaging algorithms are leading research areas in the current scenario in the field of Sonar. Various research works are improving in SAS imaging technology, still it needs more efforts. In this paper it is went through the various historical developments in the field of Synthetic Aperture Sonar. The paper also describes the existing Image reconstruction algorithms in the field of SAS. We are proposing compressed sensing algorithms for sparse recovery of SAS image. There might some disadvantages and restrictions for the compressed sensing algorithms such as Orthogonal Matching Pursuit (OMP) or Basis pursuit (BP). CS increases the computational burden but obtains higher resolution.

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