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The research in this project was aimed at developing algorithms and VLSI architectures for high resolution imaging from space. The problems studied were from two major, related categories: algorithm definition and development, and VLSI implementation of signal and image processing algorithms. In the first category, the imaging problems studied were from synthetic aperture radar, high-resolution, sensor array systems, and motion estimation and target tracking. The primary objective

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of the work was to find high-performance algorithms suitable for high-speed implementation on mulit-processor arrays. The second aspect of our work focussed on VLSI implementation of signal processors, the analysis of finite register length effects, and the development of short wordlength, low noise structures for signal and image processing.

This report summarizes the research results.

SYSTOLIC ALGORITHMS FOR IMAGING FROM SPACE

FINAL REPORT

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Statement of Problems Studied

The goal of the Strategic Defense Initiative is to develop technologies that can be used to defend against the threat of nuclear ballistic missiles. Primary components of a strategic defense system would be a high resolution sensing or imaging system for surveillance, acquisition, tracking, and overall monitoring of targets, and a weapons system possibly utilizing directed energy or kinetic energy technologies for destroying targets.

The research in this project was aimed at developing algorithms and VLSI architectures for high resolution imaging from space. The problems studied were from two major, related categories: algorithm definition and development, and VLSI implementation of signal and image processing algorithms. In the first category, the imaging problems studied were from synthetic aperture radar, high-resolution, sensor array systems, and motion estimation and target tracking. The primary objective of the work was to find high-performance algorithms suitable for high-speed implementation on mulit-processor arrays. The second aspect of our work focussed on VLSI implementation of signal processors, the analysis of finite register length effects, and the development of short wordlength, low noise structures for signal and image processing.

Algorithm Development and Definition

The primary objective of the research in this category is to develop high-quality image-formation and information-extraction algorithms that can be implemented in parallel on systolic-like multi-processor arrays. Multi-processor implementation is crucial for real-time and near real-time performance.

Imaging problems investigated in this project include monostatic and bistatic synthetic aperture radar (SAR) imaging, inverse SAR imaging, sensor array systems for data acquisition and imaging, two-dimensional power spectrum estimation, two-dimensional bandlimited extrapolation, and the detection and tracking of small moving objects from sequences of noisy image frames.

Synthetic aperture radar (SAR) is a microwave imaging system capable of forming high resolution images of terrain or target objects using a relatively small antenna. The principles underlying SAR require that the scene of interest either translate or rotate with respect to the radar during the imaging procedure. Typically, the radar is moved from point to point as microwave pulses are transmitted and received as, for example, in airborne or spaceborne reconnaissance. However, SAR can also be used in an "inverse mode" where the radar remains stationary and the target motion is utilized. Such is the case in inverse-SAR imaging of moving ships, aircraft, satellites, and objects reentering the Earth's atmosphere, such as warheads and decoys. This latter application area, of high-resolution, all-weather imaging of reentry vehicles, is obviously of interest in the SDI scenario.

In this project sponsored by SDIO/IST, and administered by ARO, we have conducted a large amount of research aimed at improving SAR digital image formation algorithms in terms of both speed and image quality. We addressed the problem of forming high resolution SAR images in a spaceborne processor that is required to handle massive amounts of data and to operate reliably for long periods of time under extreme environmental conditions. For a major part of this work it was assumed that the SAR will operate in the spotlight mode in order to produce very high resolution imaging of small target areas for use in tracking and identification of either spaceborne or ground based objects. We have studied various means of avoiding the computationally expensive interpolation step in direct Fourier SAR reconstruction methods. The errors introduced by bypassing the interpolation step were analyzed. The effect of errors in the data collection mechanism, such as sampling jitter, on the reconstructed image quality were studied. The convolution backprojection algorithm for SAR image formation was identified as an algorithm that can achieve the high resolution desired, and which can be implemented in a systolic array processor with massive parallelism, and which has an architecture that facilitates reliability and fault tolerance. A problem studied was modifying this algorithm to allow the removal of many artifacts that are commonly ignored in SAR, such as wavefront curvature, a nonideal real antenna pattern, and propagation attenuation. Also, modification for SARs operating in the bistatic spotlight mode, i.e., a mode where the transmitter and receiver are not co-located in space was addressed.

We have also studied image formation problems for SARs operating in the strip-mapping mode. Strip-mapping SAR relies on translation of the scene being imaged with respect to the radar. Research under this contract on strip-mapping SAR has been focussed on developing a better understanding of the signal processing in image formation, and a simple derivation of the imaging equations utilizing only the most basic signal processing concepts of convolution, Fourier transforms, matched filtering, and tomographic projections. We have also questioned the popular belief that the resolution ability of strip-mapping SAR comes from the Doppler effect. We have shown that while the resolution ability relies on translation of the scene with respect to the radar, the speed of relative motion between radar and scene is not important.

A more general imaging problem studied is the development of high-resolution high-speed algorithms for general, synthetic aperture, sensor array imaging systems, and the analysis of algorithm sensitivity and resolution limits. The data acquisition is with a discrete two-dimensional array configuration of imaging devices. The algorithms developed apply to both active and passive imaging systems. The image reconstruction algorithms can be partitioned into two stages *time-delay estimation* and *image formation*, and each stage was analyzed for fundamental resolution limits, as well as adapted for systolic implementation.

Fundamental problems in the reconstruction of images from limited data in the Fourier domain were addressed in this project. Such problems arise in a variety of imaging systems envisioned for space-borne usage. In some systems (at infra-red and optical frequencies, especially) the data collected corresponds to real-valued, positive intensity images. In others (at microwave and radio frequencies, for instance), the data collected corresponds complex-valued images, and the complex values of the pixels come from phase changes introduced by elementary reflectors in the object being imaged. However, often only the magnitude of the reflection coefficient is of interest, which means only the magnitude of the complex-valued image needs to be reconstructed. The first reconstruction problem can be formulated as a problem of extrapolating a two-dimensional, bandlimited, positive semi-definite signal when the passband limits are known. We have studied this problem, and the conditions for existence and uniqueness of such a reconstruction, and have developed high-speed, high-rsolution algorithms for it. The second reconstruction problem becomes a problem of power spectrum estimation for a two-dimensional, wide-sense homogeneous random field, if the phase is independent from one pixel to the next. We have addressed the 2-D spectrum estimation problem, studied the advantages of using non-causal, rational models over causal ones, derived a theory of non-causal linear prediction and innovations, and derived algorithms for non-causal system identification and spectrum estimation.

The need to quickly detect small, barely discernible objects in image sequences arises in many applications. In astronomy, the images consist mainly of sensor noise, as in the problem of using a mosaic CCD (charge coupled device) sensor at the output of a telescope for optically detecting meteors, satellites, or other small moving objects against a night sky background. A similar problem is known as night-sky satellite surveillance, where the objective is to keep inventory of the increasing number of objects orbiting the earth. Although stars may be much brighter than the celestial objects of interest, their motion can be compensated by using a counter-rotating platform, a standard practice in astronomical observation. Currently, long CCD exposure times are used to detect faint distant stars by suppressing the zero-mean noise present through temporal integration. This technique, effective for stationary objects, will yield suboptimally weak image plane streaks if the objects are moving. In other applications, the images consist of highly-structured backgrounds, as in the detection of dim moving targets on the earth's surface from a space-borne mosaic infrared sensor staring down at a fixed point on the ground. In motion analysis of outdoor optical or forward-looking-infrared scenes, the image sequence may contain drifting background clutter as caused by relative motion between the sensor array and terrain, ocean, or clouds. Here, the problem in detecting far away objects has not been properly addressed; rather it is unrealistically assumed that the object is somehow located at the center of the imaging system's field of view. Indeed, the acquisition of knowledge that large or small moving objects are present is important to systems that perform motion analysis. Unlike the previous case, there is often a real-time processing requirement in dynamic scene analysis. An important capability is to determine, as quickly as possible, when objects are present in an image sequence. We have studied this problem of detecting small (possibly, pixel-sized), moving targets in a sequence of digital images of high-noise cluttered environments, and have investigated an algorithm for the problem based on efficient trajectory matching using a combination of tree-structured search and multi-stage, sequential hypothesis testing.

VLSI Implementation Issues

The basic computational core of modern signal and image processing consists of numerical linear algebra. Systolic implementations of various matrix algorithms have already been developed, including algorithms for singular value decomposition and for the Schur-Levinsor recursive algorithm for solving a Toeplitz system of linear equations. Thus, imaging algorithms that employ these numerical linear algebra tools have the potential for high-speed implementation in VLSI. Hence, the algorithm part of our research concentrated on algorithms that used these tools. The objective of this second aspect of the work on this project was to map the imaging algorithms onto multiprocessor, VLSI arrays, to study the effects of finite wordlength errors and find VLSI structures that minimize these effects, and to study residue number system (RNS) concepts to see if they can be used to develop fault tolerant VLSI signal processing structures.

A speed incompatability problem arises in many real-time imaging systems when data has to be filtered at a throughput rate that is faster than the throughput rate of the arithmetic unit (multipliers and adders) in each processor on board. The question that is to be addressed here is: Is it possible to use a large number of arithmetic units operating in parallel to build a digital filter that can handle throughputs faster than the individual arithmetic units. We have studied this problem and developed VLSI filter structures that are very different from conventional filter structures, and are capable of overcoming the speed incompatabilty problem. We have shown that it is possible to achieve real-time image restoration and smoothing using a lot of hardware to achieve the necessary speed of filtering. Both non-recursive and recursive filtering problems were studied.

It is well established that the effects of finite register length play a crucial role in the design of digital signal processors. Processor structures must be chosen to minimize effects of round-off noise, adder overflow, and limit cycles. If improperly designed, digital signal processors will make poor use of the available wordlength and produce outputs with large errors. There are generally many possible structures (or flowgraphs) available for implementing a given signal processing algorithm. Some of these structures are much more sensitive than others to the effects of finite register length. Though there exists a big body of literature on finte register effects and design of robust structures for digital filtering and FFTs, there has been little work done on finite register effects in highly parallel, VLSI structures for various signal processing tasks. In this project, the effects of these errors were thoroughly studied and analyzed for multi-processor, very high-speed, block structures for digital filtering. New block structures, robust to these effects were investigated.

A second problem that was addressed was a study of ways to achieve fault tolerance in a SAR processor, given that the convolution back projection algorithm is selected as the image reconstruction algorithm. Residue number system (RNS) architectures were investigated for introducing modular redundancy into the hardware. An RNS is an arithmetic number code that is a a viable alternative to the more conventional binary codes used in general purpose computers, for dedicated systems that require mostly addition, subtraction, and multiplication. They are particularly suitable for imaging applications, because most signal processing algorithms require relatively few division operations. Two-dimensional digital filtering used in image enhancement and feature extraction is an an example of a computationally intensive operation that is ideally suited for RNS arithmetic. The use of an RNS code results in arithmetic parallelism and hardware modularity with nearly no intercommunication between modules. A lack of communication between residue digits means that an error in one digit does not propogate into other digit positions durin subsequent operations involving addition, subtraction, and multiplication. This property provides a basis for fault tolerance that is inherent in the basic algebraic structure, and which can be used to obtain fault tolerant architectures. Fundamental studies in fault tolerance were initiated. An experimental chip design was carried out for a small sub-component of the overall processor to determine how well these theoretic concepts can be translated into real VLSI hardware.

Topical List of Research Contributions
August 1986 through June 1989

The following is a topical list of research contributions of this project over the three-year period of the contract. A brief description of salient findings follows the listing.

Imaging Algorithms

1. A SAR image reconstruction algorithm that corrects for non-ideal effects such as a) wavefront curvature, b) propogation attenuation, and c) non-ideal real antenna patterns
2. An algorithm for bistatic SAR imaging using convolution back-projection (CBP), capable of correcting for the same non-ideal effects
3. Mathematical analysis and computer simulation of 2 fast algorithms for spotlight-mode SAR reconstruction from trapezoidal Fourier data
4. A new, fast, back-projection algorithm for SAR, where the convolution step is eliminated by transmitting the proper waveform
5. A tomographic derivation of bistatic SAR
6. A first principles derivation of strip-mapping SAR based entirely on geometrical considerations and signal processing concepts
7. A practical method for least-squares design of radar waveforms for range-Doppler radars
8. A new non-causal model for 2-D rational spectrum estimation
9. A definition of system state for 2-D non-causal systems
10. An SVD-based algorithm for identification of 2D non-causal systems from impulse response
11. Wold decomposition theorem and innovations representations for 2-D WSS random fields using non-causal linear prediction
12. An SVD-based 2-D spectrum estimation algorithm
13. An algorithm for bandlimited extrapolation observations off the signal peak
14. A test for existence of bandlimited positive definite extrapolations
15. A theory for existence and uniqueness of bandlimited extrapolations subject to non-negativity and upper-bound constraints on the spectrum
16. A 2nd-order iterative algorithm for obtaining the minimum-energy extrapolation subject to bandlimitedness, and non-negativity and upper-bound constraints on the spectrum
17. A sequential hypothesis testing algorithm for the detection of small, dim, moving objects in noisy image sequences

18. Theoretical analysis of above algorithm, verified by computer simulation on synthetic and real-world image sequences
19. A parallel implementation of the above algorithm on a hypercube architecture

VLSI Implementation

1. Highly parallel filter structures for generating more than one output per clock cycle
2. Finite-precision error analysis of these multi-processor, high-throughput, filter structures
3. A new high-throughput filter structure that has improved finite precision behavior
4. A theory of complex modular arithmetic for SAR processor implementation in VLSI
5. A scheme for fault tolerance in a multi-processor realization of the CBP algorithm for SAR processing
6. The VLSI design of a subsystem for SAR processing

Summary of Most Significant Results

Research in this project was aimed at developing algorithms and VLSI architectures for high resolution imaging from space. The problems studied were from two major, related categories: algorithm definition and development, and VLSI implementation of signal and image processing algorithms.

IMAGING ALGORITHMS

Imaging problems investigated in this project during the period of the contract, August 1986 through June 1989, include monostatic and bistatic synthetic aperture radar (SAR) imaging, inverse SAR imaging, sensor array systems for data acquisition, imaging, high-resolution beamforming, direction finding and target tracking, two-dimensional power spectrum estimation, two-dimensional bandlimited extrapolation, and the detection and tracking of small moving objects from sequences of noisy image frames.

Synthetic aperture radar

We have conducted a large amount of research aimed at improving SAR digital image formation algorithms in terms of both speed and image quality. In the case of spotlight-mode SAR, which relies on rotational motion, Fourier data is generally acquired on a polar grid. In the direct Fourier image reconstruction algorithm, this necessitates a time-consuming polar-to-Cartesian interpolation prior to Fourier inversion. In our research we have considered controlling the sampling times in the analog-to-digital converter to provide Fourier data lying on a keystone or trapezoidal grid [Arikan & Munson, 1987]. The image reconstruction algorithm then simply applies an inverse 2-D FFT to the stored keystone-format data, with no interpolation. The error due to bypassing the interpolation was analyzed and the effects of data angle, point target location, and bandwidth on the final reconstructed image were studied. Incorporation of deconvolution procedure was shown to significantly improve keystone format imagery. A comparison with polar-format reconstruction using no interpolation showed that the keystone approach is noticeably superior for larger data angles.

Recently, a new algorithm that assumes keystone-format data in spotlight-mode SAR has been proposed by W. Lawton. The spatial domain image is produced through a series of convolutions and DFT's, all performed using FFT's. The geometry of the trapezoidal grid makes this fast algorithm possible, which requires $O(N^2 \log N)$ multiplications for an N by N image. We have shown that the Lawton algorithm implements a form of trapezoidal-to-Cartesian interpolation followed by a 2-D FFT, and we have derived a closed form approximate expression for the point-target response of the algorithm composed of groups of point targets, and we determined the effects of windowing and incorporation of a Jacobian weighting factor [Arikan & Munson, 1989]. In addition, we also considered the effect on image quality of moderate levels of sampling jitter in the A/D and of deviations of actual data collection angles from those intended. Overall, the Lawton algorithm was found to be robust, and to produce high quality imagery.

Another method of image formation in spotlight-mode SAR utilizes the convolution-back-projection (CBP) algorithm from computer tomography. For this approach we have proposed a simplified back-projection algorithm in which the filtered projections are obtained automatically by choosing the radar waveform to be the impulse response of the desired filter [Arikan & Munson, 1989]. The necessary filtering is then accomplished through the physical mechanism of the waveform reflecting off the target, which is described by a convolution. A parallel processing architecture was proposed for the back-projection step and its computational and memory requirements were analyzed. Finally, we described a second potential method for obtaining projections, which assumes a conventional linear FM waveform.

Our studies indicate that the CBP algorithm is an attractive algorithm for high-speed, implementation of a multi-processor array. In addition, although the CBP algorithm is known to require considerably more computation than alternate Fourier batch algorithms, it is more flexible than batch algorithms and can be easily adapted to take into account the correction of nonideal effects that are usually ignored by the batch algorithms. A modified CBP algorithm has been developed for SAR image processing that corrects for 1) wavefront curvature, 2) propagation attenuation, and 3) nonideal real antenna patterns. It has also been adapted for bistatic SAR operation, a mode in which the radar transmitter and receiver are not located at the same coordinates in space, and may in fact be travelling in quite different flight paths.

In more conventional SAR systems, the defocussing effects of wavefront curvature are second order effects that are typically ignored in the processing. However, in higher resolution applications where the range cells become very small, the curvature of the propagating wavefront can be a limiting factor. The CBP algorithm was modified to take this into account by predistorting the recorded projections prior to application of the standard CBP algorithm. Computer based experiments show that small targets can be resolved when the modified algorithm is used, whereas they will be completely unresolvable with a conventional CBP algorithm that ignores wavefront curvature [Bauck and Jenkins 1988, Bauck and Jenkins 1989].

There is a natural loss of signal strength as the propagating wave spreads out in space. In monostatic SAR systems, the propagation from the transmitter to the target area is approximately the same as that in the return direction for all target points in the imaged area. This implies that no particular correction for this loss is required in the processing, but that the effect manifests itself as an overall reduction in signal to noise ratio in the final image. However, in bistatic SAR, where the distances between the transmitter and target and the target and algorithm was modified to take into account the propagation attenuation explicitly, thereby increasing the resolution capability of a SAR operating in the bistatic mode [Bauck and Jenkins 1989].

The CBP algorithm is a "point by point" reconstruction algorithm that is particularly suited for multiple processor implementation. This implies that fault tolerance can be more readily designed into the system, and that the demands of high computational complexity can be offset by the use of parallel processing with high overall throughput rates. This algorithm is well suited for parallel processor implementation and is theoretically capable of achieving very high resolution.

Although it is difficult to remove the effects of the nonideal real antenna pattern precisely for arbitrary cases of bistatic mode operation, we developed an approach to approximately remove it by applying an inverse weighting to points in the projection space as the image is reconstructed. At the present time we consider this to be a suboptimal result, and we will continue to address this important problem in future studies.

In recent years there has been considerable military interest in bistatic spotlight-mode SAR (BSSAR) where a high powered transmitter can be operated at a safe distance from a target area while a covert receiver is flown close to the target area, collecting returned signals and forming high resolution images. Although much work has been performed on BSSAR, little of it is documented in the literature, and most of it has taken place from a traditional Doppler radar viewpoint. In our research under this contract we have produced a basic derivation of BSSAR, starting from first principles [Arikan & Munson, 1988]. Similar to the monostatic case, we have shown that BSSAR can be explained using the projection-slice theorem from computer tomography and that BSSAR does not rely on the Doppler effect. We have shown that at each look angle the demodulated BSSAR data are approximate band-limited samples of a slice of the two-dimensional Fourier transform of the target reflectivity. The locations of the Fourier domain samples were determined and the shape of the Fourier grid was examined for several special cases of transmitter and receiver motion. We also analyzed wavefront curvature within the bistatic setting and compared it with that occurring in the monostatic case.

Strip-mapping SAR relies on translation of the scene being imaged with respect to the radar. Strip-mapping SAR has been widely covered in the technical literature for many years, but these treatments tend to be inaccessible to researchers outside the radar community due to use of unfamiliar terminology, assumption of a prior understanding of basic radar signal processing, and the use of a Doppler viewpoint. In research under the contract, we have derived the fundamental strip-mapping SAR imaging equations from first principles [Munson, 1987], [Munson & Visentin, 1989]. We have clearly shown that the resolving mechanism relies on the geometry of the imaging situation rather than the Doppler effect. Both the airborne and spaceborne cases were considered. More importantly, however, this work together with our research on spotlight-mode SAR has led to our authorship of the first monograph on SAR offering a complete description of the mathematical principles involved [Munson & Visentin, 1989]. In writing this book our intent has been to cut a swath across a very complex field to give a working knowledge of the signal processing aspects of SAR and to give an understanding of the image formation process, beginning with the original scene and ending with the final image. The topics in the book, all developed from first principles, include aperture and array theory, pulse compression, strip-mapping SAR, range migration correction, spotlight-mode SAR, inverse SAR, bistatic SAR, and general Fourier offset imaging. Our treatment of the mathematical theory of SAR is more complete than anything currently available and is offered from what we believe to be a simpler perspective, utilizing the signal processing concepts of convolution, Fourier transform, matched filtering, and tomographic projection.

Sensor array imaging

More generally, image reconstruction algorithms for synthetic aperture, sensor array imaging systems can be partitioned into two stages *time-delay estimation* and *image formation*. , The time-delay estimation component is responsible for the computation for the target distribution in the range direction. Subsequently, the delay profiles are backward propagated into the target region to form the image. Backward propagation is equivalent to the focussing process in conventional image formation. To perform high-speed, high-resolution imaging requires optimizing the resolving capability and computation complexity of each of these two steps. Without additional knowledge or constraints on the target distribution, the image resolution would be largely governed by the Rayleigh criterion which is bounded by the aperture size and the bandwidth of the received signals. For resolution enhancement, the constraints we can utilize are the finite bound of the target region, temporal frequency cut-off of the signals, and the finite bandwidth of the spatial-frequency distributions of the received wave-field. Resolution improvement in the delay estimation process is mainly governed by the bandwidth of the receiving echos, the total number of data samples in each detection period, and the knowledge of bounds on the target distribution in the range direction [HuaLee, Chiao, and Sullivan, 1988].

In this project, we discovered ways to construct matrix operators that enhance resolution by using prior knowledge in various stages. The first resolution enhancement operator was formed with the knowledge of the bandwidth of the returned echos. This matrix operator is applied directly to the received data samples in the time domain. The enhanced data sequences are then Fourier transformed into the frequency domain. Subsequent to the delay-estimation filtering process in the frequency domain, frequency samples are once again enhanced by a second resolution enhancement operator constructed by using the finite-bound constraints of the target distribution. These cascaded operations are applied to the data sequence sequence at each sensor in the array [HuaLee, Silakaitis, and Sullivan, 1989].

The resolution enhancement in the image formation process is governed by the bound of the target distribution in the cross-range directions, cutoff of the spatial-frequency spectrum, and the geometric distribution of the discrete receiving array. The spatial-frequency distributions of the wave-field are bandlimited due to the loss of evanescent waves. If the target is also bounded in the cross-range directions, a similar sequence of operators can be formed with these constraints for the image formation process.

The enhancement operators associated with both the delay estimation and image formation can be implemented on multi-processor arrays. The size of the enhancement operators is governed by the length of the received data sequences as well as the size of the receiving arrays. As a result, computation complexity of the resolution enhancement operations increases significantly for large apertures and long data sequences. To avoid the increase of computational complexity for large operator dimensions, we have also developed data segmentation techniques to retain both the resolution quality and computation efficiency. This technique can also be very effective for imaging systems with detached aperture distributions [HuaLee & Sullivan, 1989]

An analytical study of the algorithms' resolution limitations and sensitivity was also carried out.

Image reconstruction from Fourier domain data

Our work on image reconstruction from Fourier-domain data has been along two distinct lines. When the data are Fourier samples of a complex-valued image, but only the magnitude of the image needs to be reconstructed, our approach has been to treat it as as a two-dimensional power spectrum estimation problem. When the data are Fourier samples of a real-valued positive intensity image, our approach has been to treat it as a bandlimited extrapolation problem and to incorporate additional constraints such as positivity and boundedness of the image. Both kinds of image reconstruction problems are frequently encountered in a variety of imaging systems, including SAR.

For the 2-D spectrum estimation problem, we developed a novel non-causal rational model that is capable of generating the *complete* class of rational spectra, unlike other models used hitherto, which have imposed constraints such as separability or factorizability, and thus only modelled a subclass of rational spectra [Arun, 1986]. This model is a pole-zero generalization of the Markov random field model, in that while the spectrum of a Gaussian Markov random field is all-pole, the spectrum of our new model is rational. Identification of non-causal, rational systems in two or more dimensions is a difficult problem, and was hindered by the lack of a system state space that acts as an input/output and past/future information interface. To help overcome this problem, we developed a novel notion of system state for non-causal, 2-D rational systems, based on a partition of the infinite 2-D square, discrete lattice into a non-causal past and future [Arun, 1986]. A robust algorithm for identification of 2-D, non-causal, rational systems from impulse response data, using singular value decomposition was developed using this definition of system state. It was shown that the dimension of this state space is finite, and reflects the system order. Thus, singular value decomposition methods could be developed for model order and model parameter estimation [Arun, Krogmeier, and Potter, 1987].

To understand the limitations of non-causal, rational modeling of random fields, new definitions of innovations, regularity and singularity were adopted based on the error in linearly predicting a sample of a random field from all other samples of the field on the discrete square lattice. This kind of estimation is called non-causal linear prediction or linear interpolation. It was discovered that the innovations field has a spectrum which is the reciprocal of the spectrum of original field. This led to a new Wold decomposition of 2nd order, wide-sense homogeneous, multi-dimensional random fields, based on non-causal linear prediction. Spectral conditions were discovered for regularity and singularity of such a field. For regular random fields, a non-causal innovations representation was derived, which is guaranteed to be rational, when the regular random field has a rational spectrum [Krogmeier & Arun, 1989].

It turned out that the non-causal rational model that we had earlier proposed for generating the complete class of rational fields, is in fact the innovations representation of a rational field, and that the Markov random field model is the innovations representation for fields with all-pole spectra. The system identification algorithm that we derived could be used to estimate the order and parameters of the innovations represenstation of any rational random field. For general fields with spectra that are not necessarily rational, the algorithm leads to an approximate rational model and a robust spectrum estimate. Comparisons were carried out with causal Wold decompositions and causal model-based algorithms [Krogmeier & Arun, 1988].

For the bandlimited extrapolation problem, we have derived and studied algorithms for extrapolation from low-energy observations, off the signal peak [Potter & Arun, 1986]. It gives us a means of incorporating prior information that one might have about the location of signal and spectrum peaks and regions of energy concentration or suppression in either domain, into the extrapolation algorithm [Potter, 1986], [Potter & Arun, 1989]. The currently popular algorithm, the minimum energy algorithm, on the other hand, performs poorly when the observations are off the signal peak.

In some imaging systems, the image to be constructed is an intensity image, and is not only real-valued but also non-negative. With such applications in mind, we derived a computationally simple test for the existence and uniqueness of bandlimited, one-dimensional extrapolations subject to the real, non-negative constraint on the spectrum [Potter & Arun, 1987]. This problem is a combination of the classical power spectrum estimation problem from insufficient covariances with the bandlimited extrapolation problem. While the theory of existence and uniqueness is well known for the two problems, it is relatively little known for the combined problem. For the multi-dimensional case, the theory is based on convex cones, and tests for existence and/or uniqueness are intractable, and require determining membership in these cones. For the 1-D problem, we were able to generalize the classical Toeplitz test for existence of positive semi-definite extrapolations to include the bandlimitedness constraint. Our new test works with two Toeplitz matrices, is simple and uses the computationally efficient Levinson algorithm. When extrapolations exist, the test cn be slightly modified to provide an extrapolation that meets the bandlimitedness and positivity constraints [Arun & Potter, 1989].

Dynamic range and other limitations may often mean that the intensity of each pixel in the underlying image is no more than a certain known bound. We accordingly, developed a theory of existence and uniqueness of extrapolations subject to both the non-negativity and the upper-bound constraint on the spectrum [Potter & Arun, 1988]. The classical approach to constructing an extrapolation that meets all these convex constraints is an iterative approach using alternating projections onto the convex sets. Such an algorithm has first order convergence, and the limit depends on the initial guess, and the order of projections. We have found that the extrapolation subject to these constraints with the least energy is parameterized by a finite number of parameters; the number is equal to the number of observations. The parameters may be found by a solving a non-linear system of equations, by a variety of methods, including an iterative fixed-point scheme. We have also derived a Newton-like iterative algorithm that finds the parameters with second-order convergence. Each iteration can be performed in a highly parallel mode on a multi-processor array [Potter, 1989], [Arun & Potter, 1989].

Detection of moving objects from image sequences

The need to detect barely discernible, (small and dim), moving objects in image sequences arises in many applications. The background might be purely noise, in which case, a simple averaging of image frames will bring out any dim objects, if they are stationary. For moving objects, this technique is suboptimal, and will yield weak image plane streaks. In other applications, where the background may be highly-structured, as in infra-red imaging from space of a fixed patch on the ground, the averaging technique is not very useful. When the background contains large moving objects, the current approach is to assume that the moving object of interest is close to the center of each frame. Our approach has been to model the image sequence as consisting of multiple, moving objects, moving along different trajectories at possibly vastly different speeds. We have developed the capability of quickly detecting moving objects, even if they cannot be detected from a single frame.

In multiobject tracking, the computational burden of real-time processing with sufficient resolution poses challenging problems in radar signal processing. In the past, rather than addressing the task of distinguishing objects from clutter directly, the problem has been guised as one in multiple object tracking where a mixture of detected object points and clutter points are assumed as given. Performance improvement may result by incorporating object detection explicitly to the front-end of a tracker.

In our study, we invented a new algorithm for the detection of small, barely discernible moving objects of unknown positions and velocities in a sequence of digital images. First, statistically robust prewhitening techniques are used to eliminate background structure and transform the image sequence into an innovations representation, modeled as Gaussian white noise. Then, a large number of candidate trajectories, organized into tree structure, are hypothesized at each pixel in the sequence and tested sequentially for a shift in mean intensity [Blostein & Huang, 1987], [Blostein & Huang, 1988]. Underlying the algorithm are new general results in detection theory, including the use of multistage hypothesis testing (MHT) for simultaneous inference, and a new framework for quickest detection of time-varying signals in noise. In addition, exact, closed-form expressions for MHT test performance are derived; these predict the algorithm's computation and memory requirements, where it is shown theoretically that several orders of magnitude of processing is saved over a brute-force approach [Blostein, 1988]. Feasibility of a parallel implementation on a MIMD, distributed memory, message-passing architecture is also shown. Results are verified experimentally on a variety of image sequences, including outdoor scenes digitized from videotape, digitized photographs, and digital data gathered by a CCD array at the output of a telescope [Blostein & Huang, 1989].

The research presented here may impact other areas in which a problem in multidimensional signal detection can be expressed in terms of a multiple binary hypotheses search in one dimension. For example, a similar technique can be applied to the detection problems in 3-D spatial data instead of space-time data, as encountered in medical imaging or in nondestructive testing. Incorporating communication between trajectory lists may facilitate the detection of higher-level image features such as moving edges, or boundaries between moving objects, which is of particular use in video coding and computer vision applications. The algorithm may also be generalized to simultaneously operate at multiple resolutions, in order to efficiently detect objects of different sizes, though the largest size object should still be small compared to the image plane size. The basic techniques can be directly applied in astronomy, to detecting moving celestial objects in deep space. As demonstrated, our algorithm can give superior results than possible by streak detection in time-exposed imagery. Finally, the detection algorithm discussed can be used as a front-end to multiobject tracking systems for cluttered environments, such as that found in air-traffic control applications.

VLSI IMPLEMENTATION

VLSI implementation problems studied during the same 3-year period include the design and finite-precision error analysis of high-speed multi-processor filter structures, and the design of modular processors for residue number system (RNS) arithmetic units.

High-speed structures robust to finite precision error

Current systolic and wavefront implementations of digital filters utilize only as many processors as the filter order, and achieve maximum throughput rates of one output per multiply + add cycle. However, for real-time processing of images, even simple linear shift-invariant operations for smoothing, restoration, or enhancement, much higher throughput rates are required. When the throughput rate desired is faster than the arithmetic unit of each processor, a filter structure is needed that uses more processors than the filter order. We developed a simple structure of this kind for high-speed, non-recursive filtering, that is similar in form to the parallel array multiplier. Each cell in the array multiplier is an AND gate that multiplies two bits together, and the array produces the product of two numbers in binary represenation in one clock cycle. This product is also the convolution of the two binary sequences. Analogously, each cell in our array structure for high-speed non-recursive filtering is an arithmetic unit that multiples two numbers together, and the array convolves two sequences together in one multiply+add cycle. This allows a block of outputs to be generated in a single cycle, thus increasing the throughput above the throughput rate of the arithmetic unit, by a factor equal to one dimension of the array. The other dimension of the array is the order of the filter.

Producing blocks of outputs every arithmetic unit cycle is more difficult with recursive filters, because partial sums have to be propogated. Taking a lesson from parallel adders this time that use carry look-ahead schemes to produce the sum of two binary words in a single clock cycle, we developed a block, recursive filter that uses look-ahead circuitry to allow the generation of a block of ouputs per arithmetic cycle. The systolic implementation of a recursive filter is analogous to a bit-serial adder, and the block implementation developed here, is analogous to a parallel adder [Wagner & Arun, 1988].

Block implementations of popular conventional structures, such as the cascade and parallel forms were also developed, and a thorough analysis of the effects of finite precision errors on each of these structures was carried out [Wagner, May 1988]. Our investigation of the finite-precision behavior of the high-speed VLSI structures for recursive digital filters, led to some rather surprising conclusions. It is well known that block filter structures have excellent round-off noise performance in fixed-point environments. For conventional filter realizations, it is also known that structures with low round-off noise have low coefficient sensitivity. Much to our surprise we discovered that though block structures have low round-off noise, they can have very high sensitivity to coefficient perturbations. A pipelined version of the high-speed structure that uses a pipelined multiplier, instead of multiple processors, was found to be internally unstable, and it becomes BIBO unstable, when the coefficients are quantized. Rather surprisingly, this problem does not arise in the parallel version, but is peculiar to the pipelined version. The paralle version also has coefficient sensitivity problems, and this sensitivity is large when the transfer function has poles close to the origin. This is contrary to our experience with conventional digital filter structures which exhibit coefficient sensitivity problems when poles are close to the unit circle and are relatively robust to coefficient quantization errors when poles are close to the origin [Arun & Wagner, 1989].

This sensitivity to coefficient quantization errors can in fact, make the filter with quantized coefficients behave as a periodically time-varying system. To avoid this problem, we designed a new high-speed filter structure that is guaranteed to be time-invariant even after coefficient quantization. This structure has a certain symmetry in parameters, so that when the coefficients are quantized, the perturbation in parameters that are equal is identical. Since the symmetry is retained even after quantization, time invariance is also retained. Other high-speed structures including block structures do not have this symmetry, and coefficient quantization causes the block transfer function to deviate in an unpredictable way from the constraints required for time invariance. The new structure is also effected by quantization errors, but the system after quantization is still time-invariant. This advantage is gained at the expense of redundant hardware [Arun & Wagner, 1989].

Fault tolerance with residue number systems

Fundamental studies in concepts for fault tolerance in SAR processors have been initiated. It appears that although the CBP algorithm is more computationally intensive than alternate Fourier batch algorithms, the CBP algorithm provides a better capability for multiple processor realization, and it is better suited for the incorporation of modular redundancy to achieve fault tolerance. We have studied the application of modular arithmetic techniques for SAR processor implementation and have translated some of this theory into an actual chip design. VLSI design concepts based on modular arithmetic have been developed for SAR processor implementation in VLSI. In particular, the theory of complex modular arithmetic has been developed for this application, since a coherent radar requires the use of complex signal representation when processing at baseband [Jenkins and Krogmeier 1987]., It appears that modularity is the key to fault tolerance in SAR and that it lead to VLSI designs that are easily designed and tested.

A VLSI circuit was designed for a small subsystem component of a SAR processor, and was sent through MOSIS for fabrication. The circuit that was designed, referred to as a "bit sliced inner product step processor" (BIPSP), represents one element of a systolic implementation of an array that efficiently computes inner products. Since the inner product is a generic kernel required in all signal processing (and in particular in CBP SAR processing), this circuit was selected as one small component of a possible SAR processor implementation. The BIPSP chip was designed with on-chip error detection, which allows the detection of an error anywhere in the array when many BIPSPs are interconnected [Jenkins and Julien, to appear]. The fabricated chips were recently returned to the University of Illinois, and they will soon be tested. This project represents a feasibility study to determine how well modular arithmetic design techniques actually translate into practical VLSI designs.

The more encompassing problem of achieving fault tolerance in the complete systolic array SAR processor remains a problem to be addressed by our future research in this area. However, once fault detection capability is provided at the chip level, this information can be used to control and reassign system resources at a higher level. It is important to note that the use of RNS design techniques provides two important but distinctly different capabilities; 1) it modularizes the hardware at the chip level to facilitate chip design, testing, and error detection, and 2) it provides the potential for including redundant modules in the overall system that can be reassigned at a higher system level to achieve fault tolerance in the complete SAR processor.

List of Publications under ARO sponsorship

August through December 1986:

[1] K. S. Arun, "A noncausal rational model for 2-D spectrum estimation," *Proc. Third IEEE ASSP Workshop on Spectrum Estimation and Modeling,* Nov. 1986, Boston, MA, pp. 85-88.

[2] Douglas P. Sullivan, *"Two New Algorithms for Discrete-time Band-limited Extrapolation,"* M.S. Thesis (Hua Lee, advisor), Dept. of Electrical and Computer Engineering, University of Illinois, Urbana, IL, 1986.

[3] Lee C. Potter, *"Extrapolation and spectrum estimation for discrete-time bandlimited signals,"* M.S. Thesis (K. S. Arun, advisor), Dept. of Electrical and Computer Engineering, University of Illinois, Urbana, IL, 1986.

[4] L. C. Potter and K. S. Arun, "Reconstruction of bandlimited, time-concentrated signals from low-energy observations," *Paper summaries for The 1986 IEEE Digital Signal Processing Workshop,* Chatham, MA, pg. 4.2, Oct. 1986.

January through June 1987:

[1] W. K. Jenkins and J. V. Krogmeier, "The design of dual-mode complex signal processors based on quadratic modular number codes," *IEEE Transactions on Circuits and Systems,* Vol. CAS-34, no. 4, April 1987, pp. 354 -364.

[2] Hua Lee, "Image Reconstruction Algorithm Structure of Partial Discrete Systems," Invited presentation at *1987 International Electronic Imaging Conference,* February 1987.

[3] D. C. Munson, Jr., "An introduction to strip-mapping synthetic aperture radar," *Proc. 1987 IEEE Intl. Conf. on Acoustics, Speech, and Signal Processing,* pp. 2245 - 2248, April 1987, Dallas, TX.

[4] L. C. Potter, and K. S. Arun, "Extrapolation of multi-dimensional bandlimited sequences using energy concentration information," Proc. 1987 IEEE Intl. Conf. on Acoustics, Speech, and Signal Processing, pp. 1240 - 1243, Dallas, TX, April 1987.

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L. C. Potter, M.S. in Electrical Engineering, 1986 (advisor: Arun).
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