

Automated Hardware-in-the-Loop Modeling and Simulation in Active Sensor Imaging Using TI6713 DSP Units

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Abstract—This paper presents a new methodology for the modeling and simulation of active sensor imaging systems using a hardware-in-the-loop technique based on TI6713 Digital Signal Processor (DSP) units. The methodology centers on procedures to enhance the degree of automation in the modeling and simulation processes by taking the following actions: (1) improving the automated development of algorithms to compute the two dimensional (2D) discrete Fourier transform (DFT), (2) enhancing the use of 2D DFT algorithms in implementing active sensor image formation operations, and (3) estimating the ambiguity function as the impulse response function of active imaging systems using principles of time-frequency signal representation theory. These actions have produced significant results such as a 30% to 90% improvement in 2D DFT implementations over conventional techniques, enhancement on scalable techniques for computing the ambiguity function, fast implementation techniques for computing image formation operations using the 2D fast Fourier Transform (FFT), and integrated MATLAB© user’s interfaces for the overall modeling and simulation processes.

I. INTRODUCTION

This work presents a new methodology for the modeling and simulation of active sensor imaging systems utilized in remote sensing activities. In particular, the work concentrates in the modeling of synthetic aperture radar (SAR) systems [1] for environmental surveillance and monitoring applications. The objective of these applications is to gather and process appropriate environmental information through remote sensing means in order to aid in the process of effective decision making. Of great importance is the gathering of environmental information on a timely basis by using airborne radar sensor systems. This dictates the necessity for new modeling and simulation techniques for the rapid prototyping of such systems [2]. This work focuses on hardware-in-the-loop (HIL) techniques using TI6713 floating point digital signal processors (DSP) to model and simulate synthetic aperture radar (SAR) signal processing subsystems. These HIL techniques intend to improve the precision and accuracy of generated raw data and the creation of computed images (image formation operations) from acquired raw data. This work also presents a modality for the design of workstation’s user interfaces based on MATLAB© to

assist in the automation of hardware-in-the-loop simulation using DSP units. The SAR image formation process is simulated through the two-dimensional cyclic convolution operation which is based on efficient computation of the two-dimensional discrete Fourier transform operation. In the next section, mathematical formulations are presented which assist in understanding the techniques used to implement the two dimensional Fourier transform computations as well as the ambiguity function for modeling active sensor imaging impulse response functions.

II. MATHEMATICAL FORMULATIONS

A. Out of Core Two-Dimensional Discrete Fourier Transforms

A well known image processing tool is the two-dimensional discrete Fourier transform which is described below using the language of signal algebra operators. Let $x \in \ell^2(Z_{N_0} \times Z_{N_1})$, where $\ell^2(Z_{N_0} \times Z_{N_1})$ is the space of all discrete complex two dimensional signals of order $N \times N$. This space is endowed with standard inner product and Euclidean norm operations. Its Fourier transform is given by $\mathcal{F}_{N_0 \times N_1}\{x\} = \hat{x}$, where $(\hat{x})[k_0, k_1]$ is provided by the following expression:

$$(\hat{x})[k_0, k_1] = \sum_{n_1 \in Z_{N_1}} \left(\sum_{n_0 \in Z_{N_0}} x[n_0, n_1] W_{N_0}^{k_0 n_0} \right) W_{N_1}^{k_1 n_1}.$$

Let $x_{n_0}[n_1] = x[n_0, n_1]; n_1 \in Z_{N_1}, n_0 \in Z_{N_0}$. Then $\sum_{n_1 \in Z_{N_1}} x_{n_0}[n_1] W_{N_1}^{k_1 n_1} = x_{n_0}[k_1]; n_0 \in Z_{N_0}$. We, thus, have $(\hat{x})[k_0, k_1] = \sum_{n_0 \in Z_{N_0}} x_{n_0}[k_1] W_{N_0}^{k_0 n_0} = \sum_{n_0 \in Z_{N_0}} x_{k_1}[n_0] W_{N_0}^{k_0 n_0} = \hat{x}_{k_1}[k_0] = \hat{x}_{k_1}[k_1]$

B. Ambiguity Function as Point Spread Function

In this work, the discrete ambiguity function is also described using the language of signal algebra operators and it is utilized to model the impulse response function of a SAR system. Next, the ambiguity function is formulated using two different methods: the filter method and the Fourier transform method.

I. Filter Method

Let $x_T, x_R \in \ell^2(Z_N)$ the discrete ambiguity function of x_T and x_R is given by the following expression:

$A_{x_T, x_R}[m, k] = \sum_{n \in Z_N} x_T[n] x_R^*[(n+m)_N] e^{-j2\pi kn/N}$ for $k, m \in \ell^2(Z_N)$. Let $\mathcal{M}_k = \psi_k \in \Psi = \psi_k : \psi_k[n] = e^{-j2\pi kn/N}; k, n \in Z_N$.

The set Ψ is called the set of character basis vectors on simply characters. The action of \mathcal{M}_k on the signal x_T is defined as follows:

$$\mathcal{M}_k : \ell^2(Z_N) \rightarrow \ell^2(Z_N) \text{ such that} \\ (\mathcal{M}_k \{x_T\})[n] = x_T[n] \psi_k[n], n \in Z_N$$

Let, $x_{R\{-m\}_N}^* = \mathcal{S}_N^{(-m)_N} \{x_R^*\}$. Then,

$$\left(x_{R\{-m\}_N}^* \right)[n] = \left(\mathcal{S}_N^{(-m)_N} \{x_R^*\} \right)[n] = x_R^*[(n+m)_N]$$

allowing $\langle -m \rangle_N = \langle N - m \rangle_N = l < N$. Thus, $(x_{R\{-m\}_N}^*)[n] = (x_R^*\{l\})[n]$. Gathering expressions results in the following formulation:

$$A_{x_T, x_R}[m, k] = \sum_{n \in Z_N} (\mathcal{M}_k^* \{x_T\})[n] (\mathcal{S}_N^l \{x_R^*\})[n] = \sum_{n \in Z_N} (\mathcal{M}_k^* \{x_T\})[n] (\mathcal{S}_N^l \{x_R\})^* [n]. \text{ Finally,} \\ A_{x_T, x_R}[m, k] = \langle (\mathcal{M}_k^* \{x_T\})[n] (\mathcal{S}_N^l \{x_R\}) \rangle$$

II. Fourier Transform Method

$A_{x_T, x_R}[m, k] = \sum_{n \in Z_N} x_T[n] x_R^*[(n+m)_N] W^{kn}$ for $k, m \in \ell^2(Z_N)$. Let $\mathcal{S}_N^{(-m)_N} \{x_R^*\} = x_{R\{-m\}_N}^*$. Also, allow $x_m = x_T \odot_N x_{R\{-m\}_N}^*$. Thus, an evaluation of x_m at $n \in Z_N$ results in $x_m[n] = x_T[n] x_{R\{-m\}_N}^*[n], n \in Z_N$. Then, $A_{x_T, x_R}[m, k] = \sum_{n \in Z_N} x_m[n] W^{kn} = ((x_m)^\wedge)[k] = \hat{X}_m[m]$ where, $\hat{X}_m[k] = \mathcal{F}_N \{x_m\}$

III. CONCEPTS OF ACTIVE SENSOR IMAGING

An active imaging sensor system utilized to form images can be modeled, in a simple manner, as a linear and time invariant system. Using this simple but insightful model, it is possible to produce a reconstruction estimate of an image from raw data through a matched filtering process between the raw data received from the sensor and the impulse response of the system which is represented by an ambiguity function. The matched filter is performed by using a cyclic convolution which, in turn, is performed indirectly by using the discrete Fourier transform (DFT) operation. It is important to recall that the one dimensional discrete cyclic convolution based on the DFT can be expressed as follows:

$$x[n] \otimes h[n] = \mathcal{F} \{x[n]\} \bullet \mathcal{F} \{h[n]\}$$

The same concept is extended to the 2D cyclic convolution operation which is used in 2D matched filtering problems: $\gamma[m_x, m_y] = \{g[m_x, m_y]\} \otimes_2 \{h[m_x, m_y]\} = \mathcal{F} \{g[m_x, m_y]\} \bullet \mathcal{F} \{h[m_x, m_y]\}$, where \otimes_2 represents the 2D cyclic convolution operator and \bullet represents the Hadamard product operator or point by point multiplication. This method for reconstruction estimates of SAR images using the two-dimensional Fourier transform has been studied in previous works [3].

A. Two-Dimensional Fourier Transform Operator

In most previous studies [4] related with SAR imaging, the image formation process is performed using combined range and azimuth compression procedures that correspond to one dimensional signal processing operations. This work uses a two-dimensional impulse response function approach to perform the image formation operation. As it is commonly known, the 2D DFT can be implemented using, for example, the one-dimensional FFT over the rows of the data array and then one-dimensional FFT over the columns of the resulting array. The process implemented to compute the two dimensional Fourier transform is depicted in Fig. 1.

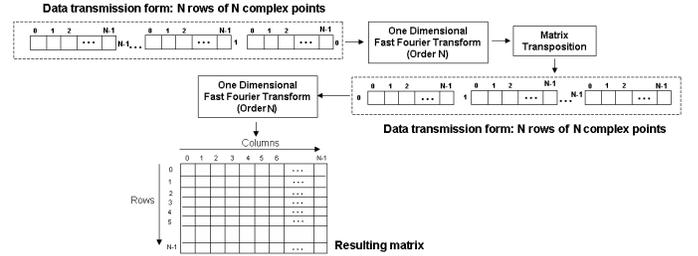


Fig. 1. 2D DFT Computation: Standard Process

Performing 2D DFT operations becomes extremely difficult when using DSP as units. As the data size increases, DSP internal memory limitations demand the use of out-of-core storage since the computation problem cannot be wholly contained in a DSP core unit. Using multiple DSP units does not solve the storage problem and it introduces a more difficult problem, the problem of partitioning a given computational operation [5]. The process depicted in Fig. 1 shows out-of-core computation where the data entry matrix is sent to a one dimensional FFT process, row by row, in such a way that just one memory buffer is utilized to store the data to be processed out-of-core. This process is slow if the data transfer is performed through standard means such as the RTDX format of the TI6713 DSP unit. An enhancement to this approach is presented here through the use of memory storage as memory buffers or register banks and shown in Fig. 2. In this particular case, for example, sixteen registers are utilized as the data pathway between a DSP core unit and external memory storage. The number of registers to be utilized in a register bank is still dictated by the target application. This process is more efficient than the single register technique as far as data transfer is concerned. Computational processes using register banks are favorable since they may be scalable to multicore units.

IV. HARDWARE-IN-THE-LOOP MODELING AND SIMULATION

In this work a novel technique is presented for SAR active sensor imaging system modeling based on the use of the ambiguity function of a transmitted signal and a received

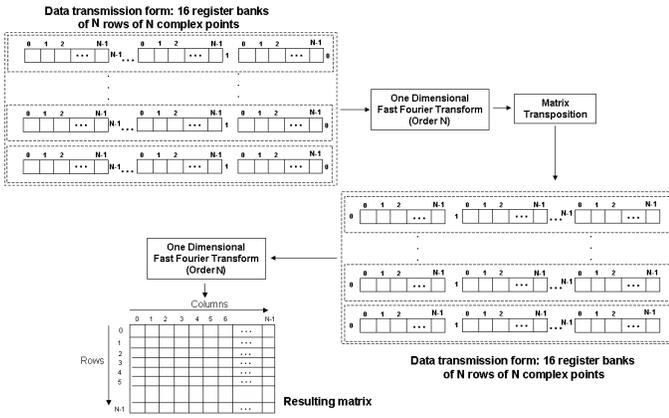


Fig. 2. 2D DFT Computation: Register Banks Process

signal as the impulse response function of the active imaging system, treated as a linear time invariant operator. It is also based on an adaptive matched filtering technique to be utilized to obtain an image reconstruction estimate. The overall active sensor imaging model is depicted in Fig. 3.

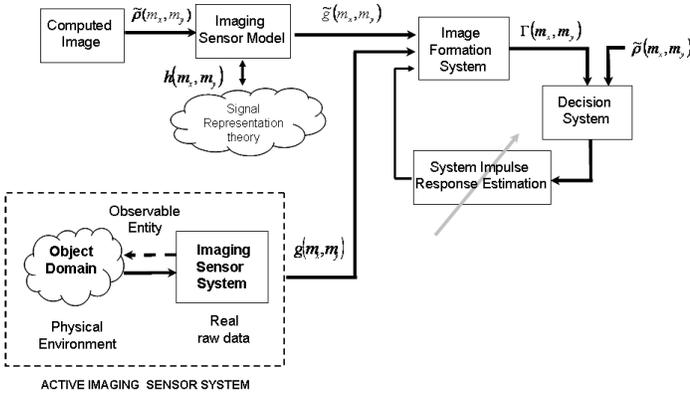


Fig. 3. SAR Active Sensor Imaging System Model

In this figure, $\tilde{\rho}(m_x, m_y)$ is the simulated reflectivity density function, $\tilde{g}(m_x, m_y)$ is the artificial raw data, $\Gamma(m_x, m_y)$ is the image obtained from the sensor imaging system and $g(m_x, m_y)$ is the actual raw data. The hardware-in-the-loop system used in this work is an aggregate of the following units: A mathematical model for SAR imaging, artificial or simulated raw data to be processed by the system, a host PC workstation with a link to a DSP unit, and a floating point digital signal processor (DSP) TI6713 unit. The PC host workstation may be replaced by embedded computer system as depicted in Fig. 4. The mathematical model for SAR image processing is based on the ambiguity function computation as point spread function or impulse response function of a SAR system and the image formation process is implemented using the two dimensional cyclic convolution between the raw data and the SAR system impulse response.

The host PC workstation has a communication link to

the DSP through the MATLAB © numeric computation and scientific visualization software package. As stated before, an embedded computer system interacting with digital signal processors may be used to replace the PC workstation to make a hardware system more portable. The PC station is used to control the hardware-in-the-loop process, to provide the data to the DSP, and to test results obtained in the simulation operation. The DSP component is used to execute the algorithms generated from a mathematical model of a SAR active sensor imaging system. Special attention is given to hardware characteristics such as portability, memory size, and data transfer rate in order to improve the overall performance of hardware-in-the-loop modeling and simulation. An integrated formulation is presented on Fig. 4 of the overall hardware-in-the-loop modeling and simulation processes.

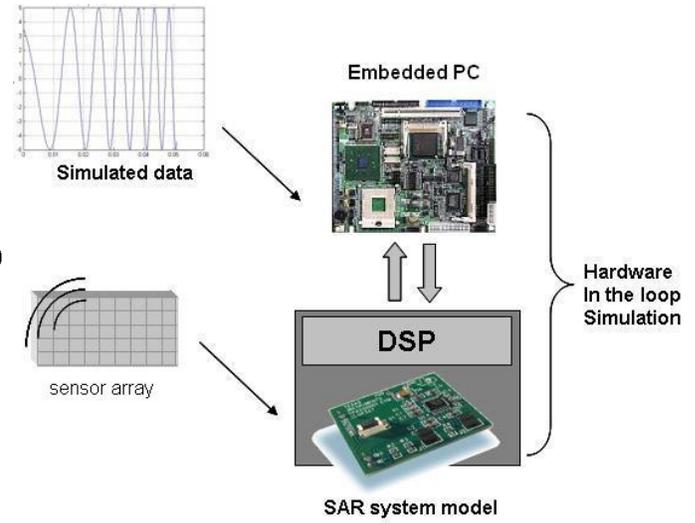


Fig. 4. Hardware in the Loop System Representation

V. HARDWARE-IN-THE-LOOP ACTIVE IMAGING SENSOR

A. Software/Hardware Interface Co-Design

The following items are examples of considerations taking into account for the design and development of the overall modeling and simulation system:

- The PC controls the hardware-In-The-Loop simulation indicating when it starts and ends. The process starts connecting the DSP board by software in order to establish communication and opening the USB port for the data flow between both units. The data transmission uses RTDX (Real Time Data Exchange) tool which allows the user to exchange data between PC and the board without stop the target application. It provides the user a realistic idea about the way the system operates.
- The user selects the process to be simulated and the data that will be used in the selected process.
- The PC contains the digital data stored in memory and sends it via USB port to the DSP board using MATLAB interface.

- On the DSP board is executed the algorithm and results are returned upon PC and stored for display or future processing.
- A graphical user interface to make the hardware-in-the-loop simulation process friendly to the user. Figure 5 shows the user interface to drive the hardware from the PC using a MATLAB environment. Path from the connection of the board up to the selection of the data to be transferred in each process can be controlled by the user. Three processes have been integrated as part of the user interface for the hardware-in-the-loop system: 2D-FFT, 2D cyclic convolution and the ambiguity function computation.

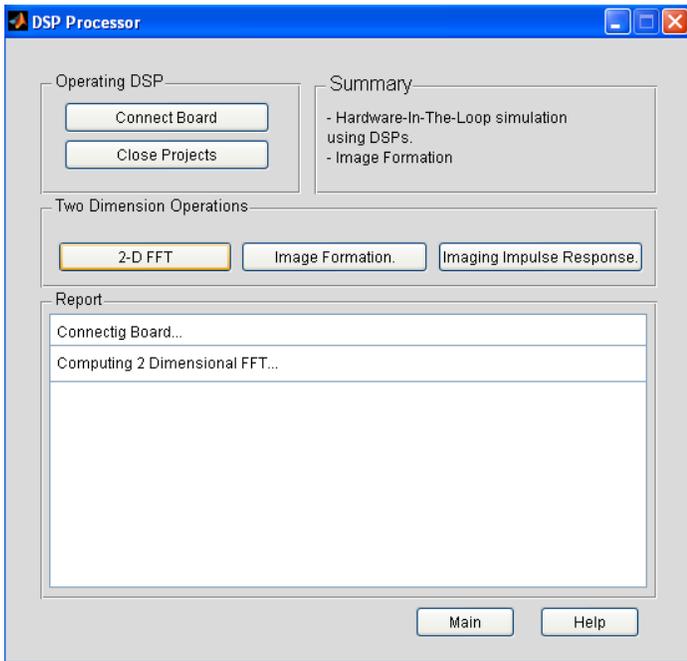


Fig. 5. Hardware-In-The-Loop Simulation User's Interface

VI. TWO-DIMENSIONAL FFT COMPUTATIONAL RESULTS

On of the main advantages of using hardware-in-the-loop simulation is the fact that it permits to evaluate the behavior of the sensor imaging systems under test in a rather faster manner contributing in this way to the decision making process about the suitability of the signal processing units for the targeted applications. One of the measurements that can be analyzed at the end of a SAR image formation system simulation is the execution time of the algorithms. Since the Fourier transform is the basis of the active sensor imaging system modeling and simulation, some results of the two dimensional Fourier transform computations were measured and they are shown in Fig. 6 and Fig. 7. Also, Tables I and Table II present the computational time for one-dimensional and two-dimensional FFT computations for different data lengths in a TI 6713 digital signal processor. Figure 6 shows the computational time for the two-dimensional Fourier transform operation where the

upper graph is the result of using just one register in the data transmission and the lower graph is the result of utilizing a bank of sixteen registers as data buffer for data exchange using standard RTDX. Figure 7 presents computational improvements improvements percentage wise as the register banks process is utilized..

TABLE I
1D FFT TIMES - TMS320C6713 DSP

No. of points of a signal (Double Datatype)	1D FFT Times (mSecs.)
16	0.0166
32	0.0363
64	0.0803
128	0.178
256	0.395
512	0.899
1024	1.969
2048	25.00
4096	55.01
8192	117.40
16384	252.40

TABLE II
2D FFT TIMES USING DSK MEMORY - TMS320C6713 DSP

No. of points of a signal (Double Datatype)	2D FFT Times (Secs.)
16x16	0.0098
32x32	0.0485
64x64	0.2133
128x128	0.9499
256x256	4.207
512x512	18.0801

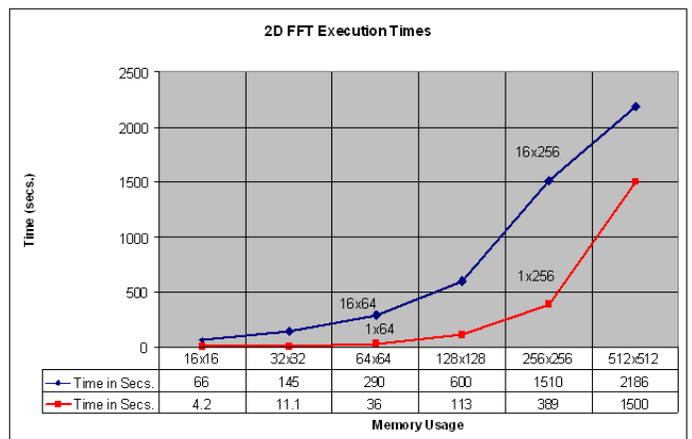


Fig. 6. 2D Fourier Transform Execution Times

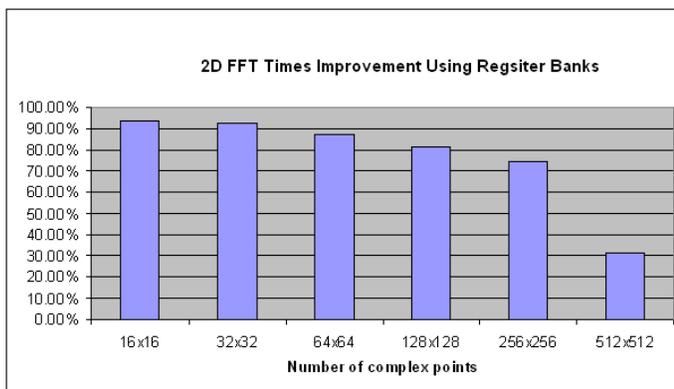


Fig. 7. 2D FFT Percentage Improvement using Register Banks

VII. CONCLUSION

This work has presented a new methodology for the modeling and simulation of active sensor imaging systems utilized in remote sensing activities. In particular, the work concentrated in the modeling of synthetic aperture radar (SAR) systems for environmental surveillance and monitoring applications. The objective of these applications is to gather and process appropriate environmental information through remote sensing means in order to aid in the process of effective decision making. A SAR model using synthetic or artificial raw data and adaptive filters was presented. Some advantages of using register banks to compute the two dimensional Fourier transform in a hardware-in-the-loop system and associated implementation performance measures were also presented. A graphical user interface tool was developed which allows to evaluate active sensor imaging system model's characteristics in an automated manner.

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