Real-Time, Simultaneous DAS, ADMIRE, and SLSC Imaging Using GPU-Based Processing

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***Abstract*—Aperture Domain Model Image REconstruction (ADMIRE) is an adaptive imaging method that has been shown to reduce sources of ultrasound image degradation that include both off-axis scattering and multipath scattering. It does so by performing a model-based fit of the aperture domain data in order to reconstruct the data by only using model predictors that are within a specified region-of-interest. By doing so, model predictors that contribute to sources of acoustic clutter can be removed. Although ADMIRE can reduce sources of clutter, one of its drawbacks is its significant computational requirements. We have been working on improving the computational speed of ADMIRE through the use of parallel processing on GPUs, but we have yet to demonstrate real-time imaging with it. Therefore, in this work, we have interfaced our GPU-based implementation of ADMIRE with a Verasonics Vantage 128 ultrasound research system in order to perform real-time imaging. Moreover, we show how other methods including delay-and-sum (DAS) and short-lag spatial coherence (SLSC) can also be computed and simultaneously displayed with ADMIRE.**

***Index Terms*—Ultrasound, GPU computing, Real-time imaging**

I. Introduction

OVER the years, a variety of advanced beamforming methods have been proposed and have been shown to provide significant improvements in ultrasound image quality. However, despite promising results, delay-and-sum (DAS) beamforming is still the primary method that is used in clinical scanners today. This is because one of the fundamental barriers to adopting these newer methods is that their computational complexity often makes it costly or difficult, if not infeasible, to develop implementations that can achieve real-time imaging using CPUs or ASICs. Now, although this is true, in recent years, GPUs have emerged as a powerful tool for general purpose computing. This is due to the fact that a typical GPU has hundreds to thousands of computational units that can be used for massively parallel processing, which is a much larger number when compared to the number that a typical CPU has. In addition, unlike ASICs, a traditional software programming approach can be used with GPUs, which allows for reduced development time and costs.

Due to these benefits, GPUs have been used to develop real-time implementations of advanced beamforming methods. For example, short-lag spatial coherence (SLSC) beamforming involves calculating the spatial coherence of backscattered echoes, and it assumes that mechanisms of image degradation contribute to signal incoherence. This method requires a large number of computations to be performed due to the fact that for a given pixel, the coherence across the aperture must be calculated. Despite this, these computations can be performed in parallel in order to achieve significant speedup. Therefore, Hyun et al. developed a GPU implementation of this technique [1], [2] that was able to achieve real-time imaging. Minimum variance beamforming is another technique that is compute-intensive. This technique improves image quality by applying an adaptive weighting scheme to the received data in order to position side lobes in directions where there is a low amount of received energy, but obtaining these adaptive weights requires the computation of covariance matrices and their inverses. However, like the coherence computations for SLSC, these computations can also be performed in parallel. Due to this, Chen et al. developed a real-time GPU implementation of this technique [3].

Examples like the aforementioned ones served as motivation for us to use GPU-based processing in order to accelerate Aperture Domain Model Image REconstruction (ADMIRE) [4], [5], [6]. This is our previously developed beamforming method that uses a model-based approach in order to suppress sources of acoustic clutter. As illustrated by the overview

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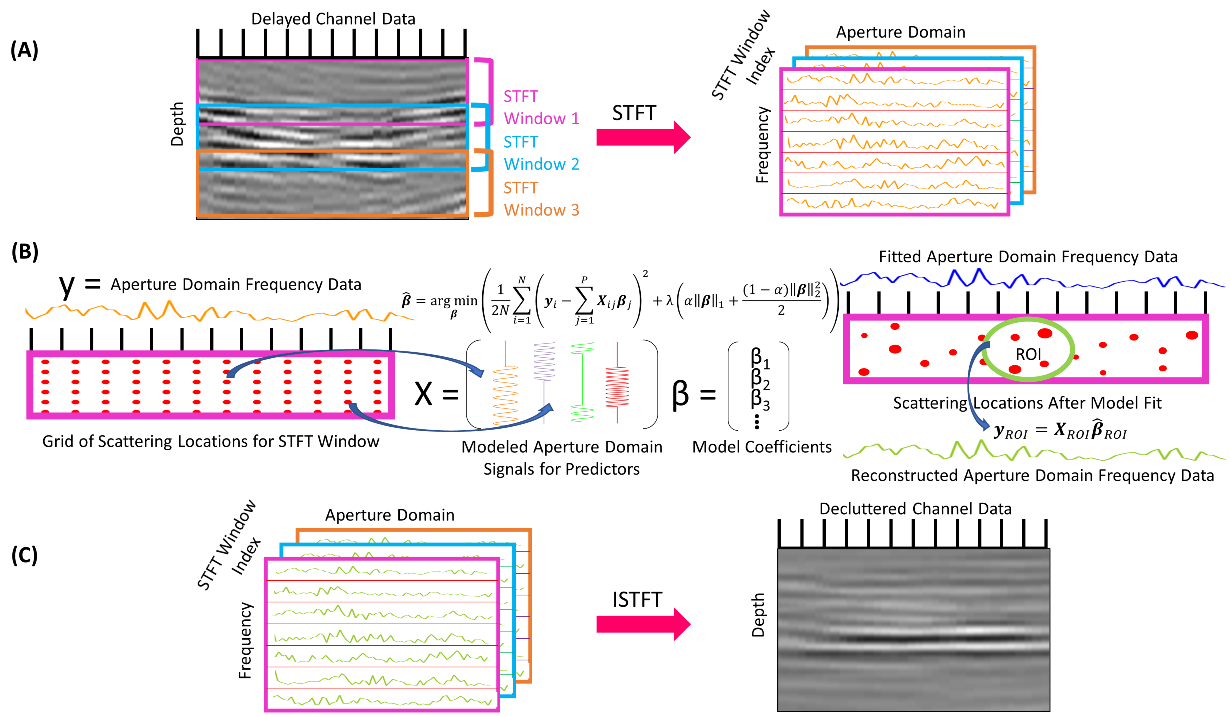

Fig. 1. Overview of ADMIRE. **(A)** Obtain the delayed channel data and calculate the short-time Fourier transform along the depth dimension for each channel. **(B)** Obtain the corresponding model matrix for each set of aperture domain frequency data that will be reconstructed in each STFT window in each beam, fit each model matrix to its corresponding set of aperture domain frequency data (sizes of red points correspond to how much each scattering location contributes to the aperture domain frequency data), and reconstruct each set of aperture domain frequency data by only using the predictors that correspond to scattering locations that are within a region-of-interest (ROI). **(C)** Calculate the inverse short-time Fourier transform of the reconstructed aperture domain frequency data in order to obtain the decluttered channel data. Note that the scattering locations are not restricted to the depth range of the STFT window. The grid of scattering locations illustrated in **(B)** corresponds to the first STFT window. For STFT windows that correspond to deeper depths, the scattering locations can also be located in shallower depths because these locations can contribute to off-axis scattering and multipath scattering that affect the aperture domain frequency data for the STFT window. Essentially, as the depths become deeper for subsequent STFT windows, the depth range for possible scattering locations also increases.

of ADMIRE in Fig. 1, the method requires a large number of computations, but by developing a GPU implementation, significant computational speedup was achieved when compared to a CPU implementation [7]. However, we did not demonstrate real-time imaging with ADMIRE. Therefore, in this work, we exhibit the ability of the GPU implementation of ADMIRE to be interfaced with a Verasonics (Verasonics, Kirkland, WA) Vantage 128 ultrasound research system in order to perform real-time imaging. In addition, we show that other beamforming methods including DAS and SLSC can also be computed and simultaneously displayed with ADMIRE.

II. Methods

To perform real-time imaging with a Verasonics Vantage 128 ultrasound research system, a MATLAB (The MathWorks, Inc., Natick, MA) MEX-file was created in order to call our previously developed GPU implementations of DAS, ADMIRE, and SLSC that were written using the C programming language along with NVIDIA's (NVIDIA Corporation, Santa Clara, CA) Compute Unified Device Architecture (CUDA) parallel programming platform. A Verasonics sequence was developed for an L7-4 linear transducer array to perform a walked aperture scan with focused transmits, and the MEX-file was called as part of an external processing event. The Verasonics hardware and software sequencers were synchronized so that one frame of channel data was collected and processed before the next frame was acquired. Verasonics GUI controls were also added to allow for changing ADMIRE and SLSC parameters in real-time. For ADMIRE, these parameters were the α value that is used in elastic-net regularization, the c_λ value that is used to calculate λ for elastic-net regularization, the maximum number of iterations of cyclic coordinate descent to perform, and the tolerance convergence criterion for cyclic coordinate descent. Note that cyclic coordinate descent is the optimization algorithm that is used to perform the model fits in ADMIRE. For SLSC, the parameters were the axial kernel size, the maximum lag between elements, and the spacing between elements that is used when a downsampled aperture is utilized to improve computational efficiency [8]. The imaging pipeline is outlined in Fig. 2 below. The host computer that was used for scanning contained dual Intel (Intel Corporation, Santa Clara, CA) Xeon E5-2650 v2 CPUs @ 2.60 GHz with 8 cores each and an NVIDIA GeForce RTX 2080 Ti GPU. A multi-purpose phantom (Model 040GSE, CIRS, Norfolk, VA) was scanned along with the carotid artery of an *in vivo* subject. The imaging and processing parameters that were used for both cases are shown in Table I. The parameters denoted with (Def.) in this table are the adjustable parameters, and the listed values are the default values that are used when the Verasonics sequence begins. In addition, FOBI-ICA [9], [10] was applied to the ADMIRE models in order to reduce their sizes and improve the computational efficiency of ADMIRE [11].

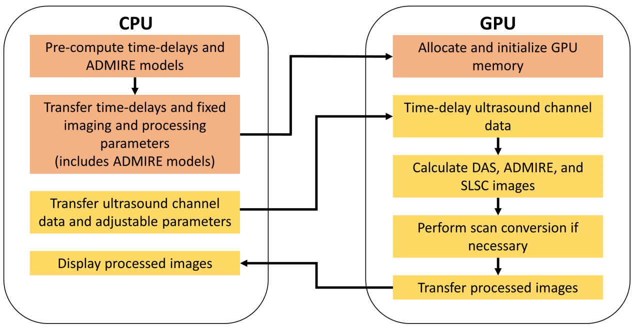

Fig. 2. Diagram of the processing pipeline for real-time imaging. Peach colored boxes represent stages that are only performed once. Yellow colored boxes represent stages that are performed for every image frame.

TABLE I: Imaging/Processing Parameters for Scans

Imaging/Processing Parameter	Phantom	Carotid Artery
Depth Samples	2,667	1,250
Elements	65	65
Beams	64	64
f0 (MHz)	5.2083	5.2083
fs (MHz)	20.8333	20.8333
Padded STFT Window Length	12	12
STFT Window Overlap	0%	0%
Frequencies Fit per STFT Window	3	3
α for Regularization (Def.)	0.9	0.9
c_λ for Regularization (Def.)	0.0189	0.0189
Coordinate Descent Max Iterations (Def.)	100,000	100,000
Coordinate Descent Tolerance (Def.)	0.1	0.1
SLSC Axial Kernel Size (Def.)	5	5
SLSC Maximum Lag (Def.)	10	10
SLSC Element Spacing (Def.)	1	1
Aperture Growth	Not Applied	Not Applied

III. Results

When performing real-time imaging of the phantom, a frame rate of 8-9 frames per second was achieved. An example screen capture that was taken during imaging is shown in Fig. 3. In addition, when performing real-time imaging of the carotid artery of the *in vivo* subject, a frame rate of 14-15 frames per second was achieved. An example screen capture that was taking during imaging is shown in Fig. 4. Videos of real-time imaging for both cases are also provided and can be accessed by viewing the corresponding ePoster.

IV. Discussion

As demonstrated by Fig. 3 and Fig. 4, real-time, simultaneous imaging with DAS, ADMIRE, and SLSC can be achieved by using GPU implementations of these beamforming techniques. The frame rate for the carotid artery scan case was higher than the phantom scan case due to the fact that the frame rate depends upon the imaging and processing parameters that are utilized. For the carotid artery scan, the depth range that was used was less than half the depth range that was used for the phantom scan. Moreover, for both cases, ADMIRE was the primary computational bottleneck out of the three beamforming methods.

V. Conclusions

We have demonstrated the use of GPU-based processing in order to perform real-time, simultaneous imaging with DAS, ADMIRE, and SLSC. In terms of frame rate, it varies depending upon the imaging and processing parameters that are utilized. Future work involves further optimizing the processing pipeline in order to achieve increased frame rates. Moreover, we have previously demonstrated a multi-GPU implementation of ADMIRE that is able to provide additional speedup when compared to a single GPU implementation [7]. Therefore, DAS and SLSC could also be incorporated into the multi-GPU implementation for simultaneous imaging like they were incorporated into the single GPU implementation in order to obtain an additional improvement in frame rate.

VI. Acknowledgement

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References

[1] D. Hyun, G. Trahey, and J. Dahl. "In vivo demonstration of a real-time simultaneous B-mode/spatial coherence GPU-based beamformer." *2013 IEEE International Ultrasonics Symposium (IUS)*. IEEE, 2013.

[2] D. Hyun, G. Trahey, and J. Dahl. "Real-time high-framerate in vivo cardiac SLSC imaging with a GPU-based beamformer." *2015 IEEE International Ultrasonics Symposium (IUS)*. IEEE, 2015.

[3] J. Chen, B. Yiu, H. So, and A. Yu. "Real-time GPU-based adaptive beamformer for high quality ultrasound imaging." *2011 IEEE International Ultrasonics Symposium*. IEEE, 2011.

[4] B. Byram and M. Jakovljevic. "Ultrasonic multipath and beamforming clutter reduction: a chirp model approach." *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* 61.3 (2014): 428-440.

[5] B. Byram, K. Dei, J. Tierney, and D. Dumont. "A model and regularization scheme for ultrasonic beamforming clutter reduction." *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* 62.11 (2015): 1913-1927.

[6] K. Dei and B. Byram. "The impact of model-based clutter suppression on cluttered, aberrated wavefronts." *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 64, no. 10, pp. 1450–1464, 2017.

[7] C. Khan, K. Dei, and B. Byram. "A GPU-Based Implementation of ADMIRE." 2019 IEEE International Ultrasonics Symposium (IUS). IEEE, 2019.

[8] D. Hyun, A. Crowley, and J. Dahl. "Efficient strategies for estimating the spatial coherence of backscatter." IEEE transactions on ultrasonics, ferroelectrics, and frequency control 64.3 (2016): 500-513.

[9] J.F. Cardoso. "Source separation using higher order moments." *International Conference on Acoustics, Speech, and Signal Processing*. IEEE, 1989.

[10] S. Jonathon. "A tutorial on independent component analysis." *arXiv preprint arXiv:1404.2986* (2014).

[11] K. Dei, S. Schlunk, and B. Byram. "Computationally-Efficient Implementation of Aperture Domain Model Image Reconstruction (ADMIRE)." *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* (2019).

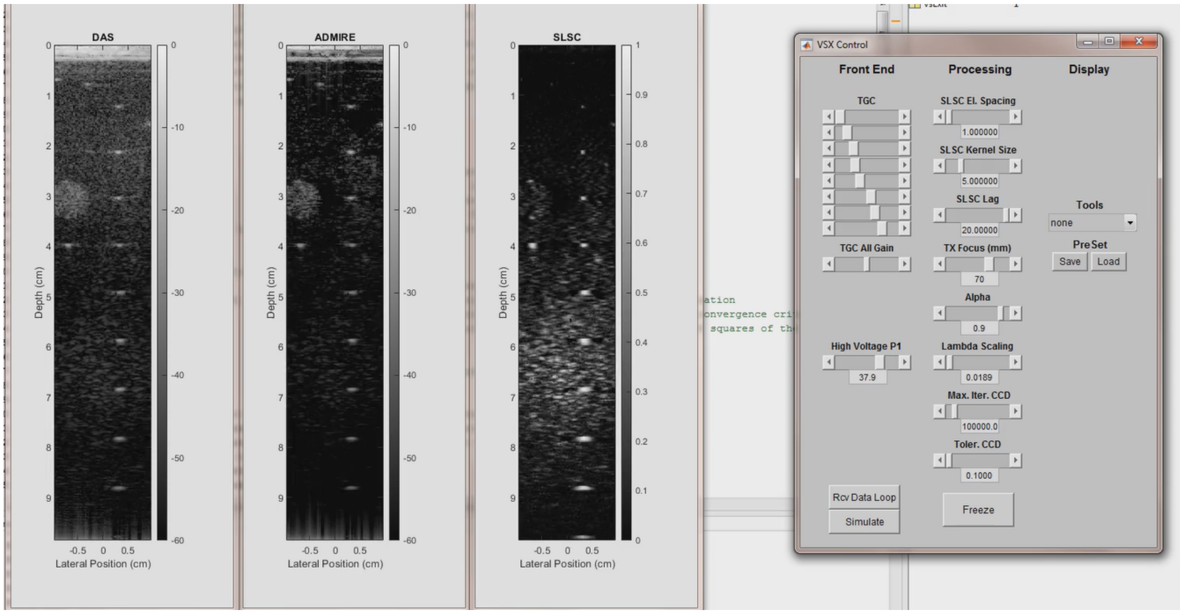

Fig. 3. Screen capture during simultaneous DAS (left), ADMIRE (center), and SLSC (right) real-time imaging with the L7-4 probe sequence. The images are of a quality assurance CIRS phantom. The DAS and ADMIRE images are displayed with a dynamic range of 60 dB, and the SLSC image is displayed using a range from 0 to 1. Note that the SLSC lag was updated to 20 in real-time.

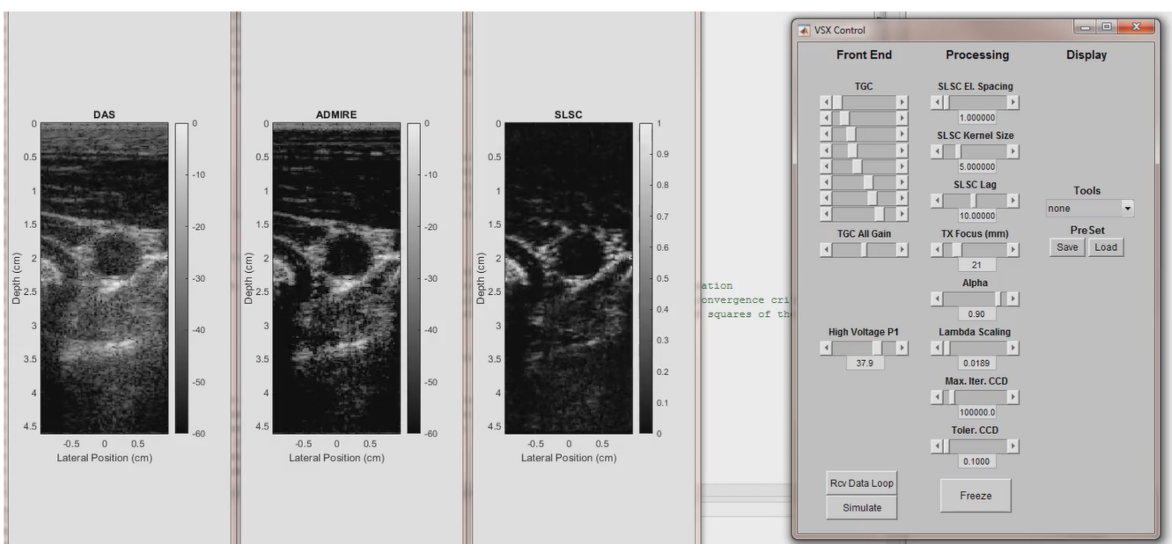

Fig. 4. Screen capture during simultaneous DAS (left), ADMIRE (center), and SLSC (right) real-time imaging with the L7-4 probe sequence. The images are of the carotid artery. The DAS and ADMIRE images are displayed with a dynamic range of 60 dB, and the SLSC image is displayed using a range from 0 to 1.