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Virtual real-time: a new US operating modality

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***Abstract*— High frame rate (HFR) imaging methods are increasingly popular but impose severe requirements to ultrasound scanners. Real-time HFR imaging is such a challenging task that, conventional scanners merely elaborate the echo-data in post-processing. Real-time acquisition and data post-processing are usually well separated: the former needs to be guided by a standard B-Mode display that is interrupted when the raw data are transferred to, e.g., a GPU board for off-line processing. In this paper we describe a different approach, called "virtual real-time" mode, implemented on the ULA-OP 256 scanner, in which the two phases are tightly interleaved: raw data that are continuously stored in RAM during a real-time elaboration can be immediately re-processed at a different rate. This enables not only to display in slow-motion possible fast recorded events, but also to facilitate the achievement of optimal conditions for US acquisition and the extraction of additional information from the echo data.**

Keywords*—*High Frame Rate, Processing, FPGA, Ultrasound System, ULA-OP

I. Introduction

Applications of High Frame Rate (HFR) imaging methods are increasingly popular due to their capability of acquiring phenomena in rapid evolution. The design and development of new high-performance systems capable of implementing HFR methods in real-time is a crucial challenge. Modern systems acquire frames at very high rates; however, the real-time elaboration of the corresponding massive amount of data, and the presentation on the display, present several challenges. For example, in case of HFR B-mode imaging it is possible to acquire and process frames at hundreds or thousands of frame/s, but this rate is not reproducible on monitors and, in any case, human eyes are not sensitive to such high frequencies. Furthermore, in demanding methods as multigate spectral Doppler [1], 2D Vector flow imaging [2], HFR color flow mapping [3], etc. the required calculation power might not be sustained in real-time. Typically, the systems first use B-Mode real-time imaging to set the best probe position, then they switch to HFR acquisition to save raw data. Finally, the raw data are processed off-line in a PC, which may use a graphical processing unit (GPU) [4] to accomplish the heaviest elaborations. In this approach, after the acquisition, several seconds may be needed to view the results.

In this paper we describe the new Virtual real-time (VRT) approach, which has been implemented on the ultrasound research scanner ULA-OP 256 [1][4]. Raw data is continuously stored on RAM during the real-time investigation and processed according to the on-board calculation power. With a simple command on the ULA-OP 256 graphic user interface, the system starts to re-process the saved raw data at the rate most suitable for full data processing and/or for the desired reproduction rate on the display. Moreover, the user can change any processing parameter compatible with the TX strategy used during acquisition. This on-demand approach to the processing of raw data is complementary to the slow-motion replay mode that is recently realized on a software-oriented open platform for HFR flow imaging [6].

This paper describes the implementation of the Virtual real-time approach on ULA-OP 256 and reports some examples of its use in different applications.

II. Methods

The ULA-OP resources used to implement the virtual real-time modality are described in the next two sections.

A. System Front-End

ULA-OP 256 is composed by 8 Front-End boards. Each board has the task of managing 32 acquisition channels, for a total of 256 independent channels. The Front-End boards are connected to the probe, as well as to the host PC through an interface Master Control (MC) board. The Front-end boards and the MC board are connected by a SerialRapidIO (SRIO) link with four lanes.

Each Front-end board include: four analog front end (AFE) integrated circuits that filter, amplify and digitize the echoes backscattered to 32 probe elements, an FPGA (ARRIA V GX Family) that manages the signals from the AFEs and implements beamforming, two DSPs that process and demodulate the RF beamformed data, and 2 GB of DDR3 RAM (Fig. 1).

In real-time, the echoes received by the Front-end are amplified and converted at 78.125 MHz sampling rate and 12-bit resolution. Raw data are initially stored in a dual-port memory buffer implemented in the FPGA. The data in the dual

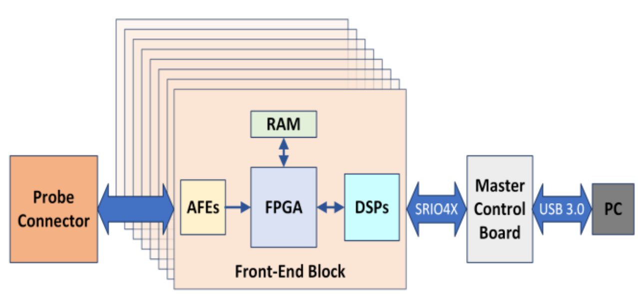

Fig. 1. Front-end system architechture

port memory buffer can be simultaneously sent to the FPGA beamformer and moved to the external RAM through a Direct memory Access (DMA). The beamformer receives data from the dual-port memory buffer, applies appropriate delays and apodization coefficients, finally performs the summation. ULA-OP 256 beamformer uses a non-standard delay and sum (DAS) approach: thanks to a special serial-parallel beamforming architecture [7][8], the system can process multiple lines per pulse repetition interval (PRI), as requested in HFR imaging. The FPGAs produce beamformed data up to 470 MSPS. The data processed and demodulated by the DSPs are sent to the MC board, which combines the data from all FE boards and transfers the resulting frame to the PC through USB 3.0.

B. Raw data storage

Raw data can be stored on RAM during real-time operation, in parallel with beamforming operations. In this condition the RAM is used as a circular buffer memory that continuously stores raw data at a rate of 41 Gb/s. The maximum system dimension of the circular buffer RAM is 16 GB, and for each of the 256 channels it is possible to store 62,5 MB of echo data. The amount of raw echo-data produced after each TX event corresponds to a total number of bits, D_{frame}, proportional to the number of channels N_{ch}, the number of samples collected at different depths, N_{Depth}, and the number of bits of each sample, N_{bit}, as showed in:

$$D_{frame} = N_{ch} * N_{depth} * N_{bit} \tag{1}$$

For example, if each image is derived from 256-channel raw echo-data of 2048 samples/PRI, and 12 bits for each sample, it is possible to store over 20000 frames.

When it is requested to process the raw data off-line, they are transferred to the host PC via USB3.0 and saved to a file.

C. Virtual Real-time

In VRT mode, the raw data saved on RAM during real-time acquisition are transferred to the dual-port memory buffer through the DMA. Then, they are beamformed, using the same hardware used to process the data in RT, as if the data came from the transducer (Fig. 2). However, during VRT the reproduction rate can be adjusted to fit the required calculation power and the desired display reproduction rate.

During a real-time acquisition, the circular buffer RAM continuously stores the raw data meanwhile they are processed by the system, until the user stops the investigation by the interface command. Now the system starts reading and processing the data stored in the circular buffer RAM (Fig. 2). The system can re-process the raw data with the same algorithms and parameters used in RT mode, but the operator can also change any setting compatible with the TX-RX strategy used during data saving. So, basically, in VRT it is possible acquiring echoes with some settings and elaborating them with different settings. The VRT modality is fully configurable through a set of parameters on the interface. Notably, it is possible to set a PRF for the acquisition (PRF_{ACQ}) and a different "virtual" PRF (VPRF) for VRT.

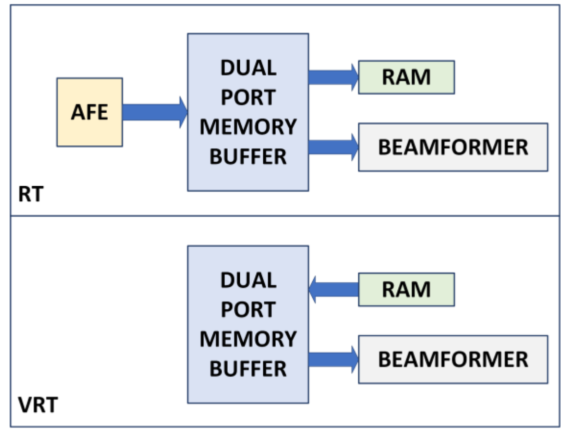

Fig. 2. Raw data flow in real-time and Virtual real-time

Virtual real-time mode can be used in different ways, like:

1) Data reprocessing
2) Variable speed reprocessing
3) Calculation-intensive elaboration

1) In Data reprocessing, the system starts the real-time operations and continuously saves raw data in the circular buffer RAM. When user switches to VRT, the system starts reprocessing the echo data present in RAM. It's possible to change all the settings as in a real-time investigation. The re-processing can be reloaded from the start as many times as desired.

2) The variable speed reprocessing is an extension of the previous case where the data are acquired at PRF_{ACQ} and processed in VRT mode at VPRF different than PRF_{ACQ}. The PRF_{ACQ} is always visible at the bottom of the window whereas, the VPRF can be changed to reprocess acquired phenomena at different speed. That case is particularly useful to appreciate quick phenomena in HFR imaging, where the VRT makes possible to reproduce in slow motion all the acquired frames.

3) This modality enables calculation-intensive modalities non feasible in RT, where the time among transmissions is not sufficient to complete the requested calculations. For example, in plane wave color flow mapping (CFM) [3], the PRF needed to detect high velocities may be so high that real-time CFM elaborations are only possible over a reduced region of interest (ROI). So, in RT a small ROI is processed while all raw echo-data are saved. In VRT the reproduction rate is lowered to allow more calculation time between consecutive frames, so that a larger ROI can be elaborated and displayed.

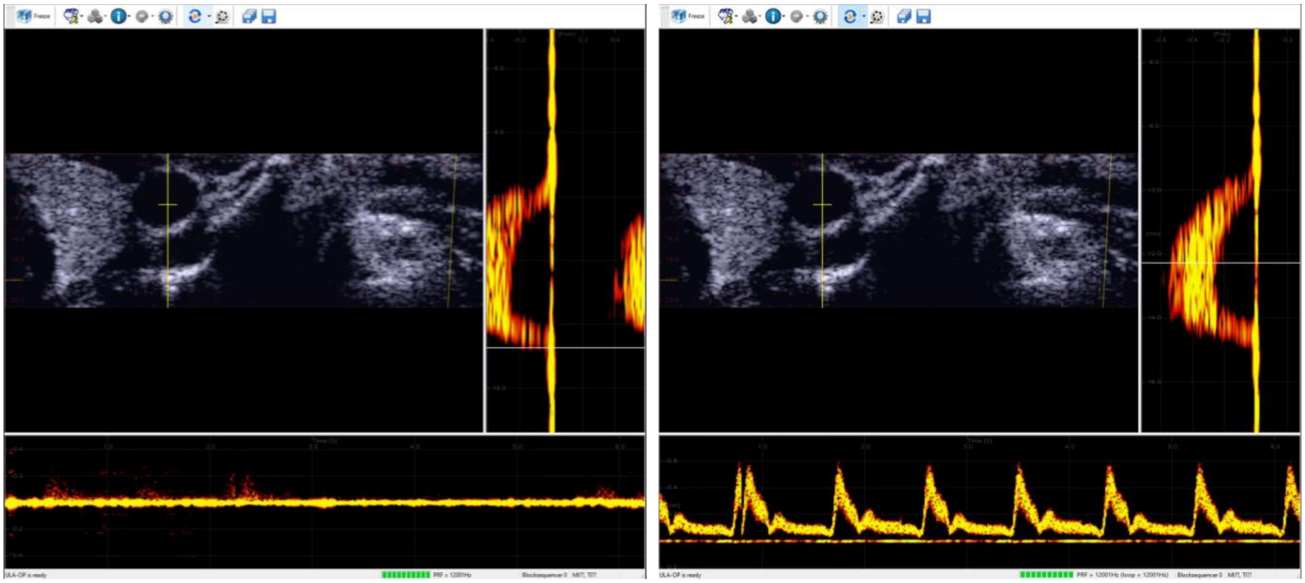

Fig. 3. Screenshots form the ULA-OP 256 display investigating a carotid with Multigate spectral Doppler. Each panel shows the Doppler scan line superimposed to the B-Mode image (left), the MSD profile with the white line indicating the depth form which the sonogram (bottom) was extracted. The MSD baseline and the sonogram depth were wrongly set in RT mode (left) and correctly set in VRT (right)

III. RESULTS

Three sample employments of the new VRT modality are here presented:

A. *Multigate spectral Doppler*

Multigate spectral Doppler (MSD) [1][9] is a method that allows displaying in real time the distribution of Doppler frequencies generated at different depths from the probe. In RT, with ULA-OP 256 [10] it is possible to show such distribution together with the B-Mode images, as well as the spectrogram originated from a selected depth. For example, Fig. 3 shows, on the left panel, a screenshot, obtained in RT, in which the baseline of the MSD distribution was wrongly set (so that aliasing effects are visible) and the sonogram was extracted from a depth corresponding to tissue. In VRT (right panel), it was possible to correct the baseline visualization and to select a suitable depth for the sonogram to be displayed (data reprocessing). Furthermore, it is possible to change parameters like the dynamics and the threshold of the profile, change the type of FFT windows, apply a video filter, change the B-Mode dynamics and threshold.

B. *HFR plane wave imaging*

ULA-OP 256 produces in real-time HFR images based on plane wave transmission [7]. In real-time, the frame undersampling caused by the monitor is high, but with VRT used in variable speed reprocessing, all frames can be displayed and individually seen by the operator.

A linear probe LA533 was immersed in a tank full of water. A metal tip was rapidly moved in front of the probe while imaged by the scanner for a duration of 200 ms. Plane waves

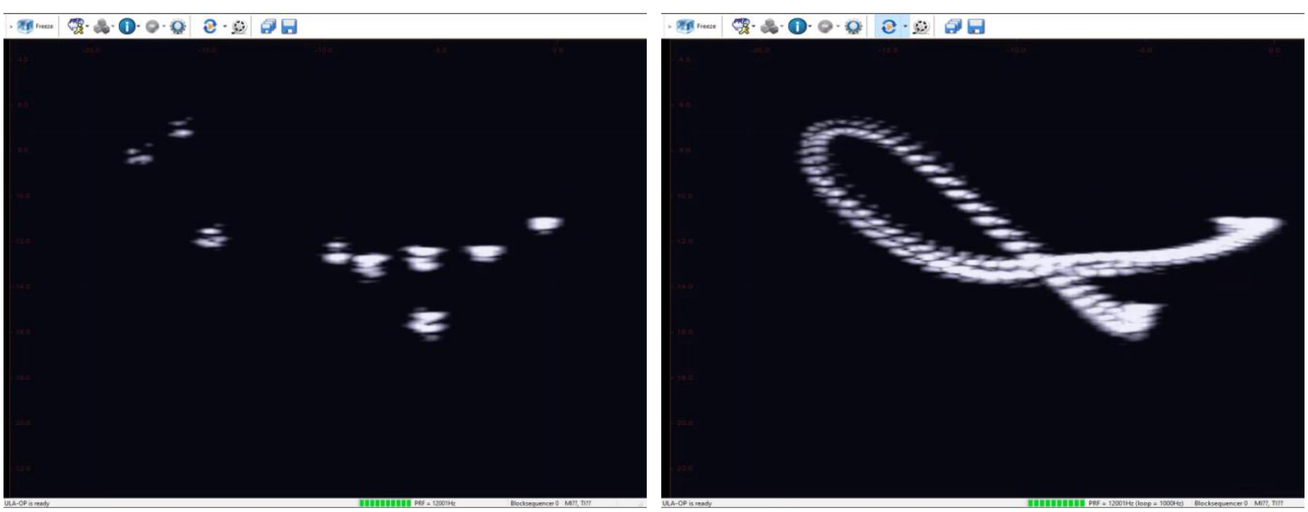

Fig. 4. Superimposed monitor frames describing the trajectory of a metal tip in RT (left) and in VRT (right) HFR modes

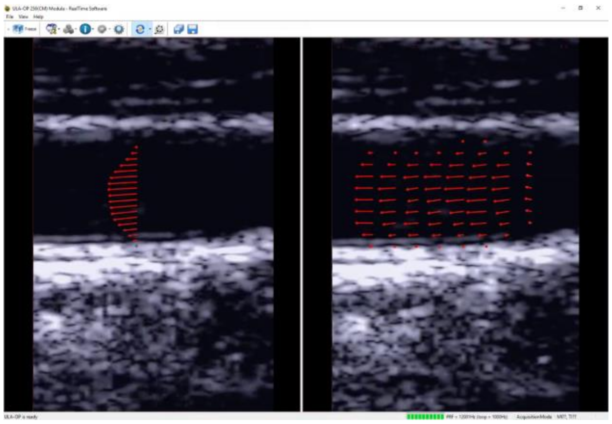

Fig. 5. Screenshots form the ULA-OP 256 display obtained investigating a carotid with single-line VD superimposed to B-mode in RT (left), and MLVD in VRT (right)

were transmitted and echoes processed in RT to produce 500 frames per second, each frame including 96 lines and 2700 depths. The left side of Fig. 4 was obtained by superimposing all the frames displayed on monitor in RT during the 200 ms tip movement. The right side of Fig. 4 shows, superimposed, all frames displayed on the monitor when the same raw data were reprocessed in VRT at 12 times lower VPRF. From Fig. 4 it is clear that while in RT it's impossible to appreciate the movements of the tip, in VRT the trajectory is neatly reproduced.

C. Multi Line Vector Doppler

The application of VRT to Multi Line Vector Doppler (MLVD) as example of Calculation-intensive elaboration, is detailed in [11]. MLVD is a method based on plane wave transmission, which produces bidimensional vector velocity maps. In MLVD the PRF is limited by the amount of calculations to be performed among frames. In this example, VRT was used to by-pass such a limit. In RT MLVD has been configured to produce vectors over a single line instead of the typical 8 lines, so that the calculation effort was reduced 8-fold with a corresponding gain in PRF limit. Data were then reprocessed in VRT at a slower VPRF with a complete configuration of 8 vector lines (Fig. 5). This strategy allows to investigate high velocity blood flows that otherwise in RT couldn't be investigated.

IV. Discussion and Conclusion

This work has presented a new US operating modality characterized by different useful features. The quality of data to be acquired on a PC can be checked immediately, i.e. before they are actually transferred to the PC. For example, the operator can immediately check if an interesting event has been captured in the buffer memory, so that only raw data of interest are effectively transferred to the PC for possible subsequent post-processing. Moreover, it is possible to appreciate quick events that wouldn't be observable in real time due to display frame undersampling. HFR acquisitions can be reproduced at lower speed to observe all the details of a dynamic event. Furthermore, the imaging settings can be tuned to optimize the image quality. It is also possible performing data elaborations not feasible in real-time due to excessive calculation efforts involved. In RT the acquired data are saved and processed at high PRF by using a light set of elaboration parameters; in VRT mode data are processed with elaboration parameters fully set to optimize the algorithm performance. These features can be used, for example, in CFM [12] and multiline [13] 2D vector Doppler [2].

Differently from the approaches typically used in other research systems, the same hardware resources, computing power and graphical user interface are used in real-time as well as in virtual real-time. Thanks to this approach, any future real-time method developed for ULA-OP 256 will be automatically suitable for working in virtual real-time mode.

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