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A NEW COMPACT EQUIPMENT FOR REAL-TIME ACQUISITION AND PROCESSING OF MEDICAL ULTRASOUND SIGNALS

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Abstract: Developing and testing novel ultrasound (US) investigation methods can be made difficult by commercial US echographs. Typically, most devices can export only the echographic images, providing either beamformed RF or demodulated echo-signal for acquisition by an external PC. Powerful but portable high-level commercial integrated circuits would be required in order to obtain access to the raw RF signal. First examples of such systems for ultrasound research are available (i.e. FEMMINA, ULA OP), although they are still far from size minimization. In this work we present a compact platform, consisting of a dedicated electronic board to be coupled with the US beamformer through an integrated analog front-end. Our platform was designed in order to simultaneously manage the RF flow data and to satisfy the following requirements: 1) ensuring that the full dynamic range of analog to digital converter (ADC) is completely exploited in order to maintain the ADC resolution capabilities through an appropriate amplifier, 2) denoising the RF signal input by a specific designed filter, 3) limited size, 4) low cost and 5) plug-and-play connection to the PC via a further USB port. Also, a suitable custom-developed graphical user interface was developed, enabling signal visualization and management of signal processing algorithms through an external PC. The output of an equivalent system, composed by commercially available stand-alone amplifier and ADC components, was assumed as the standard for comparing and grading the performances of our board. Analyzing the output of both systems in the frequency domain, we obtained matching spectra with a difference up to 0.21 dB. The so realized close synergy between hardware and software allows the acquisition and real-time processing of the echographic RF signals with fast data representation, allowing for the complete analysis of particular phenomena upon the study of the interaction between US signals and the investigated target for specific clinical diagnosis (i.e. osteoporosis in the bone tissue, tissue typing applications).

Keywords: field programmable gate array (FPGA); ultrasound beamformer; radiofrequency signals; echograph; echographic hardware.

1. INTRODUCTION

The radiofrequency (RF) ultrasound (US) signal is the ultrasonic backscattered signal collected by the receiving transducer for each time instant [1]. In most commercial echographs, the RF signal is automatically processed in order to obtain the echographic images, which can typically be represented on screen as A-Mode, B-Mode or M-Mode images and it is not directly accessible to the operators.

Specifically, the B-Mode image displayed by an echograph screen is a representation of the envelope amplitude of the backscattered signal.

Over the last 30 years, new US processing techniques have been developed to extract information about biological tissue microstructure or material properties that are not conveyed in conventional echographic images; these techniques typically exploit raw RF echo signals. For instance, in elastographic applications [2,3] RF signal is processed to investigate the deformation behavior of soft biological tissues under load. Additionally, for what contrast imaging concerns, the analysis of B-mode images exhibits limited possibility, whereas the analysis of the raw RF signal allows the extraction of typical parameters of the contrast agent [4-7]. In fact, only on the raw RF signal is possible to perform calculations, investigations and diagnosis based on measurements of signal backscatter, depending on the final application.

The US technology has emerged as a new and promising tool also in the non-ionizing diagnosis of osteoporosis, which is a systemic skeletal disease characterized by bone mass loss and microarchitectural deterioration that in turn lead to an increased fracture risk [8]. Osteoporotic fractures are often associated with an increase in morbidity, disability, and mortality, particularly in the elderly. Hence, osteoporosis is considered as a major public health problem, second only to cardiovascular diseases. The gold standard for the diagnosis of osteoporosis is the dual X-ray absorptiometry (DXA), which, however, suffers from important drawbacks, such as the use of ionizing radiations and high costs. To overcome these limitations, the use of quantitative US (QUS) has been proposed. It offers the

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advantages of being non-ionizing, inexpensive, portable and highly acceptable to patients [9].

Despite the importance of the above mentioned applications, only few manufacturers (i.e. ATL, Vigmed, GE and Siemens) other some commercial US echographs that deliver the raw RF signal, extracted just after the beamforming, before post processing. Furthermore, there are different prototypal systems that allow to capture the RF signal from an echographic device. Several research paper reported the use of a platform called FEMMINA (El. En s.p.a. Florence, Italy) [10] that allows to derive RF from commercially available echographs provided with optical fiber output. Unfortunately the combination of these devices (i.e. Megas GPX-Esaote Spa, Genoa, Italy- and FEMMINA) results in a bulky instrumentation set-up, which is not suitable in a busy clinical scenario. A further step towards system integration was made by device called ULA-OP, programmable US system allowing wide access to raw data [11].

In this regard, an innovative US device developed in Lecce (Italy) within the ECHOLIGHT Project through a collaboration between CNR-IFC and Echolight srl. The system relies on the analysis of the raw RF signals elaborated by a custom-developed platform during US scans of spine and proximal femur [12,13].

The aim of this work was to introduce the signal elaboration hardware of such novel apparatus and testing its performance in new US-based diagnostic techniques. Employment of this hardware can transform commercial echographs into an experimental system capable of working with the RF echographic signal in order to design and realize new diagnostic procedures.

The driving idea of our project is to provide a portable clinical device able to be easily connected to a PC (plug and play) and to perform real-time analysis of raw RF signal, filtered and digitalized from a US beamformer, as generally described in section A.

Detail description of hardware and firmware architecture are provided in the section B. and C. respectively. Finally the test procedure designed to compare our device with a reference system was presented in section D. and the results and drawn conclusions are discussed in the final section of this paper.

2. METHODS

The platform described in this paper, which in the following is called US signal processing device, is composed of a hardware and a firmware part and was designed to take RF signal from US beamformer, digitalized it and send it the digital data to a PC.

A. System description

The board acquires the raw analog RF signal and the synchronization signals (line trigger –LT- and frame trigger –FT-) from an external US beamformer. The RF signal is filtered, amplified, digitalized and ultimately transmitted to a PC.

The hardware part consists of three stacked electronic boards, as shown in Fig.1. The first board provides the power supply, the second processes and digitalizes the RF signal, the last board, which hosts a Field Programmable Gate Array (FPGA) module, is in charge of data transmission.

The firmware, which runs on the FPGA, determined the acquisition of the RF according to the timing of the synchronization signals.

The advantageous specifications of the US device are: (i) its compact *size*, which is 14 x 5.5 x 3 (cm); (ii) the use of *standard general purpose* hardware components, such as commercial operational amplifier and SMA connectors; (iii) the implementation of a USB connection towards the PC, that makes the platform *plug-and-play*.

The power supplied to the board is 12V, as for the US beamformer. Platform power consumption is estimated at 0.5A.

The mechanical stability is a very important point in the implementation of the platform. The system needs to ensure the strong electrical contact between the three boards.

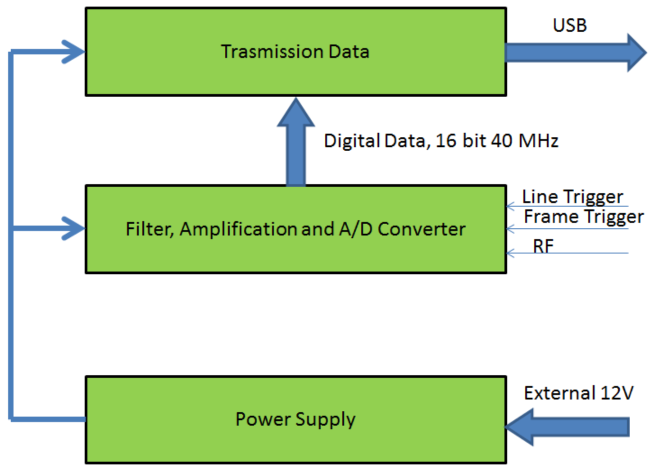

Figure 1. Structure of the platform US processing device.

B. Hardware architecture

The analog RF signal is given as input to an inverting second order passband filter. Its band goes from 1 MHz to 8 MHz and the phase response is linear within the band. The cut-off frequencies can be easily modified by tuning the RC-network depending on the application. This filter is also used as a preamplifier with a gain of 23 dB. The output of the filter is further amplified by a second operational amplifier in inverting configuration, with gain of 14 dB. Thus, the filtered RF signal undergoes a total amplification of 37 dB. Such gain allows to adapt the dynamics of the RF signal to the dynamic range input of the A/D converter (ADC).

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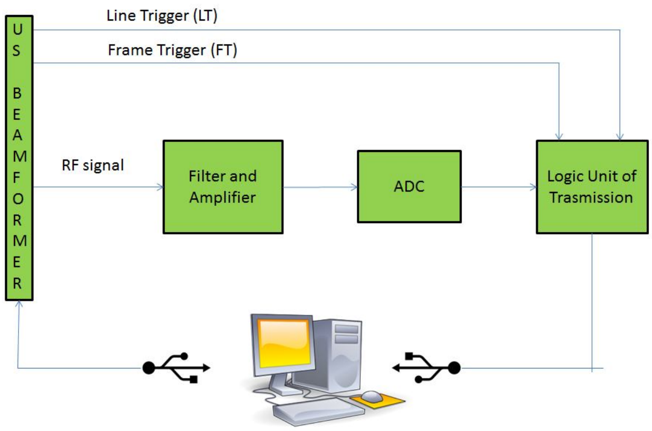

Figure 2. Scheme of the US signal processing device and its connection to an external PC.

The ADC hosted by our board is a LTC2161 (Linear Technology, Milpitas, CA, USA), which integrates a “sample and hold” circuit and meets our requirements about sampling frequency, resolution, cost, size and availability. The filtered and amplified RF signal is sampled at 40 MHz. The choice of such a sampling frequency allows US signal processing board to be compliant with a great variety of US probes: probes with impulse response up to 13 MHz can be used with our system. Moreover, such a high sampling frequency allows the use of a simple filtering and amplification circuit. The desired resolution of the ADC is 16 bit, chosen to minimize the quantization error although reducing the range choice of ADCs available on the market. It is worthwhile noting that the output of the amplifier assumes positive and negative values centered around 0 V. On the other hand, the ADC is unipolar, i.e., it accepts only positive input voltage. To overcome this issue, an adapting circuit that adds an offset to the amplified signal precedes the ADC. The operating modes of the converter have been programmed via hardware by suited jumpers, as only one mode is required to our scope.

Finally, the digital RF signal is provided in input to the FPGA module together with the synchronization signals, i.e., LT and FT. The main function of the FPGA is the correction of any possible jitter in the LT and/or FT. The FPGA used on our US signal processing board is the Spartan 6 (LX25, Xilinx, Inc. San Jose, CA, USA). It hosts a 64 MByte DDR SDRAM, which is used to temporarily store the RF signal prior to sending it to the microcontroller. The microcontroller (EZ-USB FX2LP, Cypress Semiconductor Corp., San Jose, CA, USA) receives the RF signal from the FPGA module and stacks the data according to the USB protocol. Thus, the RF signal is transferred to the PC.

C. Firmware architecture

The activity of the FPGA module is regulated by a dedicated firmware.

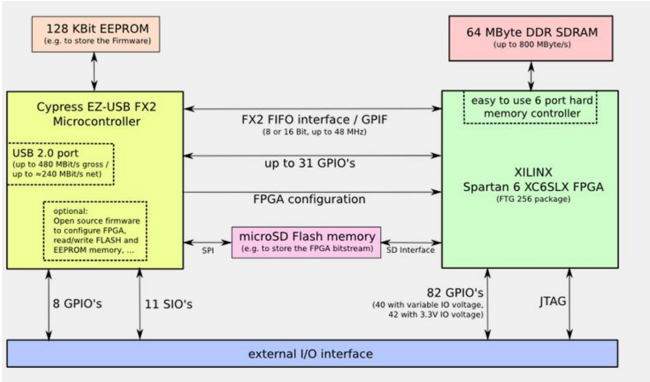

Figure 3. Block diagram of the logic data transmission unit composed by the FPGA and the microcontroller.

As noted above, the FPGA receives in input the digital RF signal and the two synchronization signals. LT and FT set the beginning of each scanning line and echographic image, respectively, in the RF record. The time interval between two consecutive line triggers varies among US scan, as a function of the us scanning depth, and may vary within the same US scans due to possible jitter phenomena. In the latter cases, the FPGA estimates the scanning depth of each RF recording and discards those undesired samples introduced by jitter. As a consequence, all lines in output from the FPGA have the same length.

When the FPGA has completely received the first frame, it is stored in the DDR SDRAM. The FPGA continues then to receive the second frame in input and stored it into SDRAM sending the first frame to the microcontroller implementing FIFO techniques.

The microcontroller receives the frame to FPGA and begin frame collection packing data according to USB standards.

The firmware of the FPGA works independently for this three operation: receiving the frame, writing the DDR SDRAM and moving the frame from SDRAM to Microcontroller (Fig. 3).

The firmware of the FPGA is able to store up to 100 frame from the acquisition start.

The user interface software running on the PC was designed in order to upload the firmware onto FPGA.

A configuration shell is responsible for configuring the hardware real-time modules, the microprocessor and the FPGA. The shell was developed in C++ and Visual C language and runs under the Windows operating environment.

The user can easily choose the programming sequence but it is important to first program the microcontroller and then the FPGA.

Platform Drivers are easy to install on the PC because the board is seen as any USB device.

If the card is not physically present, the driver can be installed on your PC through an automated program designed for the purpose.

The communication to the PC consists of a 25 Mbit/s USB link; such data rate is necessary to assure realtime operation mode while transferring the data stream to an external PC.

D. Test procedure

The mechanical and electrical connections stability of the three layers board was qualitatively verified (i.e. visual inspection).

In term of analogic and digital signal the criteria to verify the compliance with the specification requirements consist into comparison of the result obtained with the designed platform with those obtained whit the reference system composed by a signal amplifier (5077PR, Olympus Corporation, Tokyo, Japan) and an ADC PCI board (PCI 9846, ADLINK Technology, Inc., Taiwan). The amplifier receives the RF signal and passes it to the ADC board that digitizes and transmit it to the PC.

The content of the frame after digitization and transmission to a PC has been given as parallel input to both systems. An appropriate digital-to-analog reconstruction was used to compare the received RF signals; in particular they were compared in both frequency and time domain.

3. RESULT

In the fig.4 the realized platform is shown; the maximum mechanical stability obtained by the lateral connectors with a large number of pins. The three cards can be interconnected, without the use of tool.

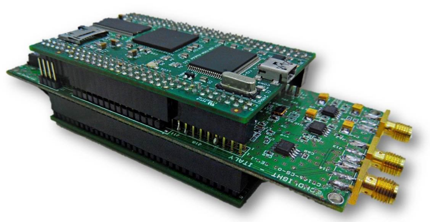

Figure 4. Picture of the US signal processing device; the three stacked electronic boards are visible.

Fig.5 shows the two RF signals obtained from the US systems and the reference system after the reconstruction in the time domain, whereas in the Fig. 6 the RF signal recorded by the two systems, is shown in the frequency domain.

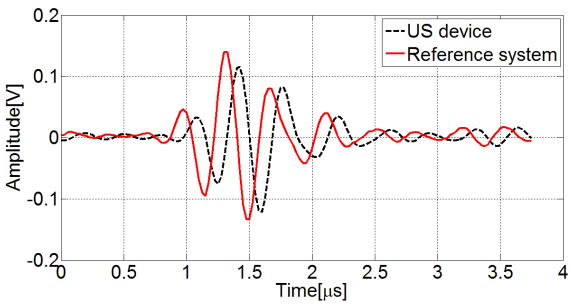

Figure 5. Analogic reconstruction of the RF signal function of time, for the frame acquired by the reference system (dashed black line) and our US device (solid red line).

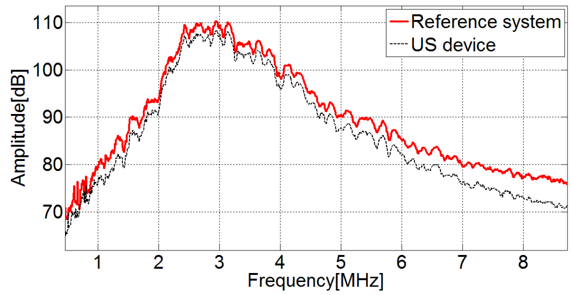

Figure 6. RF signal spectrum as function of frequency, for the frame acquired by the reference system (dashed black line) and our US device (solid red line).

The time delay between signal is 100 ns, as the “Reference system” preceeds the US device derived signal, on the other hand the pick-to-pick amplitude remains the same. The analysis of the signal in the frequency domain denotes the same morphology for the spectra of the signal processed by both systems whereas a maximum difference of 0.21 dB was observed.

4. CONCLUSIONS

In this work we have presented our US signal processing board as an apparatus for carrying out applied research both in medical diagnostics and general echography technological developments.

RF signal analysis is the only way to truly preserve all the information from the ultrasound-tissue interaction. Our US device is a system capable of directly operating on the RF echo signal, in accordance with a current trend for next generation echographic devices and within a limited size in agreement with current demand of compact system.

Foreseen applications of these platforms, providing direct processing of the RF echo signal, include not only osteoporosis related studies but a wider range of clinical focus, i.e. prostate tumor identification and blood detection.

5. ACKNOWLEDGEMENTS

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