Using Heterogeneous Hardware for Simultaneous Diagnostic and Therapeutic Ultrasound

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***Abstract*—Within the Ultrasound Array Research Platform (UARP) open research system project, imaging and high-intensity focussed ultrasound (HIFU) implementations are used independently for diagnostic and therapeutic research respectively. In this paper, the hardware of each system remains unmodified, but the timing and control subsystems present on both implementations are used to control the discrete imaging and therapy systems in a precisely synchronised manner.**

Also presented is software interface that has been developed to allow any number of UARP systems to be used as one unified platform. The simple syntax of the software interface eases development of user code that controls ultrasound experiments, whilst preserving the individual capabilities of each the systems and leaving advanced control parameters exposed for complex use cases.

The techniques discussed in this paper will enable future research into the development of advanced multi-mode sequencing techniques.

I. Introduction

The Ultrasound Array Research Platform (UARP) project is a series of open ultrasound research platforms developed by the University of Leeds [1], [2], [3]. Implementations include a 16 channel discrete connector platform for industrial and discrete transducer applications, a 128 channel implementation for medical imaging, and the High Intensity Focussed Ultrasound Array Research Platform (HIFUARP), a high intensity focussed ultrasound (HIFU) system based on the same architecture as the imaging UARP systems [3]. Unlike most other HIFU systems which use linear amplification [4], or a 3-level switched-mode excitation scheme [5], the HIFUARP uses a high-power harmonically-reduced 5-level switched-mode excitation scheme [3].

All variants of the UARP share similar architectures, and are already capable hardware platforms allowing per-channel fully-arbitrary switched waveform generation [1]. The imaging UARP allows high-framerate data acquisition for imaging [6] and the HIFUARP allows high-energy continuous wave (CW) HIFU therapy at 50W per channel.

The UARP systems are all based around 16-channel nodes (each of which contains a field programmable gate array (FPGA)). A single node is used in the HIFUARP and UARP16 implementations for a total of 16 channels mapped to 16 discrete single channel connectors. In the imaging UARP (UARPII), eight 16 channels nodes are mapped to a single 128-channel imaging transducer connector.

The UARPII and UARP16 share an identical analog front-end (AFE) configuration, based around a MAX14808 Five-Level High-Voltage Digital Pulser (Maxim Integrated, Inc., San Jose, CA, US), for transmit, and an AFE5807 8-Channel Analog Front End (Texas Instruments Inc., Dallas, TX, US) for receive [2].

The HIFUARP differs from the other UARP implementations in that it has a transmit subsystem created from discrete metal-oxide-semiconductor field-effect transistors (MOSFETs), the SQJ431EP PMOS (Vishay Intertechnology, Inc., Malvern, PA, US) and BSC900N20NS3 NMOS (Infineon Technologies AG, Neubiberg, DE) in a standard NMOS-PMOS half bridge arrangement [3]. The HIFUARP has no receive capability.

Research highlights a need to use both the imaging UARP and HIFUARP at the same time [4] as one fully synchronised system. This will enable research into spatial guidance [7], [8], cavitation detection, and temperature detection [9] for ultrasound-guided high intensity focussed ultrasound (USgHIFU) therapy applications such as liver and pancreatic cancer treatment [10], [11].

II. Software Interface

A software library has been written which allows flexible control over the UARP hardware without requiring users to have any knowledge of the hardware and system architecture. The software library is comprehensive and flexible, and allows advanced ultrasound experiment design to be realised with reduced user coding complexity.

The primary research-enabling feature of the new software interface is the experiment design language, which allows research users to describe the experiment they wish to undertake either in a heavily-abstracted, non-technical manner by default, or using low-level parameters which are more directly communicated to the hardware.

Experiment are designed hierarchically, whereby users group logical ultrasound sequences, such as multi-trigger images or HIFU excitations (known as 'scans') into execution groups (known as 'operations' and 'procedures') for flexible execution. Scans contain most of the typical ultrasound parameters such as the target medium speed of sound and imaging depth. Operations group any number of scans and allow the execution of the steps they represent in a sequential, parallel or interleaved fashion. Procedures group any number of operations and represent a complete hardware configuration that will be uploaded to the hardware prior to execution. The use of these functional blocks allow any number of imaging scans and HIFU excitations to be scheduled into flexible compound sequences.

Each of these functional blocks is a MATLAB class, and all the parameters which users need to set are properties of each class. The system is self-verifying: upon setting a new value for a parameter, automatic validation alerts the user if the value they have specified is invalid. By default, automatic functions handle transmit waveform generation for both imaging and HIFU, focal delay profile generation and time-gain compensation configuration based only on the users parameters. For advanced users, control over the transmit waveform design; transmit and receive delays; receiver, beamformer and imaging settings and timing and triggering, low-level control is exposed to allow the configuration of customised early-stage experiments.

Beamforming and imaging is handled using a plug-in system, whereby the user selects the most appropriate beamformer for each scan. The system automatically initialises and precalculates beamformer parameters before execution, and only performs the per-loop beamforming process during execution to keep execution time minimised. Optionally, efficiently-coded imaging plug-ins can be used in conjunction with beamformers to allow real time imaging with minimal configuration complexity.

Using this interface, it is possible to design parallel operations whereby independent imaging scans and HIFU excitations can be executed at the same time, either on the same system or on multiple independent systems. Included with the UARP software interface is a set of plotting and simulation tools that allow the user to comprehensively review the procedure they have created, can partially simulate procedures before they are executed on real hardware.

III. Using Multiple Systems

A. Automatic Hardware Discovery

Each of the FPGA nodes communicate with the host computer using a Gen 3 x8 Peripheral Component Interconnect express (PCIe) link. Every node presents itself as a PCIe bus device, so when using the UARPII and HIFUARP at the same time, a total of nine devices are presented. The UARP software interface has an automatic hardware discovery feature. Each of the connected nodes is queried for a system serial number, attached node serial numbers and the models of any attached transmitter, receiver and PSU hardware, allowing the software interface to automatically enumerate and group the hardware into logical representations of each of the physical systems that are attached.

The software interface then automatically adjusts its behaviour depending on the type of system and hardware being used. For example, when assigning transducers to connectors, the software checks that the type of transducer is appropriate for the connector; when generating transmit waveforms, the correct PWM algorithm for the attached transmitter hardware is chosen automatically; and when setting PSU voltages, the software checks that the combination of desired voltage, transducer and PSU model will not cause physical damage to the controlling electronics or transducer.

B. Inter-system Triggering

The UARP systems can either self trigger (known as 'internal' mode), or be triggered externally using a physical connector. Two external triggering schemes exist: external frame triggering (whereby one trigger causes the execution of a whole scan, which may consist of one or more firings); and external line triggering (where each trigger causes exactly one firing). The systems can also output latency-compensated line and frame triggers to the trigger out connector.

Using two discrete UARP systems simultaneously requires some form of inter-system triggering. One method is to use an external frame trigger signal physically split between all the systems. The main drawback to this approach is that natural clock drift will be observed due to the core timers not being synchronised, even though the systems are running at the same frequency, due to natural variations in each system's oscillator.

Another method is to use the software interface to designate one UARP the 'master system' and use it's trigger out function as the input trigger for the other systems on a firing-by-firing basis. This can allow more synchronous timing between the systems, as clock drift can only occur between line triggers - a very short period. The software can automatically configure the hardware of all the connected systems to respect the timing of the master system, and will automatically apply an extra compensatory delay to the master systems to compensate for the inter-system trigger latency, ensuring all systems fire simultaneously.

IV. Methods and Results

The UARP software interface is used to design an experiment with the following characteristics. Connected to the 128-channel imaging UARP is a L11-4V transducer (Verasonics, Kirkland, WA, US), which performs a 3-step linear imaging scan with a sub-aperture size of 1 and a inter-step period of $2.5\,\mathrm{ms}$. Simultaneously, a $7.5\,\mathrm{ms}$ HIFU excitation using a H-102 transducer (Sonic Concepts, Inc., Bothell, WA, US) is executed using the HIFUARP (which is not connected to the UARP system by any means other than a shared external trigger input signal). The parameters were chosen for clarity in the presented results. A more typical experiment using more elements of the transducer with a larger sub-aperture size, and a much longer HIFU excitation, could be described using the same configuration code by simply changing the appropriate parameter values.

Figure 1 shows the code required to configure and execute the experiment described in this section. Hardware discovery and initialisation of two discrete systems connected over PCIe to the controlling PC is achieved using two lines of code. Two independent ultrasound sequences (the imaging scan and HIFU excitation) are configured, and will be executed in parallel

```matlab
%% Discover and Initialise Hardware
UARP.init();
UConfig.initialiseHardware();

%% Define Logical Transducers (and system connections)
UConfig.newTransducer('HifuXDR', 'H102', 'Sx0002');
UConfig.newTransducer('ImageXDR', 'V_L11_4', 'Sx0001');

%% Create Procedure (base experimental unit)
UConfig.newProcedure('Prc');
UConfig.Prc.Trigger.InMode = 'ExternalFrame';
UConfig.Prc.Trigger.OutMode = 'Line';

%% Create Operation (executes the scans in parallel)
UConfig.Prc.newOperation('Op', 'Parallel');
UConfig.Prc.Op.Trigger.Period = 2.5e-3;

%% Create an Imaging Scan (linear mode, 3 elements)
UConfig.Prc.Op.newScan('Img', UConfig.ImageXDR,
                       'Linear', 'HRPWM');

% Core Scan Properties
UConfig.Prc.Op.Img.FirstElement = 1;
UConfig.Prc.Op.Img.LastElement = 3;
UConfig.Prc.Op.Img.NTimes = 1;
UConfig.Prc.Op.Img.SpeedOfSound = 1480;
UConfig.Prc.Op.Img.SubApertureSize = 1;
UConfig.Prc.Op.Img.Transmit.FocalLength = 0.035;
UConfig.Prc.Op.Img.Transmit.CentralFrequency = 7e6;
UConfig.Prc.Op.Img.Transmit.Duration = 0.5e-3;
UConfig.Prc.Op.Img.Transmit.Amplitude = 0.75;
UConfig.Prc.Op.Img.PSU.Voltages = [-20 -10 10 20];
% Image receive configuration not shown.

%% Create a HIFU scan (long multi-trigger TX mode)
UConfig.Prc.Op.newScan('HIFU', UConfig.HifuXDR,
                       'TxOnly', 'MultiTrigger');

% Transmit Properties
UConfig.Prc.Op.HIFU.Transmit.CentralFrequency = 1.1e6;
UConfig.Prc.Op.HIFU.Transmit.Duration = 7.5e-3;
UConfig.Prc.Op.HIFU.Transmit.Amplitude = 0.6;
UConfig.Prc.Op.HIFU.Transmit.SwitchingLevels = 5;
UConfig.Prc.Op.HIFU.PSU.Voltages = [-72 -36 36 72];

%% Calculate Procedure Data (TX waveforms, delays etc.)
UConfig.Prc.calculateData();
UConfig.Prc.configureHardware();

%% Execute Procedure (with PSUs enabled)
UConfig.Prc.psuEnable();
UConfig.Prc.execute();
```

Fig. 1. The user interface code that was used to configure and execute the demonstration described in this paper. The code has been included to show the minimal code complexity afforded by the new software interface that has been developed as described in Section 2. A complex, multi-system multi-mode operation is described and executed in under 50 lines of code.

due to the configuration of the operation. This operation is wrapped in a procedure, which contains all the data required to configure the hardware.

In this demonstration, a manual pulse trigger is used to initiate the procedure execution, but a signal generator or other experimental or test equipment could be used instead. The two UARP systems are not connected for synchronisation or timing apart from the master trigger input they share, as shown in Figure 2.

Figure 3 shows the traces recorded by an oscilloscope when measuring the external common input trigger, output triggers of both systems and transducer excitation (RF) outputs on both systems. It shows how two systems behave as one when executing the defined procedure despite not being

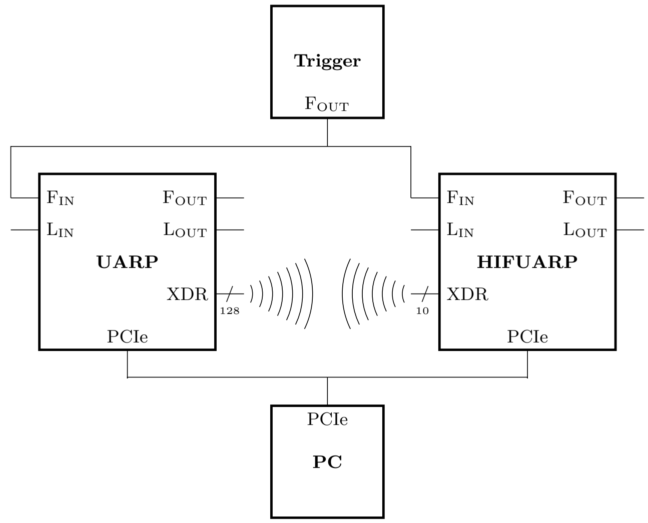

Fig. 2. Equipment setup showing manual trigger unit connected to both systems. F, L represent frame and line trigger connections respectively. The trigger $\mathrm{F_{OUT}}$, both system $\mathrm{L_{OUT}}$ and the first three transducer outputs XDR for the UARP, and first transducer output for the HIFUARP are connected to an oscilloscope.

physically linked. The UARP executes on each channel in turn, as designed, while the HIFUARP is outputting high-power continuous excitation. Once the UARP has finished all 3 steps of the imaging scan, the HIFU excitation is switched off exactly at the same time, but the length of the HIFU excitation can be fully independent of the imaging scan duration if required. Indeed, in this demonstration, the continuous HIFU waveform is actually comprised of three short HIFU waveforms, one for each trigger. A single short waveform is generated by the software interface to be executed three times sequentially. The waveform is automatically calculated such that it can loop perfectly with no jump in amplitude and no delay between each repetition at the sample level. Use of this waveform looping technique means the HIFUARP has a theoretical maximum continuous-wave transmit duration of approximately half an hour.

This experiment highlights the advanced automatic sequencing possible with the UARP software interface and how two independent open ultrasound systems can be triggered in a synchronised manner with no additional hardware. If desired, this hardware demonstration proves it would be possible to configure the UARPII to perform passive acoustic mapping (PAM) whilst the HIFU operation is being executed. The imaging UARP could be configured to only receive, whilst the HIFUARP simultaneously performs a long HIFU excitation.

V. Conclusions

A method for controlling multiple heterogeneous ultrasound systems as one was presented. This was made possible by the development of a software interface which fully abstracts the ultrasound system hardware. This abstraction software will ease the creation of new generations of ultrasound systems based on the UARP architecture.

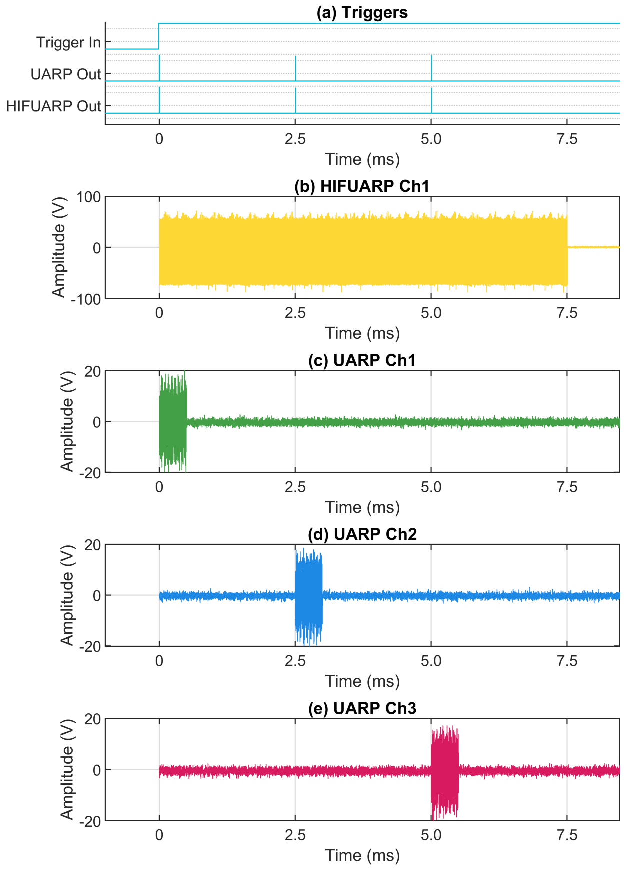

Fig. 3. Oscilloscope-captured traces showing trigger in and out signals (a, cyan traces) and the HIFUARP RF transducer output for channel 1 (b, yellow trace) and UARP RF transducer output for channels 1, 2 and 3 (c,d,e, green, blue and red traces).

In Section 3, the effects of clock drift over long periods of time when using a manual trigger shared between multiple systems was discussed. In the experiment described in this paper, clock drift does not present a problem in the 10 ms procedure execution duration. In terms of clock skew (the difference in time between each of the systems acting upon the trigger input) the measured time between the two system's triggers is negligible when compared to a HIFU excitation which would probably be on the order of 1 s or longer.

Utilising two discrete systems in a synchronised manner will allow the UARP platform to be used for research into PAM, where an imaging receiver is used to detect regions of cavitation whilst a HIFU excitation is occurring simultaneously [12]. Further to this, there are numerous examples of performing passive cavitation detection (PCD) using needle hydrophones as cavitation meters [13], [14], [15]. The UARP software interface could be used for PCD by using a cavitation meter connected to either an oscilloscope or UARP16 discrete-connector system. Due to the comprehensive lab equipment control toolbox that has been developed, either system could be used in conjunction with the HIFUARP as one platform, allowing total precisely-timed control over experiments from one controlling computer.

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