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ADVANCED ARCHITECTURES FOR FUTURE GENERATION ULTRASONIC PROCESS INSTRUMENTS

FINAL REPORT

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Background / Context

The research was undertaken within the Applied Ultrasound Laboratory chaired by Prof Richard Challis FREng (School of Electrical and Electronic Engineering, University of Nottingham). The laboratory specialises in ultrasonic wave interaction with complex media, and the NDT and process monitoring technologies. Development of new integrated architectures for ultrasonic instruments was identified as a vital step towards application of affordable ultrasonic instrumentation for monitoring and control of rapidly changing industrial processes (**aim of the research**).

The **original objectives** included

1) To establish fundamentally new integrated architectures for ultrasonic spectrometer instruments for process monitoring and control. These will dramatically reduce size, weight, cost, operating signal voltages and signal processing times and support broad application.

2) In support of (1), to establish the complex non-linear relationships between all types of system noise and ultrasonic measurements of attenuation and phase velocity.

3) To develop a software design tool to optimise the design and performance of integrated instruments based on VLSI concepts and incorporating telemetry for plant use.

4) To build and evaluate on plant an integrated ultrasonic spectrometer.

The **third objective** turned out to be redundant as the closed form formulae were derived for the error analysis analytically. Consequently it was **replaced by the objective** to develop a scalable and self-calibrating research platform for ultrasonic measurements.

Key advances and supporting methodology

1. New integrated architectures

1.1. “On-the-fly” averaging architecture [1]

Averaging involves repetitive excitation of the processes of interest (ultrasonic waveforms), and their coherent accumulation. In conventional data acquisition instruments (ultrasonic instruments and digital storage oscilloscopes - DSOs) averaging is implemented in software and requires significant time (tens of seconds) to be completed. In this project the new architecture ensured hardware averaging "on-the-fly” without any overheads for calculations. This was achieved by updating the running total as data came by retrieving the current total, adding the present sample and writing the result back using a dual port RAM. Taking into account a typical pulse repetition frequency of 2.5 kHz (generation of 2,500 coherent frames in a second) this results in a decrease of noise voltage 50 times in a matter of one second. This improvement showed a dramatic effect on the sensitivity to chemical changes comparing to an instrument where averaging was not employed due to unacceptable processing time [12].

1.2. Architecture for accurate interleaved sampling (AIS) [2, 3]

The majority of high performance DSOs support an operation mode that increases the effective sampling frequency of an ADC by collecting many signal frames shifted randomly with respect to each other (random interleaved sampling - RIS or equivalent time sampling - ETS), and then re-assembling them together based on the precisely measured time shift. Due to a random nature of these shifts a substantial time is required for collecting a conclusive dataset. The developed AIS architecture improves the 'native' sampling frequency of the ADC by a set factor (the AIS factor) at the expense of the increase in measurement time by the same factor. This was achieved by employing two synchronised oscillators with related frequencies; one of which was employed for the excitation, and another one for clocking the ADC. In most experiments 27-fold increase of the sampling frequency of an 80 MHz ADC was utilised. This provided the equivalent sampling frequency of 2.16 GHz that is available only from the top of the range expensive DSOs otherwise. The reduction in measurement time compared to a RIS DSO was over an order of a magnitude [3].

1.3. Combined AIS and averaging architecture [4]

Some of DSOs do allow the combination of RIS mode with averaging. The main drawback of this is a huge increase of measurement time required (compared to the operation of the same instrument in either RIS or averaging mode) to hundreds of seconds [3]. This happens because averaging requires acquisition of coherent records that are difficult to acquire if the incoming signal frames are shifted randomly. The combined averaging/AIS architecture requires as many data frames as the product of the AIS factor multiplied by the number of averages. This ensures flexibility for practical measurements of fast processes by trading off time resolution (determined by the equivalent sampling frequency through via AIS factor) and amplitude errors (defined by the remaining additive noise via the number of averages). For example, if the AIS factor is increased and the number of averages is decreased in proportion (that is possible if the noise is relatively low), the total measurement time will stay the same.

Quantitatively, for the pulse repetition frequency of 2.5 kHz, typical for ultrasonic measurements as was mentioned above, one can get 10-fold reduction of the noise voltage and 25-fold increase in the equivalent sampling frequency simultaneously within 1 s. This represents two orders of magnitude reduction in measurement time comparing to an averaging RIS DSO [3], and enables accurate extraction of the underlying information (e.g., delay time, signal spectrum, peak amplitude, RMS etc).

2. Analysis of uncertainty of ultrasonic measurements

2.1. Quantifying effects of the frame jitter [5]

The detrimental effect of the fame jitter was detected when processing some experimental datasets. An increase of the variability of the averaged records comparing to that expected from the additive noise level alone was observed. This effect was attributed to the loss of coherence of the averaged records due to de-synchronisation between the excitation clock and the recording ADC clock. The analytical consideration led to closed form formulae quantifying the effect that were fully verified experimentally. Apart from the frame jitter effect quantification, an important conclusion was drawn: to reduce the effect at its source, the excitation clock and the ADC clock must be synchronised tightly. This explained why dedicated ultrasonic instruments (where this synchronisation was provided purely for the design convenience) frequently outperformed experimental ultrasonic setups assembled from a stand alone top-of-the-range non-synchronised instruments.

2.2. Complete uncertainty analysis [6]

Like in any indirect measurements, measurement outcomes derived from raw ultrasonic records depend on the accuracy of the raw records and measurement conditions in a non-linear way. An instrument that is perfectly fit for monitoring of a particular process might be grossly inadequate for monitoring another. There are very many factors affecting the outcome of ultrasonic spectroscopic measurements, namely additive noise, aliasing, quantisation noise, frame jitter effects (if averaging is used), and computational errors. All of the above contribute to the bias and the standard deviation of the final estimate.

This problem was given full analytical, numerical and experimental considerations, and these were reported in a 15-page IEEE Transactions paper. The findings answered three questions essential to practical ultrasonic measurements: what is the uncertainty of a particular

ultrasonic measurement in given conditions? how to choose measurements conditions to reduce the uncertainty as much as possible? how to ensure the desired uncertainty?
At the time of writing the grant proposal it was envisaged that the problem might not have an analytical solution, thus a development of a numerical simulation tool was one of the research objectives. However the closed form formulae were derived, and the sought after uncertainties were found mostly dependent on the RMS value of the additive noise (that can be determined easily) and the RMS value of the frame jitter (that can be determined as shown separately [5]). Because of this the original third objective of the research was replaced by a different one that is reported below.

3. Development of a new research platform for ultrasonic measurements

This objective replaced the original objective for reasons discussed above.

3.1. Development of a scalable FPGA configuration and a uniform graphical user interface (GUI) [7]

Convenient experimenting with non-invasive ultrasound is often performed using expensive (£5-10k) dedicated ultrasonic instruments, or using a more flexible experimental gear assembled from stand alone pieces of equipment, or by using custom-designed devices for particular tasks. The dedicated instruments become out-of-date quickly due to recent progress in microelectronics, a combination of stand alone instruments suffers from the frame jitter as discussed above, and electronic design requires substantial expertise that can not be acquired quickly or cheaply.
That is why development of flexible and user friendly research platforms is one of hot areas in ultrasonic research. For example, a special issue on novel equipment for ultrasound research (IEEE Trans on Ultrasonics,…, October 2007) contains detailed account of development and application of 5 different platforms that are called “system”, “equipment”, “research interface”. The word “platform” seems more suitable here as it unites both hardware and software. Development for a platform (rather than for a particular integrated circuit or an FPGA board) requires high level design tools that can adapt some design automatically to another, more up-to-date, hardware. The Xilinx System Generator was used as such a design tool although some custom VHDL code was required to link together the excitation and acquisition parts that are clocked from different but synchronised oscillators.
The System Generator, which requires expert knowledge to operate the completed design, did not provide a convenient user interface. The user interface must be graphical for convenience, and ensure data flow to and from the FPGA integrated circuit (IC) irrespectively of what IC or an FPGA board is being used. These requirements were met by using the Matlab GUI. Consequently, the designed platform contained several connected layers of design, the hierarchy being VHDL code and System Generator designs – Simulink models – Matlab GUI programs.
The platform was tested using three different FPGA boards from different vendors connected to the host PC by different means – by using an internal PCI bus and an external JTAG cable. The performance achieved was dependent on the FPGA IC specification (e.g., operating frequency and memory capacity), but all three boards operated well in the combined averaging/AIS mode under the same user interface. Tuning the design to a different FPGA board required about a week instead of several months normally required for a complete re-design. The only restriction for use of the platform is that the FPGA IC must be from Xilinx – the vendor of the design tools.

3.2. Development of an ultrasonic analogue front-end application specific integrated circuit (ASIC) [8]

The analogue front end design constrains the size of ultrasonic instruments because there are no dedicated ICs on the market at present. There are excellent separate driver ICs that can excite a typical ultrasonic transducer effectively, and ICs for variable gain amplification required for the receiver part. Combined together they require substantial space (and a duplexer for connecting them to a single transducer if the pulse-echo mode is used) that is intolerable for a multi-channel design. The first ASIC candidate design consisted of an analogue amplifier and driver as the essential parts of the front end. The manufactured integrated circuit met the design specification and complied with the simulation results. It was established that if the amplifier and the driver use the same supply voltage, the dedicated duplexer is not required. The second design represents a complete mixed signal ASIC design where the operating mode and gain of the ASIC is controlled externally by means of serial communication. The manufactured ASIC is expected in mid June, and will be tested outside the calendar term of the grant as all the provisions for thorough testing have been made. The test results will be disseminated by conventional ways, and added to the project Internet site.

4. Experimental application of new instrumentation and measurement techniques

4.1. Chemical process monitoring [9-13]

Although some models are available to describe propagation of ultrasound in aqueous solutions, an experimental approach is adopted at present, as it is more fruitful. During the initial experiments (acid-base titrations related to an industrial process [9]) raw ultrasonic records were acquired. The experiments were carried out in an open laboratory space using conventional analytical equipment that resembled industrial process conditions. The ultrasonic records were analysed from various perspectives, and the propagation delay was identified as the parameter that is most sensitive to chemical changes but resilient to noise [12]. Use of the designed instrument with on-the-fly averaging achieved substantial reduction in scatter of the delay estimates [13] thus improved the resolution of monitoring. Ultrasonic monitoring was capable of tracking chemical changes as small as 200 ppm within less than a second. This was vastly superior to a conventional pH-meter used for comparison. This sensitivity was observed not only for processes that led to precipitation (clear physical change); but also for changes of concentration of non-reacting chemicals alone. This means that ultrasound senses not just the fraction of the solid phase in a heterogeneous phase mixture, but also tiny changes in composition of an ensemble of different ions in aqueous solutions.

4.2. Integrated temperature sensing [10-11]

A research in ultrasound propagation in aqueous solutions is mostly being done in some thermostatic environment as the ultrasound velocity depends on temperature strongly. As the reported experiments did not use any thermostat, the exothermic nature of some of the monitored reactions influenced the propagation delay to the extent, similar to that of chemical changes. A numerical procedure was developed that allowed discrimination between chemical and thermal changes based on temperature readings recorded separately. This procedure led to dramatic change in perception of the delay estimates giving much clearer view on the underlying process [10, 11]. Additionally, a way of retrieving the temperature from the ultrasonic records solely when using a novel ultrasonic sensor was derived. The developed sensor provided 30 distinct readings while the temperature rose by 0.1°C only [10, 11] when using the combined averaging/AIS architecture for recording. The sensor was designed as a dipstick probe that can be put into a chemical reactor with a virtually arbitrary shape.

4.3. Interrogating a biological reactor from its outside using ultrasound [7]

Manufacturing of some biocompatible materials, for example, based on polylactic acid with various molecular weights, involves placement of raw material inside a high pressure reactor and changing the inside gas pressure in a particular way during approximately 2 hours. This process needs to be monitored, and optical observation of it was found complicated for various reasons. The developed ultrasonic research platform was used to monitor the reflection coefficient at the “reactor case-evolving material” interface as the material transforms from powder into liquid then into a conglomerate of elastic films containing trapped gas bubbles. The experiments were conducted in a conventional biochemical environment. Preliminary results were found promising as the behaviour of the reflection coefficient coincided with predictions well. However when a dedicated transducer holder was fabricated, and experiments were repeated, the result seemed much less profound. This second set is being analysed by biochemists at present. Nevertheless the metrological performance of the developed platform was demonstrated yet again, and a possibility of interrogating high pressure bioreactors from their outside has explored successfully, paving a way for new potential application of ultrasonic process monitoring.

Research impact and benefits to society

The research has already resulted in 5 journal publications (all in IEEE Transactions), 7 conference presentations and papers in proceedings (all were peer reviewed, and made at IEEE meetings) and 1 invited presentation at an international conference. These contributions were unanimously welcomed by their referees. A substantial number of printed copies were distributed at scientific meetings, and emailed on request. The publications were put on the Internet recently for a public access (subject to the IEEE restrictions). 2 BEng projects, 4 MEng, 2 MSc individual student projects were related to different aspects of the present research directly.

Developed architectures allow cutting the cost of high accuracy ultrasonic instrumentation by an order of magnitude by employing slower ADCs and reduce noise by averaging without much impact on the measurement time.

Ultrasonic non-destructive testing is being presently used for largely qualitative purposes in industry (non-destructive testing of solid parts and layered structures) and medicine (imaging of human body and blood flow). The present research established metrological foundations for assessment of uncertainty of quantitative data derived from raw ultrasonic records that opens a way for confident quantitative ultrasonic non-destructive evaluation as well.

The research resulted in development of an inexpensive research ultrasonic platform operable with different FPGA boards and ultrasonic front ends. This platform provides means for search of new applications of ultrasonic instrumentation without much cost and/or expertise required otherwise.

The developed instrumentation and techniques were experimentally applied to monitor chemical processes and biomaterial manufacturing successfully in a way that was not reported before.

Explanation of expenditure

The project development required manufacturing of ASICs which were produced at an external foundry previously used by our school (Austria Microsystems - AMS). This enabled the school to provide all the necessary design licenses at no cost to this grant, and share the cost of the fabrication of the first designed ASIC. However the AMS had a particular schedule with fixed time slots for cost effective manufacturing of our designs, and the fabrication time was about 4 months. Consequently the project RA was temporarily employed on another grant when the first designed ASIC was in production. This saved funds for thorough testing of the fabricated second ASIC outside the original time schedule. A request for the grant extension without extra funding was sent to the EPSRC on 10 Jan 2007, but was rejected on 07 Feb 2007. The rejection caused an urgent need to complete as much work (electronic design, experimental verification, development of test boards) and accumulate as much test equipment (DSO, signal generator, electronic components, FPGA and printed circuit boards) as possible before the grant end date. That is why an expert experimenter (Dr Andrew Holmes), an assistant electronic designer (Dr Albert Phang), and a VLSI officer (Mr Roger Light) were made available for the project, and contributed enormously to the work plan; and some staff costs were re-allocated to consumables. This manoeuvre led to return to the EPSRC of £3,300 in unspent overheads, and, excluding this, the grant exceeding £134k was under spent by just £19.

Further research & dissemination

The reported research showed feasibility of designing inexpensive ultrasonic instruments with data acquisition capabilities compatible to expensive stand alone DSO at a fraction of their cost. The next logical step is to design a stand alone custom FPGA board with an integrated ultrasonic front end that will cost £100-£200. This will render wide deployment of ultrasonic instruments economically viable for a range of industrial processes. Additionally, ultrasonic process imaging by employing several such boards simultaneously will become possible. This further research goal has already attracted a self-funded PhD student (Mr Wei Chen), and he is making good progress.

The developed architectures would be beneficial for high frequency medical ultrasound (for example, intravascular ultrasound - IVUS - employs transducers that operate above 30 MHz). At the moment we are forging links with medical practitioners as their involvement is essential for further research.

There is a huge potential for applications of the developed instrumentation and measurement techniques for chemical process monitoring. Some other applications that require preliminary experimental trials are envisaged.

The research findings were published and reported extensively. The publications resulted from the present research were made available for public access (subject to the publisher's restrictions) using an internal laboratory web server that does not have any running costs thus will be freely accessible for a foreseeable future (ftp://128.243.76.144/RA1360.htm). The developed principles and instruments will be used for the new MSc in Electronic and Ultrasonic Instrumentation course that is available from academic year 2007/08.

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