Architecture of EVT4 data acquisition system for electrical capacitance tomography

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A B S T R A C T

An EVT4 system for electrical capacitance tomography, which enables fast data acquisition and a high frame rate for dynamic process imaging, is presented. A hardware architecture based on distributed control logic and multi-gigabit transmission is proposed. The multi-channel system consists of front-end measurement boards, data read-out boards and a main board. The front-end analogue board is equipped with 4 transmitter-receiver channels, each with an individual ADC. Data transmission between the read-out and the main board is performed using SATA standard allowing high speed data transfer and modules synchronization. The system can be equipped with up to 8 front-end boards (up to 32 channels). The embedded software installed in the programmable logic devices ensures the flexibility of the system and offers the opportunity to explore different methods of capacitance measurement using different front-end boards. The control logic distributed between the read-out boards and the main board is presented. The system data throughput is discussed. The preliminary results of measurements using 2D tomographic sensor and image reconstruction were presented.

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1. Introduction

Electrical capacitance tomography (ECT) allows to visualize cross-sectional or three dimensional distribution of dielectric permittivity inside an examined space. The image is reconstructed using capacitance measurements performed between electrodes placed around the investigated volume [1]. The spatial resolution of an ECT image is limited because of a small number of electrodes. Usually a sensor consists of not more than 32 electrodes due to small capacitance values in a range from few femtofarads to single picofarads which have to be measured [2]. On the other hand this technique is characterized by high temporal resolution – it is possible to acquire even more than one thousand images per second. This enables studying dynamic processes such as multiphase flows or combustion processes. ECT is one of process tomography techniques and has applications in the industry [3].

In order to obtain high frame rate, not only fast measurement method must be applied, but also data acquisition system has to be able to process a large amount of data. The development in electronics in past years made it possible to construct such systems. In 2005 a data acquisition system architecture for ECT consisting of capacitance-measuring circuit modules for each channel was proposed [4]. The parallel detecting scheme was implemented. The whole tomograph was controlled by a microprocessor which was responsible for channel selection, output of analogue to digital converters and setting gains of programmable amplifiers. Such a design allowed replacement of measurement method without changing the main board of the system. RS232 and RS422 were used for communication with the host computer. Authors were able to obtain 800 frames per second for a sensor with 12 electrodes, although they did not provide signal to noise ratio (SNR) or measurement uncertainty. Another multichannel architecture was presented in 2008 in the field of electrical impedance tomography, another soft-field technique [5]. Like in the previous solution, the control module controls and synchronizes up to 16 modules, 4 channels each. Digital logic of all modules was distributed in digital signal processors and field-programmable gate array (FPGA) chips. The system was able to collect 182 frames per second when acquiring 15 spatial patterns. The authors report SNR equal to 96 dB when averaging the signal from 32 samples. In 2011 another ECT system was described [6]. The authors decided to use digital data processing using FPGA chip which governed the whole system. An embedded software processor was used and critical paths were implemented in the FPGA logic. Sequential data collection was applied. Using high-speed USB 2.0 it was possible to acquire 1851 frames per second with an SNR of 56.2 dB for a 12-electrode sensor using only two analogue-to-digital convert-
ers (ADCs). Another EIT data acquisition system allowing high frame-rate and hardware upgrades was described in 2015 [7]. The system was divided into a system manager module and analogue front end module. The control module was placed in PXI chassis and consisted of National Instruments modules instead of custom electronics. Analogue front end module was controlled by FPGA. This architecture allowed to capture over 100 frames per second with an SNR greater than 90 dB when averaging the signal. The idea of reconfiguration was also implemented in ECT system based on a programmable system on a chip [8]. Modern electronics allowed to develop a portable ECT system which could be easily adapted for a task it has to perform. The authors did not state a signal to noise ratio or a measurement uncertainty. Few companies offer commercial electrical capacitance tomography systems. Industrial Tomography Systems offers M3c data acquisition system [9]. It can work with up to 24-electrodes sensors and allows to acquire 50 frames per second with a 12 electrode sensor. Although SNR is not presented, the producer claims that accuracy of the system is in the range from 0.01 to 1 pf. Another example is the TFL R500 from Process Tomography Limited [10]. The system which is based on FPGA and digital signal processor, consists of 16 channels and is characterized by capacitance measurement range controlled from 0 to 2000 fF, measurement resolution equal to 0.005 fF and measurement noise level equal to 0.01 fF rms at 100 frames per seconds which results in SNR equal to about 60 dB for 10 fF measurement at 100 frames per second. It is possible to obtain 5000 frames per second with up to 8 electrodes sensor using this system.

Over past sixteen years our Division developed a number of electrical capacitance systems, including constructions like 16-channel ET1 from 2001 [11] or ET3 which debuted in 2003. ET3 32-channel system found many applications, for example in 3D tomography [12]. Recently, the single shot high voltage (SSHV) method of capacitance measurement was developed by our group [13]. In this method a measured capacitor is charged and discharged using a single pulse, which increases speed of the measurement in comparison with the classic charge-discharge method. The application of high voltage exciting pulse and over-sampling of the output signal preserves the signal to noise ratio at acceptable level. The method was tested using single channel setup. The SNR obtained for 500 fF capacitor was equal to 58 dB and the measurement speed was about 50 μs. Having developed the new capacitance measurement method we started to design the multichannel data acquisition system. In this paper the newest instrumentation for ECT, elaborated by our group and named EVT4 (Electrical Volume Tomograph 4), is presented.

The aim of developing this instrumentation was to create a data acquisition system for ECT enabling high frame rate imaging, essential for process tomography. It was assumed that the system throughput should be high enough not to be a limiting factor for any method of small capacitance measurement. The modular architecture should allow easy exchange of measurement board and would be suitable for both more accurate but slower and less accurate but faster measurement methods. This is an original feature which is not available in other ECT data acquisition systems.

2. Modular architecture of EVT4 data acquisition system

2.1. Hardware overview

The main concept of the hardware design is to provide a modular architecture which would allow easy expanding and exchanging of modules. The tomograph should allow usage of different measurement methods with simple switch of measurement boards. Additionally, it was intended to separate analogue circuits from digital circuits in order to minimize interferences between them. Modern FPGA chips and processors are used in order to achieve high data throughput. A distributed control logic and multi-gigabit transmission is applied. Modular architecture of EVT4 acquisition system hardware is shown in Fig. 1. The system has a star topology. The whole system is governed by a main board. One of crucial elements of the main board is ARM Cortex-A8 processor on which Texas Instruments Linux runs. The processor is responsible for communication with a host computer over Gigabit Ethernet as well as communication with another part of the main board, Xilinx Spartan 6 FPGA. Communication between the processor and the FPGA is held by general purpose memory controller (GPMC). The FPGA is used to transmit data to and from read-out boards. Xilinx multi gigabit transceivers called GTP are used to achieve fast serial communication between the main board and read-out boards, as well as synchronization of read-out boards. Due to clock recovery from GTP it is possible to achieve synchronization between 80 ps and 100 ps [14]. SATA physical layer is used for GTP transmission. A small extension board with 8 SATA sockets is connected to the main board through DIN connectors. Up to 8 read-out boards can be attached via SATA cables to this extension board. Read-out boards control measurement process, receive data from analogue measurement boards and exchange data with the main board. The main part of the read-out board is Xilinx Spartan-6 FPGA which contains the whole control logic. EVT4 can have up to 32 channels thanks to 8 analogue boards with 4 channels each. The analogue board channel has two parts: a transmitter, also called an excitation circuit and a receiver, also called a measurement circuit. Each channel has its own analogue to digital converter. Both parts of the channel are alternately connected to an electrode using analogue switches. The analogue boards are connected to the read-out boards through DIN connectors. An interface used for data transmission between read-outs and analogue boards is a custom solution which allows exchange of analogue boards realizing different measurement methods.

However, this will also require modification in control logic placed in read-outs FPGA. Currently charge-discharge and single shot high voltage [15] measurement methods were implemented. All boards are placed in a 19’’ 6U EURO chassis.

Two supply modules are used in EVT4. One is used to deliver voltage for digital circuits (+5 V) and for analogue boards (+12 V). Another power supply unit is used to generate high voltage for transceiver in single shot high voltage boards (up to 220 V).

2.2. Main board

The main board is realized as a printed circuit board in 6U Eurocard format, which is a requirement for all boards used in EVT4. The main board receives commands from the host computer, interprets them, controls measurement process, receives measurement data and transmits it to the host computer over the Ethernet. The block diagram of the main board is shown in Fig. 2. Following elements are used in the main board:

- ARM Cortex-A8 processor,
- Xilinx Spartan-6 FPGA,
- DDR SDRAM,
- SD memory,
- Flash memory,
- Gigabit Ethernet port,
- USB-RS232 port.

ARM Cortex-A8 is a 32-bit processor which is characterized by high performance and low power consumption. Frequency of the processor is set to 1 GHz. A Linux distribution optimized for ARM
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