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DEVELOPMENT OF ELECTRICAL CAPACITANCE TOMOGRAPH DESIGN IN THE NUCLEAR AND MEDICAL ELECTRONICS DIVISION

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Abstract. *Electrical Capacitance Tomography is a technique which allows to visualize a spatial distribution of electric permittivity in an examined volume. ECT allows to achieve hundreds of frames per second which is suitable for the industrial application, e.g. monitoring of multiphase flows or material mixing. Construction of such ECT system which enables precise data acquisition with sufficient speed is a challenge. In the Division of Nuclear and Medical Electronics ECT systems which have found applications in many research facilities in Poland and all over the world have been constructed for over 15 years. In this article a multichannel ET3 tomograph and its successor,EVT4, are presented. EVT4 will allow to obtain more than 10 thousand frames per second. This will allow to make progress in studies of dynamic processes and 3D visualization.*

Slowa kluczowe: electrical capacitance tomography

ROZWÓJ KONSTRUKCJI ELEKTRYCZNEGO TOMOGRAFU POJEMNOŚCIOWEGO W ZAKŁADZIE ELEKTRONIKI JĄDROWEJ I MEDYCZNEJ

Streszczenie. *Elektryczna tomografia pojemnościowa pozwala na obrazowanie przestrzennego rozkładu przenikalności elektrycznej w badanej objętości. Technika ta pozwala na uzyskanie setek obrazów na sekundę, dzięki czemu istnieje możliwość wykorzystania jej w przemyśle, na przykład do monitorowania procesów dynamicznych, takich jak przepływy wielofazowe lub mieszanie materiałów. Skonstruowanie systemu tomograficznego pozwalającego na bardzo szybką akwizycję obrazów o dobrej jakości jest jednak dużym wyzwaniem. W Zakładzie Elektroniki Jądrowej i Medycznej Politechniki Warszawskiej od lat powstają konstrukcje tomografów pojemnościowych, które znajdowały zastosowanie w placówkach naukowych w Polsce i na świecie. W tym artykule prezentowany jest wielokanałowy tomograf ET3 oraz jego następca, EVT4, który pozwoli na uzyskiwanie 10 tysięcy obrazów na sekundę. Pozwoli to na dokładniejsze badanie procesów dynamicznych oraz wizualizację trójwymiarową.*

Keywords: elektryczna tomografia pojemnościowa

Introduction

Electrical Capacitance Tomography (ECT) is used to visualize spatial distribution of electrical permittivity in an examined objects [2]. An image with a cross-section or 3D distribution is reconstructed from capacitance measurements between electrodes placed on a tomographic sensor in which examined objects are put. ECT is a very fast technique which allows to apply it in dynamic process imaging, mainly two-phase flows monitoring [3, 6]. In comparison to other tomographic modalities ECT is relatively cheap. Main drawbacks of ECT are low spatial resolution and low sensitivity. It is assumed, that spatial resolution is equal to around 10% of the diameter of a tomographic sensor. Quality of the image reconstruction is presented in Fig. 1 which shows image reconstruction of the cross-section of the phantom consisting of 7 rods with relative permittivity $\varepsilon_r = 3$.

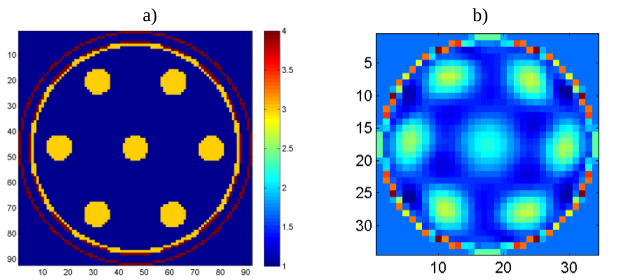

Fig. 1. a) Cross-section of the phantom consisting of seven rods with permittivity ε = 3; b) image reconstrucion with Kaczmarz algorithm from numerically simulated projections

One of main challenges in ECT is a measurement of very small capacitance values. In a typical tomographic sensor which has over a dozen electrodes mutual capacitances vary from tens of femtofarads for opposite electrodes to single picofarads for adjacent electrodes [7]. It is not possible to increase values of mutual capacitances which could be achieved by increasing surface area of electrodes because this would result in a lower number of electrodes and lower sampling rate and thus lower spatial resolution which is already low. Because of this very precise and sensitive measurement methods have to be used in ECT which allow to measure a wide range of small capacitances in a short time.

In Nuclear and Medical Electronics Division of Warsaw University and Technology research works on ECT started around 2000. Under the leadership of doc. dr. eng. Roman Szabatin several models of capacitance tomograph were constructed. The first model ET1 was a 16-channel tomograph working with probes with 8, 12 and 16 electrodes. As part of further work, a prototype of a new model of tomograph ECM was built. Number of channels was increased to 32. Around 2005 the 32-channel ET3 was created. This device was a unique device on a world scale. This article describes the design and construction of ET3 and his successor – EVT4.

1. ET3 tomograph

ET3 Tomograph (shown in Fig. 2) can work with 8, 12, 16 and 32-electrode sensors as well as with three-dimensional probes containing several layers of the electrodes (up to 4 layers of 8 electrodes) [1]. The system consists of:

- motherboard with connectors for measurement cards and control card. The motherboard also includes eight programmable Altera chips for digital signal control;
- 16 signal cards, each of which has two measurement channels. Channels carry out "charge-discharge" measurement method in which alternating capacitance charging and discharging cycles are performed and integration of electric charging and discharging current is held. In the multi-channel device the measurement is possible in which one of the electrodes is a transmitting electrode and the others are the measurement electrodes;
- control card with a programmable FPGA chip which is responsible for measurement process control and communication.

Electrodes of the sensor are connected to the coaxial connectors located on the motherboard. Printed circuit boards are installed in 19-inch Euro rack with own power supply. To communicate with a PC two independent serial ports are used: RS-232 and RS-422. Control of the measurement process and image reconstruction are done by software installed on a PC computer.

ET3 tomograph allows to change amplifications on the signal cards by switching RC elements in feedback loops of AD8620 amplifiers with analogue multiplexers. In addition, amplifications can be set with two PGA206 programmable amplifiers connected in series. It is possible to change the amplification factor programmatically in the range of 1 to 100 in the integrators, and from 1 to 64 in the amplifiers. It is possible to program amplifications for each measurement channel for each pair of electrodes separately. As a result, it is possible to measure the electrical capacitance in a wide range with similar sensitivity for each measurement channel. This can significantly improve the signal to noise ratio. At the time this was a unique solution that has never been used in Electrical Capacitance Tomography before.

The analogue signal which is a result of the "charge-discharge" method is digitized by the analogue-to-digital converter AD676.

Measuring algorithm performed by the control board is as follows:

a) set amplifications in the measurement channels;
b) send the tag of the new data frame when it is a beginning of a frame;
c) start transmission of a signal on a transmitting electrode and start measurements on the measurement electrodes. Signal detection is performed synchronously with the transmission of the active signal;
d) activate analogue-to-digital conversion for a fixed number of periods. The signals from the measurement circuits are sequentially converted by an analogue-to-digital converter. After each conversion result is sent to the output communication interface as a 16-bit word;
e) stop the transmitting signal and turn off measurement switches;
f) after the last period of the transmitting signal proceed to step a) of the next sequence.

After switching on ET3 tomograph immediately realizes measurement cycle which is periodically repeated. The resulting measurement is sent in a frame consisting of 16-bit words after conversion to digital form. The frame contains a marker which denotes start of the frame, a word describing the state of the tomograph and data, the number of which depends on the current tomograph state. The default mode of the tomograph and measuring circuits amplifications settings are stored in configuration memory and can be reprogrammed while the tomograph is turned on with commands sent from the PC.

ET3 tomograph performs one of two measurement modes: with repetitions, i.e. when each electrode is transmitting while all other electrodes are measurement electrodes which leads to repetition of the measurement for the electrode pair, and a mode without repetition, when the capacitance value of a reciprocal pair of electrodes is measured only once. The software used to operate the tomograph using a PC allows to collect data in real time and performs simultaneous visualization. For image reconstruction (32x32 pixels) LBP algorithm is used. Although electronic components with low tolerance values were used for the construction of the tomograph, the channels may have different characteristics. In addition tomographic sensor electrodes may be made with a limited accuracy. Therefore, prior to measurement it is necessary to perform the calibration consisting of the measurement of the smallest and the largest capacitance value. Assuming linear channel characteristics data are normalized using the maximum and minimum values obtained during calibration. Normalization compensates the characteristics of measuring circuits and the measured values are in range from 0 to1.

ET3 tomograph is characterized by exact measurements (measurement uncertainty of less than 0.025%) and small differences between the channels (less than 1% without calibration). The system allows to acquire approximately 300 pictures per second, but the frame rate may be limited by the bandwidth of the serial RS-232 interface.

ET3 tomograph has been applied in many institutions, including the Institute of Applied Computer Science at Lodz University of Technology, TUNRA Bulk Solids Handling Research Associates at University of Newcastle in Australia and the Faculty of Electrical Engineering at Warsaw University of Technology.

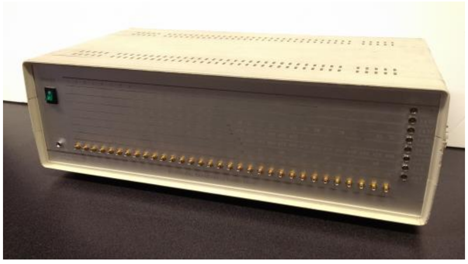

Fig. 2. ET3 tomograph

2. EVT4 tomograph

EVT4 tomograph (Fig. 3) which is currently constructed in the Nuclear and Medical Electronics Division is the successor of ET3 tomograph [4, 5]. The construction is characterized by the following features:

- 32-channel system with the possibility of extending to more channels by combining two or more tomographs;
- parallel measurement of the 31 electrical capacitances in a 32-electrode setup (one electrode is a transmitting electrode and the other are measuring electrodes);
- fully modular - the ability to replace any module without the need of hardware changes in other parts of the tomograph (only replacement of read-out modules embedded software is necessary);
- synchronization between modules implemented through the mechanism of the clock recovery from serial transmission circuits;
- ability to implement different capacitance measurement methods in replaceable analogue cards;
- uniform standard for future creators of capacitance measurement methods;
- flexibility - the ability to cooperate with tomographic sensors with various configurations of electrodes;
- control and diagnostics remotely from a PC via Ethernet;
- system based on the latest available chips on the commercial market of programmable technologies;
- acquisition of 10000 images per second in 32-electrode configuration with measurements repetition for each electrode pair.

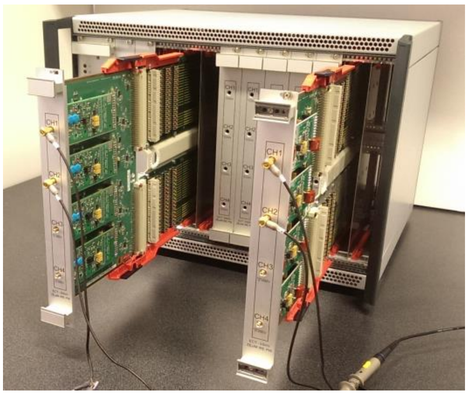

Fig. 3. EVT4 tomograph

EVT4 tomograph consists of the following components:

- control board which contains an ARM Cortex-A8 processor and Spartan-6 FPGA which communicate with each other over the 16-bit General Purpose Memory Controller (GPMC). The control board is responsible for communication with the PC via Ethernet, control of the measurement process and receiving measurement data;
- eight read-out boards controlled by the Spartan-6 FPGAs. Read-out boards receive messages from the control board and transmit data from analogue boards to the control board;
- eight analogue boards that carry out the measurement method and send the data to read-out boards. Analogue cards use high-

speed analogue-to-digital converter AD7626, which reaches 10 million samples per second.

The system works with tomographic sensors having up to 32 electrodes, a PC equipped with an Ethernet and software for data acquisition and image reconstruction.

2.1. Control board

The control board is responsible for communication between a computer and the tomograph, control of measurements, reading the measurement data from the read-out cards, data buffering and data transfer to a computer. Moreover, it provides synchronization between read-out cards. The main elements of the motherboard are:

- 32-bit ARM Cortex-8 Texas Instruments AM3874 RISC processor;
- Xilinx Spartan-6 XC6SLX75T FPGA, coupled to the processor via the GPMC. The GPMC interface is a set of multiple 16-bit registers that the processor sees as addressable memory. GTP transceivers which perform serial communication with speed up to 3.2 Gbps are built-in to FPGA and are ensuring the transmission of data between the control board and read-out boards. An additional advantage of the GTP interface is the ability to recover the clock on the read-out boards which provides synchronization of all of the digital cards of the EVT4 tomograph;
- DDR SDRAM, Flash memory and SD;
- Gigabit Ethernet for communication with the computer. The physical layer is implemented by the transceiver circuit Micrel KSZ9021RL;
- USB-RS232 converter, which is a secondary interface to communicate with the computer. FT232 UART/USB converter was used;
- expansion card with SATA connectors which is connected to the control board via two DIN-41612 connectors.

It is possible to connect up to 8 read-out boards to the motherboard through SATA interface utilizing expansion card. In the EVT4 tomograph physical SATA layer was used due to the high speed data transmission and immunity to electromagnetic interference. Solutions such as multi-layer PCB in which signal layers are separated from powering layers with many layers of ground and a ferrite filters on the power supply lines were used to minimize the distortion and noise.

2.2. Read-out boards

Read-out boards are responsible for controlling the measurement circuits and the analogue-to-digital converters located on the analogue cards (each measurement card contains four measurement channels). Read-out boards are also responsible for the initial data processing and transmission to the motherboard after receiving data from the transmitters.The most important element of each read-out card is Xilinx Spartan-6 XC6SLX75T FPGA containing GTP transceivers used to communicate with the control board. The physical layer of the serial transmission is performed using connectors and SATA cables. Read-out boards are connected to the corresponding analogue boards via 96-pin DIN 41612 connector. Communication with the analogue-to-digital converters AD7626 which are located on analogue measurement boards (each channel of an analogue board contains one transmitter) is implemented in the physical layer using Low-Voltage Differential Signalling (LVDS) standard.

It is possible to additionally mount the DDR SDRAM memory (512 MB) on the cards in case when there is no space for processing measured data in the built-in memory of the FPGA.

Clock signal of the read-out boards is the clock signal coming from the motherboard which is recovered from transmission through the GTP. This solution allows to synchronize all the cards, and thus the measurement cycle in the transmitting and measurement channels.

2.3. Analogue measurement boards

In the EVT4 tomograph it will be possible to mount up to eight measurement cards, wherein each card has four measuring channels, which gives up to 32 channels. The design does not require the use of a particular method of capacitance measurement, which makes the system possible to operate with different sets of measurement cards constructed according to the tomograph project. The limitation is that the size of the PCB has to be in the Eurocard standard, analogue-to-digital converter (AD7626) has to be used as well as GPIO pins which are used to control the measurement card by read-out boards.

Analogue measurement board measures the capacitance and produces a data stream that is transmitted to the read-out board. Every analogue board is connected to the corresponding read-out board with two DIN41612 connectors. By separating the analogue channels from the digital interface it is possible to use different methods for capacitance measurement. It is only needed to exchange measurement board and install a new measurement algorithm in the FPGAs of the read-out boards. At the moment analogue cards with the following measurement methods were created:

- "charge-discharge";
- "single-shot high voltage".

Measuring method "single-shot high voltage" refers to the charging capacitance with a pulse which amplitude is in range of 200 V to 400 V. Fig. 4 shows a block diagram of this method. The measured capacitance is proportional to the U_{diff} voltage.

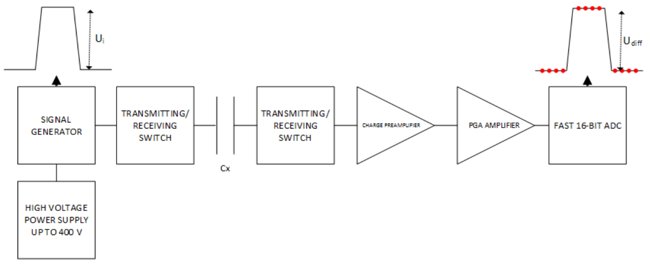

Fig. 4. Block diagram of the analogue board which realizes "single shot high voltage" method

2.4. Embedded software

Embedded software of the EVT4 tomograph is distributed between the control boards and read-out boards. Linux system runs on the control board's ARM processor. Data transmission between the tomograph and the PC is performed by a program written in C language and running on Linux. This program collects data from and transmits data to the Spartan-6 FPGA on the motherboard with a Linux character device driver. FPGA chip on the control board is programmed with a design written in VHDL. Embedded software of Spartan-6 FPGAs of the read-out boards consists of circuits described in VHDL and PicoBlaze software microcontrollers which execute a measurement sequence and are responsible for data transmission.

Each analogue card has four analogue measurement channels where analogue signals are sampled by the AD7626 analogue-to-digital converter which can produce 10 million 16-bit samples per second. Each transmitter therefore transmits 150 Mb of data per second, and therefore each analogue board produces and sends 600 Mb of data per second. Data from the analogue boards are sent to the read-out boards through LVDS which enables the transfer of approximately 655 Mbit/s. The measurement process and data receiving process from analogue boards are controlled by software running on PicoBlaze processors installed on the read-out boards FPGAs. PicoBlaze soft processor is an 8-bit RISC microcontroller running with 100 MHz clock. A special feature of this processor is the fact that each instruction is performed in two ticks of the clock. Accordingly the PicoBlaze enables data transfer at 380 Mb/s. First soft processor receives the commands from the host computers. Second soft processor performs measurement control. Third PicoBlaze microcontroller is responsible for transferring data to/from the control board through the GTP interface. In the prototype version of the tomograph GTP units are configured to obtain the speed of 1.25 Gbit/s. The data from the read-out boards go to the control board where they are sent as 16-bit words from the FPGA to the ARM processor using the GPMC. In FPGA GPMC protocol support is provided by the Moore finite-state machine described in VHDL. Currently GPMC controller is configured for single readings from the FPGA FIFO queue in which data from the read-out boards reside. Each word should be read by GPMC within 200 ns. This time ensures proper data reception. However, the GPMC introduces additional overhead time associated with the internal arbitration of method for data reading. This additional time is 70 ns for each reading. ARM processor reads data from the GPMC using a driver written in C language. Measuring sequence in the read-out boards has been written so that the CPU of the control board can read data without interruption. This allows it to reach speeds of about 54 Mbit/s. Individual readings by the GPMC are bottleneck of the data transfer in the EVT4 tomograph. With the current measurement method ("single-shot high voltage") where each measurement consists of about 128 samples per channel it is possible to achieve about 44 frames per second in 32-electrode configuration when measurements are made without repetition. In the production version of the device all measurement samples will not be sent. The FPGAs of the read-out boards will calculate measured U_{diff} value and instead all samples only the result will be sent. This will make it possible to obtain more than 2500 frames per second. The further acceleration of data transmission is possible through the use of the DMA transfer in the GPMC. This will speed up the data transmission about the order of magnitude. The target speed of the GPMC is estimated to be about 640 Mb/s. This will allow to obtain over 10000 images per second for the tomographic sensor with 32 electrodes and with repetition of each measurement, i.e. when in each pair of electrodes once one is a transmitting electrode and next the second is a transmitting electrode. Fig. 5 is a diagram of data transmission in the prototype device.

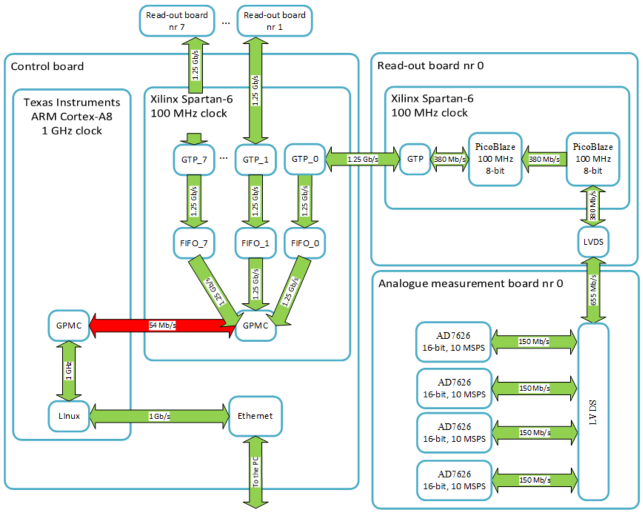

Fig. 5. Diagram of data transmission in EVT4 tomograph

Preliminary tests of the EVT4 tomograph showed that it will be possible to measure capacitance values lower than 10 fF. Further work will include the development of the data acquisition and image reconstruction software for PC.

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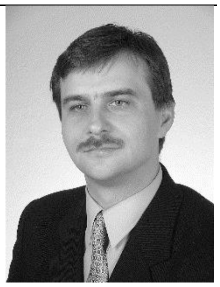

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