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FPGA TECHNOLOGY IN PROCESS TOMOGRAPHY

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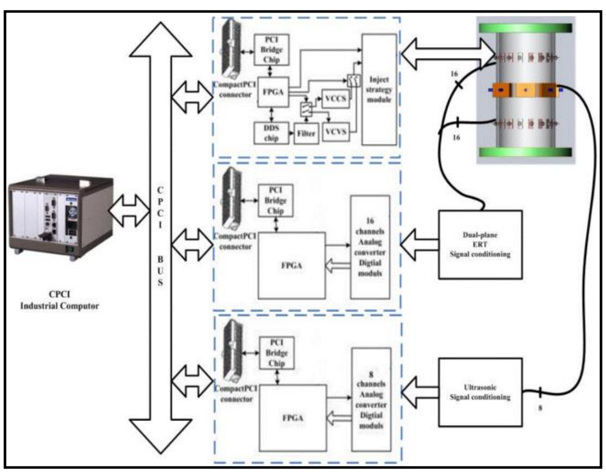
Graphical abstract



Abstract

The aims of this paper are to provide a review of the process tomography applications employing field programmable gate arrays (FPGA) and to understand current FPGA related researches, in order to seek for the possibility to applied FPGA technology in an ultrasonic process tomography system. FPGA allows users to implement complete systems on a programmable chip, meanwhile, five main benefits of applying the FPGA technology are performance, time to market, cost, reliability, and long-term maintenance. These advantages definitely could help in the revolution of process tomography, especially for ultrasonic process tomography and electrical process tomography. Future work is focused on the ultrasonic process tomography for chemical process column investigation using FPGA for the aspects of low cost, high speed and reconstructed image quality.

Keywords: FPGA, process tomography

1.0 INTRODUCTION

The gradually developing Field Programmable Gate Array (FPGA) technology has grabbed great attention of researches both from the academia and industry whom are always seek for an alternative high speed data acquisition and signal processing system [1]. FPGAs do have the ability to accelerate a system's signal processing speed, as it is the result of the parallel computation technique applied in certain applications. Typically, FPGA uses as the signal processing engine, which is suitable for multi-task applications.

In the traditional way, the programming language of the FPGA is either schematics or Hardware Description Languages (HDLs) that is used to design a circuit or to describe the size and complexity of designs. But, the design method has extended to the use of C-to-FPGA tool flows such as the Impulse C, which allows designers to use C language in designing FPGA hardware. Impulse C is promising to reduce the expertise requirement of proceeding design and programming [2], [3].

FPGA-based integrated circuits consist of a large number of Configurable Logic Blocks, example like the loop-up tables (LUTs) that used to define a logic function, additional selection and carry logic. Currently, several special elements, such as multipliers, analogue-to-digital converters (ADCs), and large memories, are built within the fabrication of FPGA to boost capacity and speed [4]. This paper provides a brief explanation to the FPGA technology applied in various process tomography, the benefits of employing a FPGA in process tomography system and the recent research worked with applying FPGA technology, whilst, comparisons of performance between FPGA and Graphical Processing Units (GPU) have also being concluded in this paper.

2.0 PROCESS TOMOGRAPHY

Process tomography is an alternative approach that is widely use to investigate the internal characteristics of a process column, especially in oil and gas engineering, chemical process engineering and medical healthcare industry [5], [6]. The measured data helps in the modelling stage and the complex process design by interpreting the measured data for the purpose of control and monitoring of processes [38]. Basically, tomography sensing techniques are capable to produce tomogram images in two-dimensional and/or three-dimensional which will well illustrate the flowing condition of a single phase or multiphase in the process column. Various types of tomography measuring techniques are available for sensing measurement, which include techniques such as needle probe, neutron computed tomography, magnetic resonance imaging (MRI), positron emission tomography, X-ray and gamma-ray computed tomography, ultrasound computed tomography, optical computed tomography, wire-mesh tomography, electromagnetic tomography and electrical computed tomography.

Electrical tomography techniques can be divided into several branches as the normally invasive type electrical resistance tomography (ERT), the electrical impedance tomography (EIT) which is used to measure resistance and capacitance and the non-invasive type electrical capacitance tomography (ECT). These tomography systems have received significant attention from the industries in recent years, this may be because of their low cost, convenient, and safe to use compared to others radiation tomography techniques. Electrical process tomography produces low resolution cross-sectional images, based on the measured data of permittivity and conductivity.

Among the sensing methods of process tomography, electrical process tomography including EIT and ECT is more popular in recent years. This is because of electrical process tomography is convenient, low cost and safe compared with other methods based on nuclear magnetic resonance (NMR), X-ray or y-ray and ultrasound etc. [7][39]. The main disadvantages of electrical process tomography is the sensitivity problem, inverse problem [8] and fast forward problem [9]. More information on electrical tomography techniques can be referred in [6], [10]–[14].

Figure 1 shows the electrical process tomography system's basic components of an ERT system [5]. The sensing electrodes are equally located with same distance at the periphery of a process column in the purpose of extracting the maximum information. Noninvasive capacitance-sensing electrodes are usually installed outside the process column, while, the invasive but nonintrusive resistivity-sensing electrodes normally placed flush with the inner surface of the process column. The electrical tomography systems measurement strategy is executed by a control personal computer (PC).

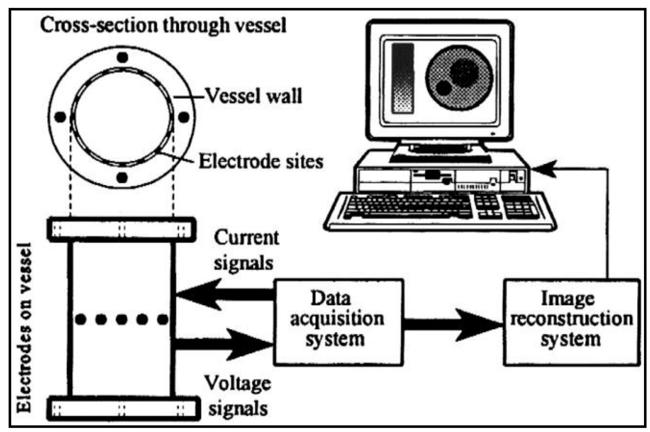


Figure 1 Schematic diagram of an ERT system

3.0 RECENT FPGA RESEARCH APPLICATIONS IN PROCESS TOMOGRAPHY

3.1 Tomography System Uses FPGAs

Implementation of analogue designs have faced with problems, as components miss-matching, input offset, noise and limited processing speed due to switching transients, conversion time delays and multiplexing overhead. Thus, an affordable and high performance FPGA-based data acquisition and processing module was developed for optical tomography with providing a speed of 50 Mbps. The designed system helps to reduce analogue hardware and the processing time. Future work was introduced to focus on the dual wavelength fast tomography, tomography with real-time spectral scanning, and the far-IR (T-ray) tomography with electro-optic sampling [15].

Douraghy *et al.* [16] had developed a dual-modality optical and PET (OPET) small animal imaging tomograph prototype. The implementation of FPGA had greatly reduced the recorded data size and events post-processing procedure. A digital ECT system that consists of FPGA and DSP had greatly improved the time of reconstructing one image with only 90μs [17]. The digitized ECT system has three main components as shown in Figure 2, there are the sensing electrodes, the data acquisition and processing unit and the PC.

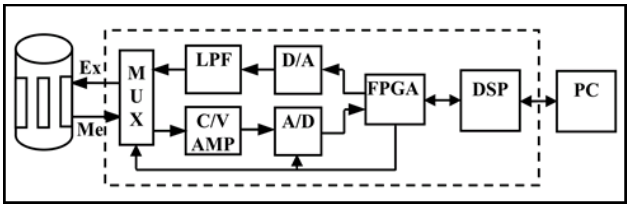


Figure 2 Digital ECT system architecture [17]

The capacitance-sensing electrodes are symmetrically installed around the process column. The data acquisition strategy and measured data are processed and control by FPGA, then, the digital signal processor is used for communicate with the PC. The PC in the system is mainly used for GUI and display in tomographic images.

In a research about FPGA technologies in medical equipment, Artem and Dmitry [18] introduced the FPGA-based architecture design for parallel data processing and experimental work which had proved that it was applicable for electrical impedance tomography system hardware implementation. Future research works are focusing on FPGA-based electrical impedance tomography reconstruction algorithm implementation. Yang *et al.* [19] applied a real time and integrated FPGA-based induction measurement system, which was developed for low conductivity object detection. Several experimental tests were conducted to ensure that the system are functional to low conductive objects. With the ability in the measurement to the multiphase fluid conductivity, phase fraction measurements in complex flows are the working direction in the future time.

3.2 Frame Rate Capacity Using FPGAs

Recently, an active electrode-based system was developed to improve the quality of electrode contact and the sensitivity to changes in contact, and to overcome the problem of time-consuming and difficult execute on numbers of patient. The volunteer tests showed that the system work on a frequency between 80 and 200 kHz, which provides frame rate of 10 to 30 images per second. The future work aims to develop an equipment with specifications of reusable, low ownership and maintenance cost said Gaggero *et al.* [20].

Process tomography system employing FPGA-based Compact PCI (peripheral component interconnect) bus had been presented in few research works. Xu *et al.* [21] had experienced with dual-modality FPGA-based data acquisition system, experimental results showed that FPGA-based system is flexible, high processing speed, stable, expansible and good signal-to-noise ratio (SNR), moreover, the FPGA-based data acquisition system can be expanded to multi-modalities process tomography by adding related function cards on the system. The illustration of the dual-modality data fusion system as Figure 3.

For multiphase flow measurement, researchers, Xu and Dong [22] had described a parallel ERT system based on Compact PCI, the parallel ERT system performance greatly improved and the framing rate are 1420 frames/s and 1041 frame/s with Over Zero Switching (OZS) scheme. Future work aims to execute online real-time monitoring, phases flow regime data extracting with dynamic experiments on the ERT system. Another research work by Dong *et al.* [23] as the structure of the ERT system shows in Figure 4, which used to investigate the parallel ERT system design based on a fully programmable and reconfigurable FPGA-based Compact PCI bus. The results recorded with an error less than 5% under low flow rate and relatively good result for related experiments. Zhang *et al.* [24] had tested a data acquisition system based on Compact PCI bus and FPGA, the system had greatly improved in overall. When the system's current injection at 100 kHz, the frame rate can achieve almost 1689 frames/s. And, the signal-to-noise ratio (SNR) in the system had recorded above 73dB. The designed data acquisition system can be expanded by adding related functional cards, flexible, and to be applied in industrial field.

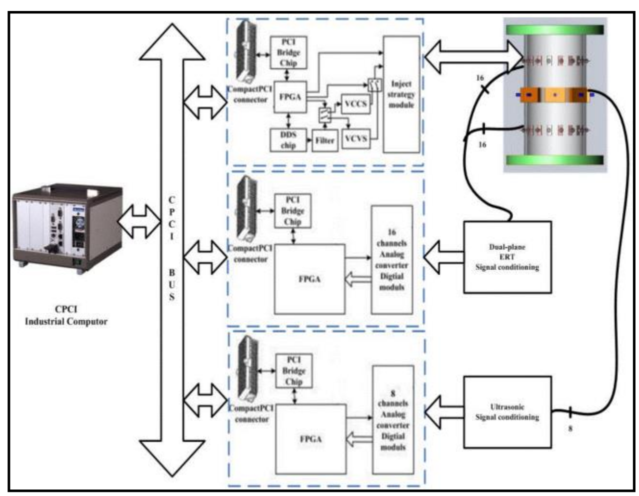


Figure 3 Structure of the data fusion system [21]

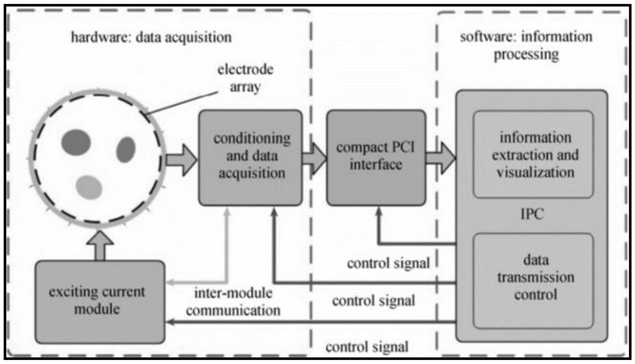


Figure 4 Structure of the ERT system [23]

The result of a specific data acquisition scheme implemented to electrical tomography showed that the FPGA-based system is a highly compact and flexible system, which achieved over 150 frames per second of online data acquisition rate in a research conducted by Cui *et al.* [25]. A modular 32 channel FPGA-based data acquisition (DAQ) system was developed to enable high frame rates, where the FPGA throughput rate was 32 times faster than a PC [26].

3.3 Comparative Performance of FPGA Devices

There are quite a number of researchers that work to evaluate the performance and power consumption between the FPGAs and GPUs devices. A dedicated architecture for FPGA had increased the system memory bandwidth and further accelerated the Expectation Maximization (EM) algorithm. The research work had concluded that the FPGA-based system is 85 times faster than single-thread CPU [27]. The proposed system architecture is as Figure 5.

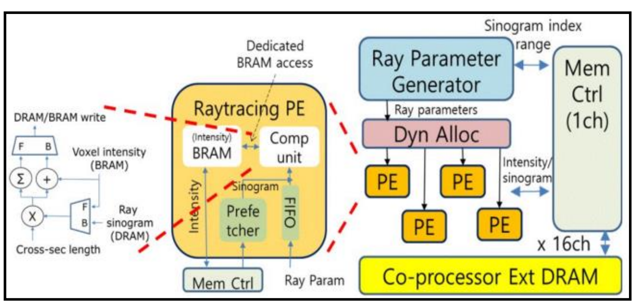


Figure 5 The architecture of the proposed system [27]

Birk *et al.* [28] compared the processing performance and architectural efficiency with two processing algorithms for a 3D Ultrasound computer tomography on GPUs and FPGA. The results of 40 nm generation top-notch devices showed that the GPU has a higher performance than an FPGA if power consumption is not considered. But, if power input and cooling requirements have taken into consideration, the FPGA is superior to a comparable GPU. Future research work is to use metrics' set for the groups of algorithms for identifying variability of GPUs and FPGA. And, more types of data processing devices are planned to be used to determine application characteristics as an accelerator.

In the investigation of Fourier domain Optical Coherence Tomography (FD-OCT) [29], although the image quality of FPGA output is slightly disappointing compared to the General Purpose Graphical Processing Units (GPGPU) output image, but, the FPGA processing engine has a potential to integrate to meet future FD-OCT processing demands as the real-time, three-dimensional imaging. While the GPGPU platform has the limiting factor of data transfer between CPU and GPU memory, which could not be applicable for future FD-OCT processing demands. Therefore, the future research work is focused on how to allow the FD-OCT with FPGA implementation of swept-source based systems and selecting a suitable scaling method to improve the FPGA output image quality.

Furthermore, one of the reasons that FPGA-based system became more popular in the field of process tomography is because of the capability to process large size and complex application with exceedingly fast and easy to interface with other electronics devices. An FPGA-based co-processor was developed to accelerate the singular value array reconciliation tomography (SART) algorithm. The results showed that a single FPGA running with a frequency of 200 MHz can provide throughput that is six times greater than the 3 GHz Pentium 4 machine with no co-processor. This research had opened a gateway towards development of a small, low power, SART-based tracking system for mobile search and rescue application [30].

3.4 Demodulation Methods Tested Using FPGAs

Many researchers had tested several types of FPGA-based demodulation techniques in different process tomography. Ge and Lifeng [31] had tested FPGA-based digital phase-sensitive demodulator and the results showed that it is suitable for the digitalised EIT system. The demodulator has a high signal to noise ratio (SNR), high precision and speed that is needed in a digitized EIT system. Zarifi *et al.* [32] presented that an EIT system with digital demodulation technique can be used for narrowband filtering and the variable frequency sinusoidal reference was applied to successfully obtain input signal spectrum. A FPGA-based wide frequency range (0-16.67 MHz) excitation source and demodulation module gives result as high precision, good stability and convenient adjustment in the electrical impedance tomography system. The pipeline design technique had contributed to the efficiency of demodulation said Zhang *et al.* [33]. Zeng *et al.* [34] said that the Prony demodulation method is a method that is more flexible and time-efficient to the quadrature demodulation method for the research application.

3.5 FPGA for Clinical Diagnostic Application

Chowdhury *et al.* [35] had implemented a novel smart data processing hardware system that is capable for medical diagnostic. The system used a FPGA chip for fast design cycle and the most important process is to seed up the computation process of the smart processing system. The system employed pipelined data processing architecture for the purpose of speeding up the computation process to approximately three times. The system is designed with the aims to provide an inexpensive, portable and user friendly hardware system for rural applications in developing countries.

Chowdhury *et al.* had presented the functional architecture of a smart diagnostic system as shown in the Figure 6. Minimum of three entities is needed for this concept of diagnostics. The first entity is the health care personnel help in measuring patients' health parameters. A second entity is the physician who interacts with the smart instrument, while the smart instrument is the third entity with a function of confirming or denying the diagnosis. The smart instrument plays the role of diagnosing on a regular time basis and uses fuzzy logic to predict future states of the patient. The system will indicate the possible next physiological state of the patient based on predictions made by previously fed data. In order to realize the FPGA based diagnostic system, the proposed VHSIC Hardware Description Language (VHDL) model had developed and mapped onto the FPGA chip, EP1C6Q240C8, as the top-level entity shown in Figure 7.

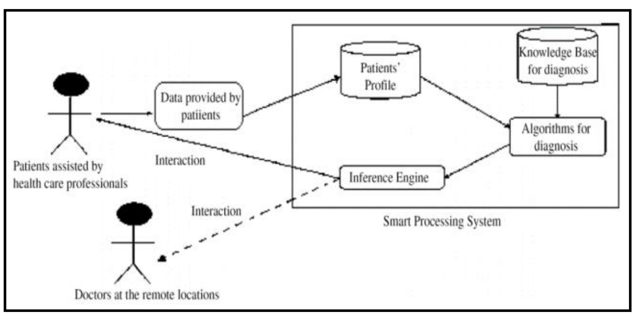


Figure 6 Functional architecture of the smart agent based telediagnostic system [35]

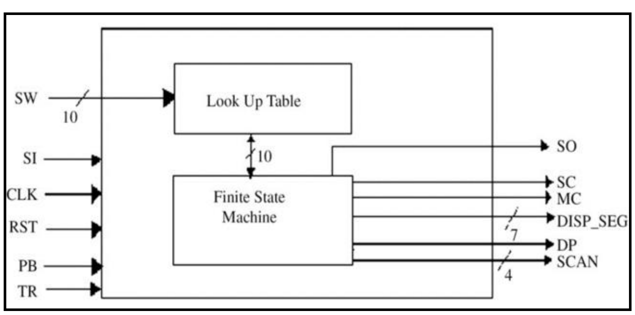


Figure 7 VHDL model of the proposed system [35]

Figure 8 shows the block diagram of the FPGA based smart agent, which comprising of 10 input ports (SW), clock input (CLK), reset input (RST), a control input (PB) used to enable data reading from input ports, seven output ports named as DISP_SEG for LED 7-segment displays, a four bit output code called SCAN used for selection of 7-segment displays and DP is used for displaying the decimal point.

Pipelined data processing architecture are used for high speed computation as Figure 9. Four arithmetic logic unit (ALU) in the system are used to perform clinical diagnostic application tasks. This pipelined architecture can compute decision about all pathophysiological parameters with just 14 clock pulses against 44 clock pulses required in an unpipelined architecture. Thus, FPGA pipelined data processing technology is highly suggested to be applied on process tomography data acquisition and processing system.

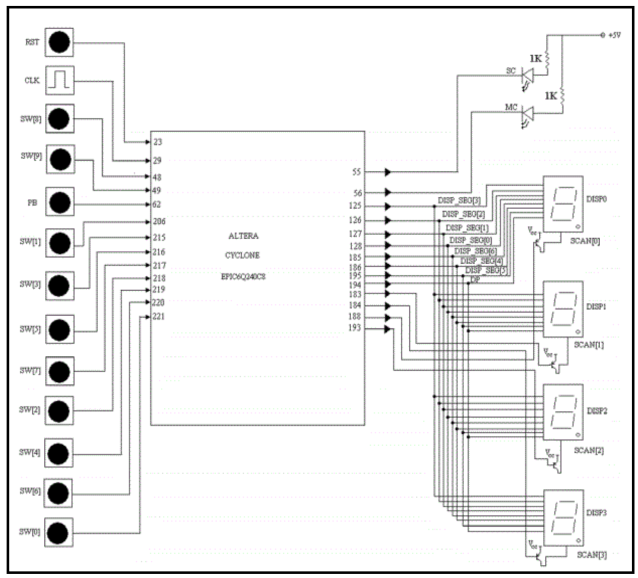


Figure 8 Block diagram of the FPGA based smart agent [35]

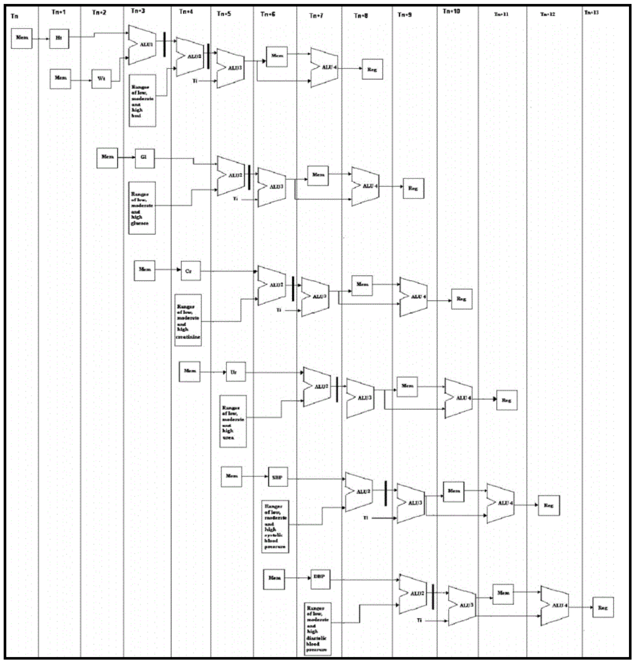


Figure 9 Pipelined architecture realized on an FPGA chip [35]

4.0 TRENDS IN RESEARCH EMPLOYING FPGAs

The quick evolvement of FPGAs has made a single FPGA chip consists of multimillion gates, and integrated with various special elements, such as multipliers, analogue-to-digital converters (ADCs), and large memories on a printed board. This has allowed the implementation of computing process algorithms, large size and complex designs in cost-effective and reliable way. Modern FPGAs are built capably operate at a speed of 50 MHz and beyond [36] and allow dynamic reconfiguration [37-40]. The FPGA-based research efforts towards comparison to several signal processing devices, realizing and accelerating real-time applications as the wireless communications, image processing and image reconstruction, medical imaging, network security, and signal processing.

5.0 CONCLUSIONS

Relevant literature surveys on process tomography employing FPGAs devices has presented in this paper. The adoption of FPGA technology in process tomography can boost the signal processing capability, reduce the analogue hardware, and allow for executing a fully-digital system in certain applications. Future work is focused on the ultrasonic process tomography for chemical process column investigation by using a faster data acquisition and processing integrated circuits device, FPGA, for the aspects of low cost, high speed and reconstructed image quality.

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