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Abstract of Ph.D. Thesis

Parallel computing algorithms using graphics processing units (GPU) for processing and visualization of measurement data from industrial process tomography systems

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Monitoring and proper control of processes in industry are crucial for their efficiency and safety. Researchers are trying to develop tomographic techniques, which can be applied to investigate these processes. However, it is not possible to develop a universal method for every scenario. As the result existing measurement or visualization methods are more or less suited, depending on the type of processes, materials and requirements for spatial and temporal resolution. One of the commonly used is an Electrical Capacitance Tomography (ECT). In principle an ECT system comprises a sensor of 8 to 32 electrodes, which are uniformly arranged on the boundary of a vessel. An associated electronic circuit consecutively measures electrical capacitance between all pairs of electrodes at high speed. Electrical capacitance is directly related to relative permittivity ε_r by (Eq. 1):

$$C = \varepsilon_0 \varepsilon_r k_g \tag{1}$$

where ε_0 is the absolute permittivity of vacuum (8.85 pF·m^{-1}) and k_g is a geometry factor, which depends on the geometry of the problem. The relative permittivity distribution inside a sensor is obtained by the process of image reconstruction, in which a numerical solution of an inverse problem is calculated, according to equation (Eq. 2):

$$C_{ij} = -\frac{1}{\varphi_j - \varphi_i} \oint_{\Gamma} \varepsilon_0 \varepsilon_r(x, y) \nabla \varphi(x, y) d\Gamma \tag{2}$$

Here, i corresponds to the detecting and j to the source electrode, whereas φ is the electrical potential and Γ the directed area of integration on the detecting electrode. There is a choice of solution strategies to this inverse problem, whereby the most popular are fast Linear Back Projection (LBP) algorithms. They give a straightforward approximate solution with some compromise in spatial resolution. The opposite of inverse problem is forward problem, which gives capacitances on the base of permittivity distribution. The solution of forward problem can be applied to more sophisticated non-linear iterative image reconstruction algorithms that require higher computational effort. As the result, the use of ECT is often limited by the large amount of computation required to achieve the necessary spatial or temporal resolution.

Till now, Central Processing Units (CPU) were commonly used to compute forward solution for ECT. However, the computation sometimes takes too much time to be applied in industry. In the past few years, there has been a rapid development of graphics processing units (GPU), which began to be used to perform general purpose computing. GPUs allow to achieve several-order speed up for algorithms that can be executed in parallel. The level of this speedup is limited by the Amdahl's law, which constitutes that the speedup of a program using multiple processors in parallel computing is limited by the time needed for the sequential fraction of this program. On the other hand, since the design of GPUs is much different form CPUs it is not possible to directly run algorithms dedicated to CPU on GPU. Furthermore, for the same reason, it is also impossible to perform algorithms developed for computational cluster on GPU.

The author has taken a pioneering research on the use of graphics processing units for parallel computations for the process tomography. The aim of this work was to develop algorithms for processing tomographic measurement data using GPUs to accelerate computations and finally achieve higher temporal and spatial resolution of reconstructed images.

The most important component of this work is a novel algorithm for solving forward problem in ECT systems. This algorithm utilizes the author's developed method of spreading the coefficient matrix in linear equation into the matrices of $\mathbf{L}$ and $\mathbf{L^T}$. Matrix decomposition algorithm is based on Cholesky-Banachiewich method. However, while the Cholesky method is a typical algorithm that can be executed only in sequence, the developed algorithm of matrix decomposition enables most arithmetic operations to be run in parallel. This modification permitted the use of GPU processing of measurement data from industrial computed tomography systems.

However, the method for decomposing matrix in parallel way is not sufficient to achieve the performance advancement of GPU algorithm in comparison to the classic version of this algorithm for CPU. The difficulty to be overcame in order to accomplish this advancement is the too slow access to global memory (RAM), which prevents from utilizing of the full GPU computing potential. Therefore, the next step of this work was to identify the groups of arithmetic operations that are performed on the same data ranges. The algorithm has been therefore further redesigned so that the arithmetic operations within these groups can be conducted simultaneously by one multiprocessor, and the operations within each of these groups can be carried out independently from the operations of the other groups. This procedure of computations grouping lead to the more efficient use of the global memory and thus resulted in more efficient use of local memory and registers in the stream processor.

In order to achieve the main scientific goals of this thesis, the author has implemented and verified experimentally the following GPU-designed and developed measurement data processing algorithms:

1) Algorithm dedicated to the capacitance planar sensor,
2) Algorithm for solving forward problem for ECT,
3) Iterative image reconstruction algorithm for ECT using forward problem algorithm.

Algorithms implementations were developed for CUDA technology, which at the time that this research was conducted, was the most mature and commonly used technology for general purpose parallel computing on the GPU. However, the outlined methodology can be applied to another GPU technologies such as OpenCL. Additional work presented in this thesis was a comparative analysis of the proposed algorithms for the 32 and 64-bit platforms.

The performance tests have shown that with the use of the proposed algorithms for GPUs it is possible to gain more than 8-times shorter measurement data processing time for algorithms dedicated to ECT. The author also managed to achieve about 40% reduction of measurement data processing time for algorithms dedicated to a capacitance planar sensor and a wire-mesh sensor. Figure 1 presents the acceleration of solving the inverse problem for ECT in relationship to the number of the coefficient matrix elements. The red line corresponds to the scale located on the right and shows how many times the proposed algorithm using the GPU will be faster in comparison to an algorithm designed for the CPU. Moreover, it should be noted that with the increase of the number of coefficient matrix elements the benefit of using the GPU algorithm is growing.

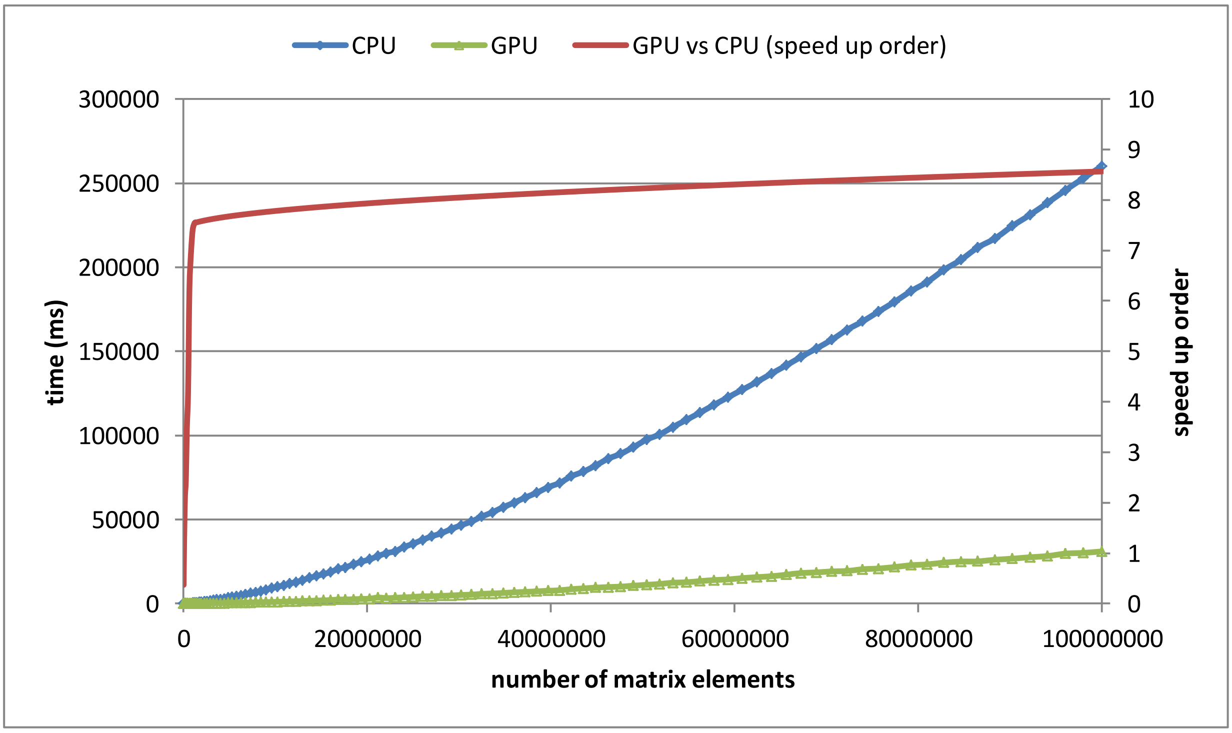

Figure 1. Acceleration of solving the inverse problem for ECT in relationship to the number of the coefficient matrix elements.

This significant increase in the number of calculations that can be performed within a time unit can be deployed in industrial tomographic systems in order to:

1) Rise the spatial resolution of the reconstructed images,
2) Generate higher number of images per second (rise of the temporal resolution),
3) Increase the spatial-temporal resolution of the images.

In order to verify the proposed algorithms in the semi-industrial conditions it was necessary to design, construct and build the experimental set-ups allowing the measurement for two different industrial processes. Author's contribution to the development of process tomography domain is an innovative design of a capacitance planar array sensor (numerically simulated beforehand and experimentally verified). Another sensor used by the author was dedicated to ECT and was used in the first-ever-conducted comparative study between ECT and an invasive capacitance wire-mesh sensor. Both innovative sensors were awarded on the international exhibitions of inventions in 2010 and 2011.

The results presented in this doctoral thesis reveal the possibility for a wider use of process tomography for monitoring of the highly dynamic industrial processes. This capability is especially important for monitoring processes that so far , the measurement data processing time was struggled to be minimized effectively in order to use the results of this processing to control the process itself. The relatively low price and small size of cards with GPUs compared to solutions that provide similar computing power, but based on CPU systems is another advantage of GPU devices. All these factors shall lead to growing interest in the GPU-based computational solutions for supporting the measurement systems and, consequently, to the propagation of the GPU for computing applications in industrial diagnostic process tomography systems.