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**INTERNATIONAL COLLABORATION
OF COMPUTER ENGINEERING DEPARTMENT
IN PROCESS TOMOGRAPHY FIELD**

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Paper describes Computer Engineering Department (CED) activities in international collaboration in process tomography field. It presents chronologically, the history of transfer of knowledge, incoming and outgoing staff mobility between CED and other European and world tomography research centres. History dates back to beginning of process tomography development research of the CED team in year 2000, when collaboration with Professors Andrzej Płaskowski, Tomasz Dyakowski in tomography field was established. Summarized significant of CED activities in process tomography world is 7th World Congress on Industrial Process Tomography which will organise by CED in 2013.

1. INTRODUCTION

From the very beginning, *Computer Engineering Department* is systemically increasing activity in the field of industrial tomography systems. The research programmes on process tomography in Lodz were initiated in the Department by encouraged collaboration with Professor Andrzej Płaskowski from the Warsaw University of Technology 10 years ago. Professor Tomasz Dyakowski, who died in 2006, was strongly involved in this research giving a lot of inspiration for the

rest of team. Thanks to great activity of cooperation between Professor Dominik Sankowski, Professor Tomasz Dyakowski and Professor Andrzej Płaskowski (fig. 1) CED received the world recognition and the international research position in the area of process tomography. The international collaboration with the main tomography centres in the world influenced development of a class of non-invasive methods of analysis of multiphase flow industrial processes by tomography image reconstruction, data processing and analysis in Computer Engineering Department. The CED's research group working in tomography field, the so-called *TomoKIS*, has participated in many international projects, since year 2000. This paper covers the history of international cooperation concerning the developing new IT techniques and modern hardware for investigation of various industrial applications.



From the left: prof. A. Płaskowski, prof. D. Sankowski, prof. T. Dyakowski

Fig. 1. Photo of prof. A. Płaskowski, D. Sankowski, T. Dyakowski

2. COLLABORATION WITH UNIVERSITY OF HANNOVER

In the frame of collaboration of the *Computer Engineering Department* with the *Institut für Verfahrenstechnik* at *University of Hannover* Dr Radosław Wajman had his training in Germany since 1.10.2000 to 30.11.2000. In that period he, in collaboration with Dr T.Loser, was involved in the project “*Image reconstruction methods for Electrical Capacitance Tomography*”. His main tasks was to build the computer application of image reconstruction methods for electrical capacitance tomography (ECT). This software was completely implemented in C++ and included the most common image reconstruction algorithms. Additionally, in order to solve the mathematical model of electrical field inside the ECT sensor, he used the Finite Element Method (FEM). During this work Dr Wajman developed the method of sensitivity analysis along the electrical field lines. he applied this method in the iterative image reconstruction

process where the sensitivity matrix was updated (recalculated) in every step of this process considering the current reconstructed permittivity distribution (image). Thanks to this the reconstruction of details in the measurement plane was significantly improved [1].

3. COLLABORATION WITH UMIST (AT PRESENT UNIVERSITY OF MANCHESTER)

Collaboration with group of tomography from *Manchester University* was very fruitful for *Computer Engineering Department* as well as *Chemical Engineering Department* and *School of Electrical and Electronic Engineering* from Manchester. Main role for this partnership acted Professor Tomasz Dyakowsk from the Department of Chemical Engineering of the UMIST (at present *University of Manchester*). The two main projects concerned on applied electrical tomography to monitoring industrial processes.

In 2001 Dr Lukasz Mazurkiewicz visited (two months visit) UMIST and took part in the CRAFT project. The main aim of the project was to develop a new technique of solids mass flow measurements by using the capacitance tomography. The plan of the CRAFT project was to build a flow meter for pneumatic particles transport systems based on capacitance tomography. The author's part was to develop the method of deriving solids velocity using the cross correlation technique [2].

The next step in collaboration between CED and UK Universities concerned on investigation on new sensor technology to monitoring pressure filtration process using Electrical Resistance Tomography. Dr L. Mazurkiewicz in collaboration with Professor Tomasz Dyakowski and Professor Trevor York worked on the exploration, using reconstructed 3D images, of the pressure filter process. In the project *ProceMon* founded by UK took part *Syngenta Ltd*, *Avecia Ltd*, *Rosenmund Ltd*, *Industrial Tomography Systems Ltd*, UMIST and *Glasgow Caledonian University*. The filtration unit was 36m³. In order to explore [3].

Other project "A new approach of modelling multi-phase flows using tomographic data" funding by the Royal Society (nr 207043) in 2003/2004 year concerned on the developing of academic skills in non-destructed techniques like tomography through staff training and preparing of innovative program ideas. It was occasion to increase the number of scientific men involving in rapid growing industrial process tomography field. The aim of the project was to develop the field of electrical capacitance tomography (ECT) for application in different industrial processes containing dielectric material. To deliver of this aim the project was integrated a wide range of research skills including computing electronics, mathematics, physics and process engineering. Professor Tomasz Dyakowski was a UK Project Leader of the Grant and Polish Project Leader was Professor Dominik Sankowski. They provided UMIST/CED staff meetings on a

regular basis to discuss chosen scientific areas and to solve problems that created barriers to future collaboration. These staff meetings allowed generating a lot of ideas to keep our staff focused on activities in tomography area. Polish partner have got access to the latest development of modern measurement techniques by taking an active role in designing and interpretation of tomographic data. This helped to introduce modern measurement technique to Technical University of Lodz. British partner benefited from collaboration with a strong research team having a very good background in programming, statistical methods of data analysis. The CED performed statistical analysis of measurement data coming from multi-phases flow [4] and CED staff took an active role in conducting investigation at British Universities.

During this project few person from CED visited UMIST. In July 2004, dr. Włodzimierz Mosorow spent three weeks in *Department of Chemical Engineering* of the UMIST. Between June/July 2004 dr Chaniecki, Banasiak and Romanowski familiarized with measurement capabilities of electrical tomography systems. Some people from UMIST visited, as well, *Computer Engineering Department*; for example Dr Philip Martin from Department of Chemical Engineering gave lecture on applied other modalities tomography to measure gas mixture.

4. COLLABORATION WITH INTERNATIONAL ATOMIC ENERGY AGENCY, WIEN, AUSTRIA

The *Computer Engineering Department* was co-leading with International Institutes from USA, Norway, United Kingdom, Brazil, Malaysia and Mexico, a project " *Software Development for Industrial Tomography* " funded by the IAEA (*International Atomic Energy Agency*). The project concerns the ability to use dual-modality system composed of gamma-ray and electrical tomography systems to study industrial process. The overall objective of this Coordinated Research Project (CRP) was to introduce and enhance the use of gamma transmission and emission tomography, electrical tomography (CT) and of radioactive particle tracking (RTP) in scale-up and troubleshooting of multiphase processes. Particular task was to evaluate the feasibility of computer tomography for investigation of multi phase engineering processes. The main scope was to formulate and validate simple practical CT methods for obtaining reliable quantitative results about multiphase flows in industrial process vessels in order to improve and optimize their design and operating efficiency. In particular, hardware CT configuration and software for image reconstruction was evaluated to select the CT techniques that can be transferred to developing countries [5].

Between September 2003 and September 2006, many representatives of *Computer Engineering Department* held short-lived stays in partner Universities. Among the others, Professor Dominik Sankowski visited *Chemical Engineering*

Department in University of Manchester and University of Bergen, Dr Jacek Nowakowski visited University of Bergen, Dr Robert Banasiak and Dr Włodzimierz Mosorow visited Chemical Engineering Department in University of Manchester being hosted by Professor Tomasz Dyakowski.

5. COLLABORATION WITH UNIVERSITY OF LEEDS

The collaboration with University of Leeds started with an interdisciplinary project “*Spatial and Temporal Modelling for Electrical Capacitance Tomography*” funded under the *Computational Engineering Mathematics* initiative of the EPSRC, UK. The project investigated the use of statistical, spatial and temporal, modelling for dynamic imaging of industrial process. Between October 2003 August 2004 Dr Andrzej Romanowski and Dr Krzysztof Grudzien spent about 5 months at University of Leeds each, working with Professor Richard Williams (from *Institute of Particle Science and Engineering*), Dr Robert Aykroyd (*The Department of Statistics*), Dr Robert West (*Institute of Genetics, Health and Therapeutics*) and Professor Tom Dyakowski from UMIST.

The main goal was to apply Bayes’ approach coupled with Markov chain Monte Carlo (MCMC) methods to modelling of solids pneumatic conveying and silo discharging processes study. Implemented statistical algorithms were validated on the basis of electrical capacitance tomography both: measurements data simulation of above-mentioned part of pneumatic conveying process and experimental data of the gravitational flow in hoppers. Applied Bayesian approach allowed incorporating prior knowledge into data processing and direct estimation of control parameters of industrial processes in contrast to usually applied ‘low-level’, pixel-based methods of data analysis [6].

6. DENIDIA PROJECT

The international project „*Development of Excellence in Non-Invasive Diagnostic System for Industrials and Scientific Applications*” acronym DENIDIA foresaw to reach excellence in non-invasive diagnostic systems for industrial and research applications. This project was founded by European Union - Marie Curie Actions. The non-invasive techniques considered in Transfer of Knowledge was based on the tomography technology.

Researchers from *Computer Engineering Department* acquired a lot knowledge in terms of data acquisition, reconstruction, and visualisation of electrical capacitance tomography (ECT), a system particularly well adapted for real time industrial process measurements like multi-phase flow in pneumatic conveying. Department carried out technological and programming research on

ECT to develop systems with a higher resolution and three dimensional acquisitions, without losing the main advantage of fast data acquisition.

The project, for a global cost of around 946000 euros, recruited and delegated of experienced researchers (between 4 and 10 years of experience in research) and more experienced researchers (more than 10 years of experience in research), and staff training in 5 partner institutions from France, UK, Norway and Malaysia, which all responded to the need of the project.

Realization of DENIDIA project took place in the academic years 2006/2007 to 2009/2010. In Table 1 is the list of partner institutions.

Table 1. Partner institution in DENIDIA project

Partner Institution	Research Dept	Expertise related to the project	Country
The University of Manchester	The School of Materials	Materials Science, X-ray tomography	UK
The University of Bath	Department of Electronic and Electrical Engineering	image reconstruction, Electrical Capacitance Tomography, Electrical Resistance Tomography	UK
Institut National des Sciences Appliquées	The Metals and alloys Group of MATEIS laboratory	Materials Science, X-ray tomography	France
University of Bergen	Department of Physics and Technology	Gamma-ray Tomography, Dual modality Tomography	Norway
Malaysian Nuclear Agency	Industrial Technology Division	Optical Tomography, Gamma-ray Tomography	Malaysia
École Supérieure d'Ingénieurs en Électronique et Électrotechnique	Laboratoire Algorithmique et Architecture des Systèmes Informatiques (A2SI laboratory)	3D Computer graphics	France

The objectives was additionally achieved by acquiring more scientific knowledge from other fields of research which use non invasive techniques (i.e. chemical engineering, materials science, medical science), and by widening our

expertise to technological and programming knowledge from other systems such as optical, gamma-ray, X-ray and dual modality tomography techniques.

It is also worth mentioning that in *Computer Engineering Department* buildings was built the *Tom Dyakowski Process Tomography Laboratory* that was inaugurated the 28th of October 2008. This laboratory includes a brand new flow facility (two-phase flow - gas/water and solid flow - gas/solid) that will take an essential role in testing and optimizing the different tomography systems developed within DENIDIA.

The next chapters cover detailed descriptions of collaboration between *Computer Engineering Department* researchers and partner.

6.1. Collaboration with University of Bergen, Institute of Physics and Technology, Norway

Collaboration of TomoKIS Researchers with *Researchers of Department of Physics and Technology, University of Bergen* in Norway belong on Transfer of Knowledge and Researchers between both Universities Professor Erling Hammer 4 months in Lodz, Dr Volodymyr Mosorov 6 months in Bergen, Dr. Jacek Nowakowski 3 months in Bergen, Dr Zbigniew Chaniecki 3 months in Bergen.

Investigations Dr Volodymyr Mosorov was concerned on stochastic modelling and simulation of the radioactive tomography systems with low-energy gamma-ray source (<100 keV). Additionally was prepared conception of dual modality tomography (gamma and electrical impedance tomography). The conception of the system has been done by Professor Erling Hammer, when he was stay in Lodz, and validated by simulation. The sensor structure was checked by Dr Mosorov to be radiation-safe using MCNP5 simulation [7]. Dr Jacek Nowakowski continued this investigations during stay at Bergen. He developed new multi-modality sensor for gas/salt water/oil concentration in pipelines. Such combination has never been tried before to analyse flow regimes occurring in horizontal three phase flows. This has a potential interest for oil industry [8].

Dr Zbigniew Chaniecki with Professors Erling Hammer, Geir Anton Johansen and Dr Bjorn Tore Hjertaker, during his stay at Bergen, developed and constructed original uninsulated electrodes sensor for multiphase flow related to impedance measurements. Moreover they used LabVIEW environment for wireless communications between measurements unit, computer based on Personal Digital Assistant simulator (PDA) and National Instrument PXI devices. This part of works allow to create mobile system for monitoring industrial installations in two-phase flow rig [9].

6.2. Collaboration with Malaysian Institute of Nuclear Technology

Dr. Włodzimierz Mosorow spent five months at *Industrial Technology Division of the Malaysian Nuclear Agency*, Malaysia. Dr Jaafar Abdullah, leader of the Plant Assessment Technology Group was his supervisor during his stay.

The research work was focused on the Prompt Gamma Neutron Activation Analysis (PGNAA), which is a non-destructive technique to identify elements and determine their concentration in a sample by using neutron flux [10]. The method is based on the detection of capture gamma rays emitted by a sample during neutron irradiation. Then, the elemental concentration is retrieved for the identified elements. This method is useful as an analytical technique for both qualitative and quantitative multi-element identification of major, minor and trace elements present in the sample. For many elements and applications, this technique offers more sensitivity, accuracy and reliability compared to other conventional methods. Furthermore, PGNAA requires no special preparations of samples.

6.3. Collaboration with École Supérieure d'Ingénieurs en Électronique et Électrotechnique, France

Dr Marcin Janaszewski during stay at *École Supérieure d'Ingénieurs en Électronique et Électrotechnique* - ESIEE, Paris, developed algorithms for advanced 3D visualisation, 3D image processing and 3D data analysis by collaboration with Professor Michel Couprie between 03.2009-09.2009. Especially he prepared software for hole filling in 3D volumetric objects – applications to Stress Corrosion Cracking, 3D modelling of bronchial tubes based on 3D chest tomograms, detection and approximation of volume of 3D bridges in stainless steel samples subjected to intergranular stress corrosion cracking, quantitative description of geometric features (volume, area of boundary, aspect ratio, surface etc.) of approximated volumes [11]. His training at ESIEE consisted in studying and applying in practice computer algorithms for 3D image analysis based on discrete topology. The main task consisted in building an original algorithm of hole filling in 3D volumetric objects. In the frame of the training he participated in three conferences and more than ten seminars. These seminars were organised by ESIEE.

6.4. Collaboration with Institut National des Sciences Appliquées, Lyon, France

Dr Krzysztof Grudzień during stay at *Institut National des Sciences Appliquées* in Lyon was trained on the use of laboratory X-ray tomography

system (vltomelx Phoenix X-ray company) between 04.2009-10.2009. Collaboration with Drs Eric Maire and Jerome Adrien concerned on the application of X-ray tomography system to visualize the changes of solid concentration during the silo discharging process. The obtained results (2D X-ray radiographs and 3D X-ray tomographs) were very helpful to better visualize and understand the physical phenomena of gravitational silo flow process. The simultaneously Electrical Capacitance Tomography and X-ray tomography measurements of sand flow during silo discharging, which were conducted in X-ray laboratory, is the first attempt to combine both techniques [12].

He also got the opportunity to visit the ID19 beamline at the ESRF (Grenoble, France) which is one of the most well-known beamline devoted to synchrotron X-ray microtomography.

6.5. Collaboration with Department of Electronic and Electrical Engineering, The University of Bath, UK

Collaboration of Dr Banasiak with Dr Soleimani at *University of Bath* was focused on the 3D and 4D ECT visualization. During the stay at *Department of Electronic and Electrical Engineering* between 02.2008-07.2008 Dr Banasiak developed a new nonlinear 3D image reconstruction algorithm which takes into consideration the electric field behaviour inside a 3D ECT sensor interior during the reconstruction process. The conception was verified using special phantom and 32 channel-3D ECT system. This work proved the effectiveness of the proposed idea and resulted in both good three-dimensional images and well-running image reconstruction convergence that proved its fully non-linear approach. Simultaneously they continued to develop new 3D ECT sensor structures. This work resulted in the novel 3D ECT sensor numerical model in which the complete shielding structure has been taken into consideration during a forward and inverse solution computation [13].

6.6. Collaboration with the School of Materials, University of Manchester, UK

With the arrival of Dr L. Babout at the *Computer Engineering Department* in October 2005, a long term collaboration has started with the *School of Materials*. This collaboration, mainly with Professor P.J. Withers, Professor T.J. Marrow and Dr P.M. Mummery, was the natural continuation of the work that Dr Babout has carried out in Manchester during 2.5 years as a Post Doc Research Associate (PDRA) under the supervision of the above mentioned researchers. It was the occasion for Dr Babout to spend again 6 months in this university, between September 2009 and March 2010.

During that time, his work has focused on working on three parallel materials science projects dealing with X-ray tomography data. More precisely, he has been working on the study of bridge ligament formation and failure in stainless steel during stress corrosion cracking. This, study, that was originally started during his PDRA position, but more on a qualitative aspect, has been done quantitatively thanks to the algorithm that has been developed by Dr M. Janaszewski during his own training period at ESIEE-University (see Section 6.3) and which is able to detect and segment bridges. The 2 other projects have been started during his secondment and have dealt with the morphological study of polyurethane foam after auxetic deformation and the study of 2 solid-state welding processes, i.e. Friction stir spot welding and ultrasonic spot welding, for aluminium alloy sheet assembly. The latter project, that has initiated a new collaboration with Professor P. Prangnell from the same department, has focused on the detection and quantification of defects and weld profile/quality using different X-ray tomography set-ups of the Henry Moseley X-ray Imaging Facility, a new facility of the University owned by the School of Materials [14].

7. COLLABORATION WITH RESEARCH CENTRE, DRESDEN, GERMANY

The collaboration between Computer Engineering Department and Forschungszentrum Dresden-Rossendorf (FZD), Germany, was established in 2009. The formal collaboration was established with dr habil. Uwe Hampel within German Saxony research framework.

The first project, which passed for 5 months (in 2009), was concentrated on comparison between a capacitance wire-mesh sensor and ECT. The wire-mesh sensor technology was developed for many years in FZD but recently Dr Marco Jose da Silva, who participated in this project, has expanded it by a capacitance modality. Since it is an intrusive technique, the interest in this project was to compare it with a non-intrusive method employing the same electrical phenomena. For this very reason ECT was a very good alternative. The investigated industrial process was a trickle bed reactor (TBR) [15]. During the project, work of Bartosz Matusiak was advised not only in Germany, but he had a support from dr Romanowski and dr Grudzien, who both visited FZD during the project for a short collaboration visit in 2009.

In 2010, Bartosz Matusiak together with Uwe Hampel, Marco Jose da Silva and Sebastian Thiele started a new project, which took 3 months. This project was concentrated on developing a new type of capacitance planar array sensor for investigating bed fluidization. The project assumed utilization of the already existing measuring device originally prepared for a capacitance wire-mesh sensor with the newly developed planar sensor in order to monitor the situation of entire column in fluidized bed reactors [16].

Other project concerned on developed hardware for optical tomography system. During stay at *Research Centre* in Dreseden, in 2010 (6 months), Jakub Betiuk worked at rebuild twin plane of optical tomography system, which consisted on 32 measurements points. The tomography system was projected and built for cooled reactor process.

8. CONCLUSION

International collaboration is very important aspect in development skills and knowledge of CED staff. Transfer of knowledge took place not only with international partners but of course with tomography centre in Poland: Technical University of Warsaw, Wroclaw or Opole. 10 years international collaboration in tomography field allowed to increased position of CED in process tomography world.

The Computer Engineering Department is also strongly involved in dissemination of process tomography sciences. It organized the 3rd and 5th International Symposium on Process Tomography (in Łódź 2004 and in Zakopane 2009). Professor Dominik Sankowski is also member of Advising Committee of World Congress on Industrial Process Tomography. Additionally in 2007 Professor Dominik Sankowski was nominated as in the Communicating Director of the International Society of Industrial Process Tomography – ISIPT.

Research and organisation CED activities was perceived by world tomography society and 7th World Congress on Industrial Process Tomography was organized by CED in 2013 in Cracow.

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**WSPÓŁPRACA MIĘDZYNARODOWA
KATEDRY INFORMATYKI STOSOWANEJ
W DZIEDZINIE TOMOGRAFII PROCESOWEJ**

Streszczenie

Artykuł prezentuje obszary współpracy międzynarodowej Katedry Informatyki Stosowanej w dziedzinie tomografii procesowej. Przedstawia chronologicznie przebieg transferu wiedzy zrealizowany przez naukowców wyjeżdżających do znanych i cenionych ośrodków naukowych tomografii procesowej oraz przyjeżdżających do Katedry Informatyki Stosowanej. Informacje obejmują również początkowy okres współpracy z prof. Andrzejem płaskowskim i prof. Tomaszem Dyakowskim, współpraca z którymi zapoczątkowała badania w dziedzinie tomografii procesowej. Artykuł podsumowuje osiągnięcia Katedry Informatyki Stosowanej w dziedzinie tomografii procesowej, a jednym z nich jest organizacja przez Katedrę 7. Światowego Kongresu Tomografii Procesowej w 2013 roku.

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