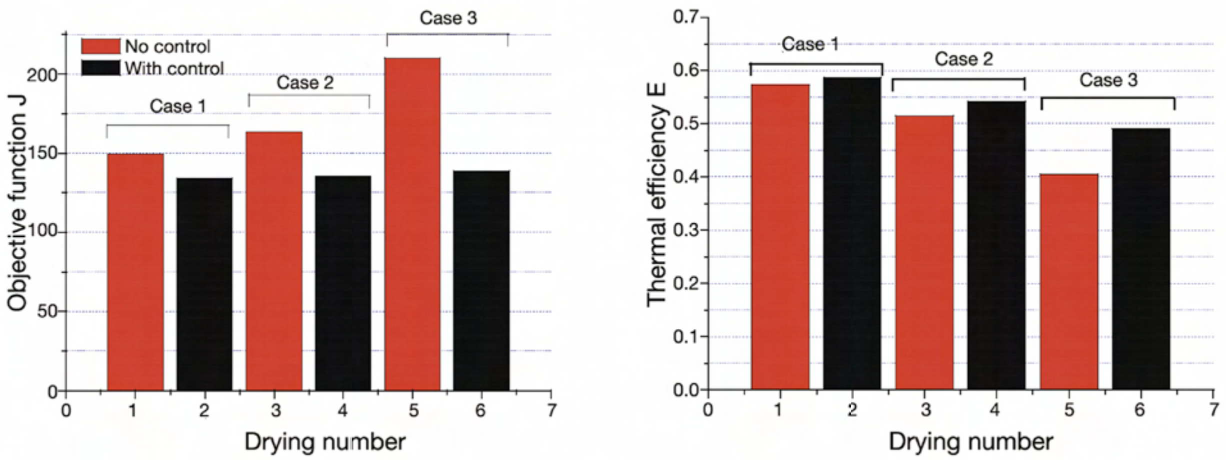
Optimum control of fluidized bed dryer by electrical capacitance tomography

Haigang Wang, The University of Manchester

This work describes the use of electrical capacitance tomography to control a fluidized bed dryer. The ECT enabled control and monitoring of the aforemtnioned process allows a more economical operation. The thermal efficiencies of the non-ECT and ECT controlled processes were then compared.

In this presentation, the author gives closed-loop control of a fluidized bed drying process based on online moisture measurement by electrical capacitance tomography (ECT). A twin-plane ECT sensor with 8 electrodes in each plane is mounted in the bottom of a glass tube. From the adjacent electrode pairs, the water content of the particles is estimated based on correlation between the moisture content and the permittivity value. The fluidization velocity is estimated by a semi-empirical function based on the measured water content and the information is sent to a controller to adjust the air flow rate of the fluidized bed. To compare and validate the moisture measurement by ECT, a simple mathematical model has been developed based on the temperature and relative humidity (RH) of the outlet air phase. To improve the image quality and reduce the imaging error at the cross-sectional area, the Landweber iteration method is applied. The averaged solids concentration along the radial direction at different fluidization conditions are given and compared with the linear back-projection (LBP) method. Also, some results from batch drying processes are given and compared with no feedback control. To evaluate the drying process, the thermal efficiency is given and results are compared based on this parameter. The results as shown in the following figures show the possibility of online control of the fluidized bed drying based on moisture measurement by ECT.



a) Objective function   b) Thermal efficiency J

Drying/evaluating results based on E and J

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The Aims of the VCIPT are to advance the field of industrial process tomography to best meet the long-term needs of its participants. It integrates a wide range of research skills: computing, physics, electronics, maths, process engineering and particle science, interfaced with users from diverse sectors: food, minerals, pharmaceuticals and petrochemicals.

See http://www.vcipt.org for more information

INSIGHT
The Virtual Centre for Industrial & Process Tomography
World Congress on Industrial Process Tomography
Summer 2008

ISIPT & Beijing 2010

The VCIPT have been sponsoring and organising the World Congress on Industrial Process Tomography (WCIPT) series since it began in 1999, when we held the first event in Buxton, UK. Since then the Congress has become well established and has been growing in numbers and quality, with subsequent events in Hannover (Germany), Banff (Canada), Aizu (Japan) and, most recently, in Bergen (Norway) in 2007.

The next World Congress (WCIPT6) will be in Beijing in September 2010 – mark it in your diary now!

Moreover, WCIPT6 will be organised by ISIPT, the International Society for Industrial Process Tomography. ISIPT has been established as a learned society to promote, represent and support the many hundreds of process tomography researchers and users around the world. ISIPT now “owns” the World Congress. In addition to planning, organising and co-ordinating the World Congress, ISIPT will provide a focus for the dissemination of advances, networking opportunities and a platform to promote the subject and promulgate international standards.

Dr Masahiro Takei, (Nihon University) is the first Chairman of ISIPT, Professor Brian Hoyle (University of Leeds) is the Treasurer and Professor Anthony Peyton (University of Manchester) is the Secretary. The ISIPT website can be found at http://www.isipt.org.

As well as the World Congress, ISIPT will organise and support other events in three regions: North & South America; Europe & Africa, and Asia & Pacific. The next event will be the 5th International Symposium, at Zakopane, Poland, to be held on 25-26 August 2008, followed by the International Workshop on Process Tomography to be held in Tokyo on 17-19 April 2009.

VCIPT is proud to have developed the WCIPT series and to have piloted the creation of ISIPT, and it gives us great pleasure to have reached this exciting juncture. We wish ISIPT well and we look forward to participating enthusiastically in its work.

New Appointment at Manchester

Steve Stanley of Nexia Solutions has been appointed as Visiting Lecturer at The University of Manchester, in the Department of Chemical Engineering and Analytical Sciences. Steve is an industrial member of the VCIPT Management Committee. He obtained his undergraduate and postgraduate degrees at Manchester and is involved in a number of collaborative projects with the University. Nexia Solutions, who are about to form the core of the new National Nuclear Laboratory, are pleased to strengthen collaborations with the academic sector as it looks to share best practice and the latest advances in technology.

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5th World Congress: Best Paper

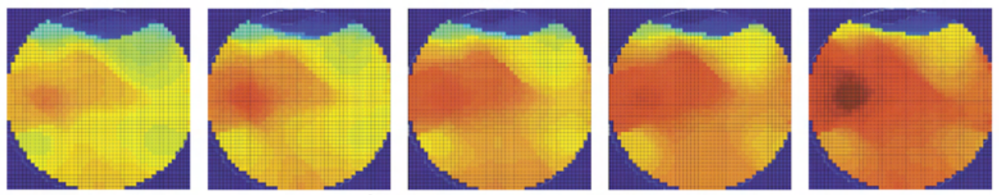
IMAGER Scoops the Maurice Beck Prize

Paul Wright receives the Maurice Beck Prize for Best Paper on behalf of the IMAGER project team

An important feature of the World Congress series is the award of the Maurice Beck prize to the authors of the paper judged to be the most significant advance presented at the Congress. At WCIPT5 the winning paper was presented by Dr. Paul Wright of the University of Manchester, and entitled 'High-speed Chemical Species Tomography in a Multi-cylinder Automotive Engine'. IMAGER uses near-infrared absorption tomography to monitor the distribution of hydrocarbon fuel vapour within one cylinder of an essentially standard vehicle engine. Developed by the University of Manchester, in partnership with Roush Technologies Ltd., AOS Technology Ltd. and the Ford Motor Company, the system offers sufficient temporal resolution (over 4000 frames per second) to reveal the detailed evolution of the fuel distribution in the period before ignition. Paul represented the IMAGER project team, which comprises AOS Technology Ltd. and Roush Technologies Ltd. in addition to the University, and the project was supported by Ford Motor Company Ltd. and the UK's Department for Trade and Industry and Engineering & Physical Sciences Research Council.

The paper described a major engineering break-through, whereby the hydrocarbon fuel in one cylinder of a 4-cylinder automotive engine was imaged at framing rates up to 4000 frame per second. The challenges to the project team ranged across optical, mechanical and electronic engineering, to enable imaging in the extreme environment of the engine, with temperatures cycling from near ambient to over 2000K, and pressure from atmospheric to 10bars, in just 10milliseconds or so. The figure below is a sample image sequence showing the fuel distribution during part of a single compression stroke of the piston when the engine is operating at 1500rpm under a load of 1.5bars BMEP: each image shows the average fuel distribution during a period of 3 degrees of crankshaft angular rotation (° CA), as the ignition point is approached at 15° CA before Top Dead Centre (BTDC). The technique that underpins the IMAGER system is being adapted for a range of other automotive applications, e.g. a consortium from Brunel, Brighton, Leeds, Manchester and Stanford Universities is now funded by the UK EPSRC to research an advanced engine concept that offers very high fuel efficiency. The technology can also be applied to many other types of reaction system.

Previous winners of the Maurice Beck prize are Mathias Buchmann and Professor Dieter Mewes, Dr Bert Masschaele, and at the Aizu Congress in 2005 it was Uwe Hampel and colleagues at FZ Rossendorf in Germany (high-speed X-ray imaging). In every case, the judging panel have had a very tough job, and the Bergen Congress was no exception, due to the very many high-quality and insightful papers that were presented. We fully expect this tradition to be continued at the Beijing Congress in 2010.



Blue represents zero fuel concentration; red represents maximum.

The Use of Multimodal Tomography in the Study of Precipitation

I. Edwards[1,2], S.A. Axon[1], M. Barigou[2], E.H. Stitt[1]
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During this work two types of tomographic techniques were used to study the hydrodynamics of a precipitation reaction. Precipitation represents one of the main chemical processes used throughout numerous industrial sectors for product manufacture. In this study the combination of Electrical Resistance Tomography and Position Emission Particle Tracking provided a means to study the system both on the macro and local scales.

Precipitation is an important unit operation in chemical engineering practice and is one of the main routes for the manufacture of heterogeneous catalysts. Typically, a stable salt is reacted with a precipitating agent to produce a supersaturated solution resulting in finely divided solid particles being precipitated out of solution.

It is understood that mixing conditions during semi batch precipitation determine particle properties, and the way the reactants are brought together at the feed point is vital. Inferring the effects of global parameters in terms of precipitate properties is not instructive however. A full understanding of the relationship between mixing parameters, the hydrodynamics in the feed region and product properties is needed.

Multi-modal tomographic techniques have been applied to the in-situ study of semi-batch precipitation to interrogate the mixing conditions. Techniques such as Electrical Resistance Tomography (ERT) and Positron Emission Particle Tracking (PEPT) can provide new insights into how the feed reactant is dispersed into the bulk reactant during semi-batch precipitation.

While ERT gives useful information on the temporal and spatial distribution of the fed ionic species in semi-batch operation, it does not allow interpretation of the localised velocities and hence understanding of the global flow field. There is therefore a need to combine the first order approximation of spatial chemical speciation provided by ERT with detailed flow field information. PEPT is a technique that can provide this complementary information. Both techniques are non-invasive and do not rely on optical transparency to analyse mixing, so they can be applied to a broad range of opaque systems of industrial significance.

For the first time ERT and PEPT have been used concomitantly to study precipitation and hydrodynamics. This combination of techniques allows a step change in our ability to understand industrial precipitation processes and the relationship between feed region flow conditions and mixing performance.

Experimental Set Up

A level set technique for inverse multi-phase problems

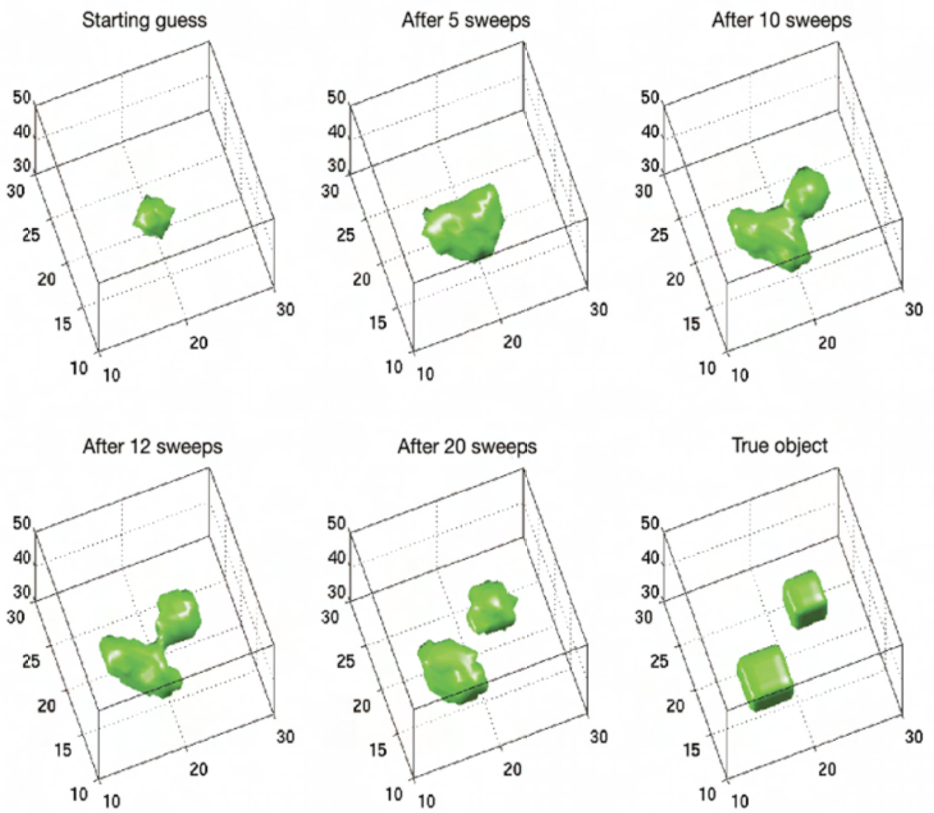
Oliver Dorn, University of Manchester

A novel technique has been developed for tomographic image reconstruction of subjects that consist of different regions separated by sharp interfaces. This situation is frequently encountered in industrial problems. The new so-called "level set technique" has been tested with simulated data from Electromagnetic Induction Tomography and Microwave Tomography.

In many industrial inverse problems the goal is to detect and identify regions of different materials from indirect data. The basic characteristic of these problems is that the different regions are separated by sharp interfaces. Inside each of these regions the materials can either be fairly homogeneous or they might show some structure which often is approximately known. Most reconstruction techniques are not designed to take into account the presence of sharp interfaces between different regions. Instead, they employ standard regularization tools which typically have the effect of providing a smoothly varying image from the given data. So, all possible interfaces in the true measurement subject are smoothed out in the reconstructions over a larger domain and cannot be identified reliably.

In this work, a novel technique has been developed which allows for reconstructing an image which consists of different regions separated by sharp interfaces. If necessary, it also allows for interior profile estimates inside each region. To model the interfaces during reconstruction, a level set technique is employed. This gives the algorithm substantial freedom in modifying topologies during the reconstruction process whenever it is required by the data. An evolution is designed for this level set function whose goal is to reduce a least squares data misfit cost functional. If internal medium profiles need to be recovered as well, an additional evolution equation is derived for finding these internal medium parameters simultaneously with the interfaces.

Two different applications of inverse problems governed by Maxwell's equations have been used as test cases. The first is 3D Electromagnetic Induction Tomography (MIT), with a geophysical focus, and the second is microwave imaging in 2D for a biomedical problem. Both are intended to be very general and the method can be applied without significant changes also to industrial non-destructive testing applications. The end goal is to recover electromagnetic parameter profiles (conductivity or permittivity, or both) from electromagnetic data gathered at few measurement locations. Numerical experiments have shown the performance of the new technique for several test cases, as illustrated in the figure below in the MIT case. The true object is shown at the bottom right, and the starting guess for the reconstruction is shown at the top left. As the algorithm completes more "sweeps" through the simulated measurement data, it recognises that the true solution lies in the direction where the regions within the subject are clearly separated (at 20 sweeps).



Annual Meeting

Tom Dyakowski Prize 2007/8

Dominic Rhodes presents Eugenio Constantino with the Tom Dyakowski Prize

The VCIPT research consortium encompasses the work of about 80 university-based researchers, as well as the large research resources of its member companies. VCIPT conducts two major member-only private meetings per year, and each of them includes a research symposium. The standard of the research presentations is excellent.

Each year, to recognise a presentation of outstanding quality, VCIPT sponsors a prize that was inaugurated in memory of our much-loved colleague Prof. Tom Dyakowski, whose devotion to process tomography was an inspiration to all who knew him.

After careful deliberation (and hot competition!), the Tom Dyakowski prize for 2007/8 has been awarded to Eugenio Constantino, of the School of Electrical and Electronic Engineering at the University of Manchester. The picture below shows Eugenio receiving his award from Dr. Dominic Rhodes of Nexia Solutions and Chairman of the awards panel. You can read the resumé of Eugenio's presentation in this edition of *Insight*. Having recently completed his PhD, all at VCIPT wish Eugenio well in his career as he goes off to work at BP in September 2008.

Technical Symposium

Reports from the Annual Meeting

The following reports in the rest of this newsletter are resumés from the Symposium at our last Annual Meeting in April 2008. They represent a snap-shot of the current and ongoing research in Industrial and Process Tomography.

Tomography for Schools - What's in the Box?

Will Carr and Trevor York,
University of Manchester

This work involved a study to establish the feasibility of creating a hands-on tomographic imaging activity for schools. The motivation for doing the work is to engage schoolchildren with an imaging challenge to help illustrate the links between Science subjects taught at School and Engineering practice and to promote our activities in process tomography. A prototype optical tomograph requiring only modest mathematics to reconstruct images was developed and trialled in local schools.

As part of the EPSRC Platform grant, "Industrial Process Tomography", we are considering possibilities for outreach activities. One of our stated aims is to submit a Partnership for Public Engagement (PPE) proposal to EPSRC to publicise our activities.

Will Carr has been working since September 2007 to explore an "imaging challenge" for schools. The goal is to enable schoolchildren to tomographically "image" the contents of a black box using only basic mathematics and low-cost equipment. Will has had some success using an optical method. Basically, a box containing an opaque object has a series of small holes, about 1mm diameter, in one side and a screen on the opposite side.

Light is shone through the holes and the size and location of the shadow is recorded. The object is then turned through a known angle and another shadow is recorded. Shadows from a number of angles are recorded on an OHP transparency and the shape of the object can be deduced as suggested in Figure 1. Reconstruction of an object with internal features is shown in Figure 2.

Preliminary ideas have been trialled in local schools and have been well received – attracting feedback such as "It was perfect, I can't wait to go to university". A PPE proposal was submitted in May 2008 and a decision is expected in October. This proposal aims to set up an "imaging challenge" between a number of local schools who will receive a set of boxes which present an escalating level of challenge. The challenge is introduced with a number of simple black boxes to be explored using basic senses and intuition. Then we progress via

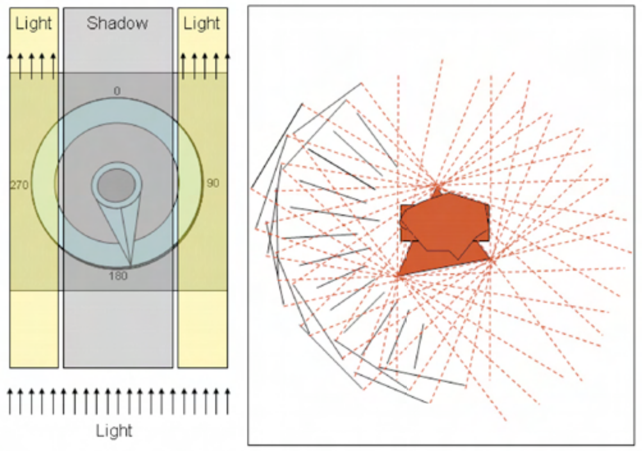


Figure 1: Illustrating the technique to generate tomographic images

a pinhole camera before considering the simple optical tomograph. The challenge will culminate in a visit to the University, with local media coverage. Pupils will be exposed to an automated version of the optical tomograph that can build up 3D images together with a demonstration of X-ray imaging equipment to reveal the contents of the box and finally a quiz to deduce the winners.

One particular challenge is to extend the technique to be able to accommodate objects with varying optical transparency and reconstruct these using only basic, school level, mathematics. Answers on a postcard please!

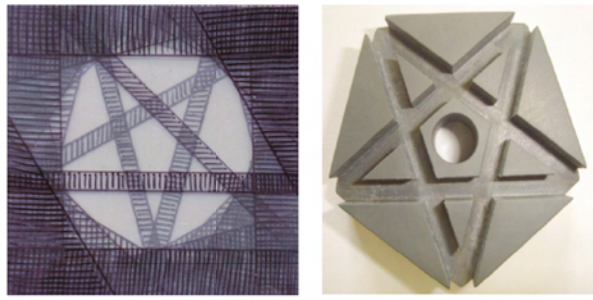


Figure 2 : Example Reconstruction and Original Object

Application of Flow Continuity Theory for investigating Dispersion in a 2D miscible mixing process

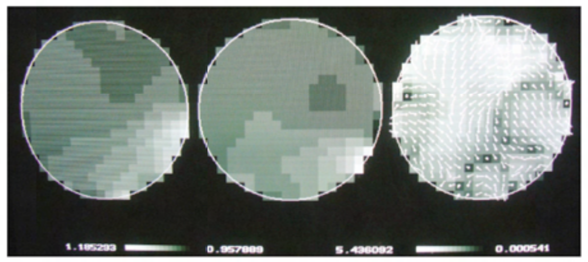
Vasuki Ramachandran and Mi Wang, University of Leeds

Feasibility experiments to demonstrate the recently proposed approach for disperse phase velocity measurements have been conducted using the ultra-fast ERT system. In addition, some suggestions have been made to reduce the level of error in the calculations.

Flow characteristics, such as disperse phase concentration, gradient and velocity distribution are important in fluid dynamics. The cross-correlation method is widely used to extract the velocity profile from a series of tomographic concentration data. However, this method does not take into account the dynamics of the system in terms of either mass balance or flow continuity and only provides an average velocity distribution over a period. A new method, based on flow continuity theory, has already been proposed (*5th World Congress on Industrial Process Tomography*, Bergen, 2007 and *CT2008*, India 2008) to derive the 2D disperse velocity distribution by assuming the change of elementary velocity to be negligible over a very short time and a very short distance.

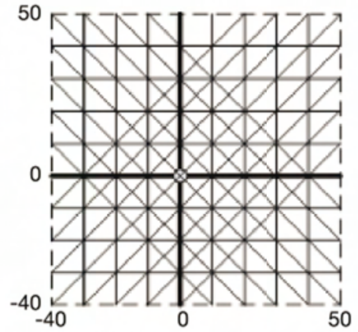
The aim of the current research is to find ways to reduce the error in the calculated velocity which is due to the computational noise being dominant over the concentration change during the dispersion process and the signal-to-noise ratio of the sensing electronics used for the measurement. It is demonstrated that the distribution of disperse phase instantaneous velocity in a 2D miscible liquid can be extracted by using the high temporal resolution provided by an ultra-fast electrical impedance tomography system (1000 dfps) at the University of Leeds.

Additional experiments were conducted, during a 2D dispersion process, to study the effect of a vortex (created either manually or with the use of an impeller) on the change in concentration with time and space relative to the level of noise. More research is on-going to improve the signal-to-noise ratio and possible extension of this theory for application to a 3D system.

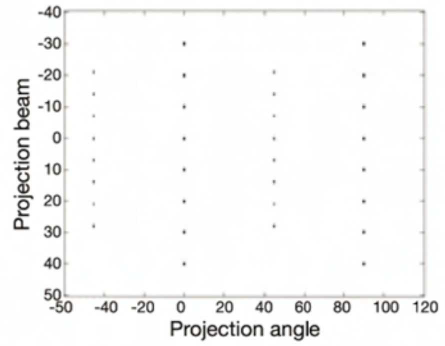


The disperse phase velocity distribution in a miscible mixing (a swirl was created manually) estimated using the method at 1.7 seconds. The circles on the left and the middle represent the conductivity profiles, the circle on the right represents the velocity profile and the grey scale bar at the bottom represent the conductivity value (left) in mS/cm and disperse phase velocity (right) in m/s.

at $\Delta t_{0°}$ and $\Delta t_{90°}$ and 7cm at $\Delta t_{\pm 45°}$ respectively. The results suggest the algorithm can be applied to recover an irregularly sampled sinogram from an irregular imaging sensor by strategically positioning the beams to create crossings in the subject space.



a) the PGPT imaging sensor



b) the sparse sinogram that it produces.

The dark points in the sinogram are the 2D Radon transform samples.

Linking X-ray microtomography with computer simulations

R. Moreno-Atanasio, R. A. Williams, X. Jia, University of Leeds

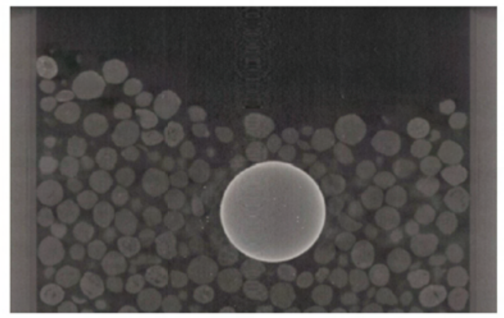
X-ray microtomography (XMT) of granular systems has been used to validate dynamic computer simulations. This conjunction of technologies promises a greatly enhanced range of applications for XMT. The DEM simulation method was able to reproduce the penetration of a projectile impacting on a particle bed, as a case study.

The use of XMT as an imaging technique has drastically increased during the last decade due to its non-destructive nature. Its use ranges across many different process applications, including the study of granular matter. However, XMT has even greater potential when it is used in conjunction with computer simulations, either in the form of studying the parameters input to the simulations or as a way of validating the computer modelling.

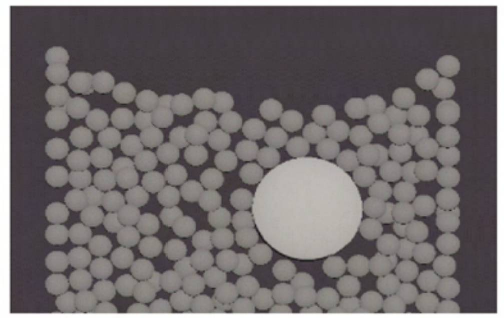
The current task is to produce a high level of fidelity between XMT image data and those generated by computer simulations based on the Distinct Element Method (DEM). As a case study, the main objective was to link XMT and DEM of the penetration of a particle bed by a large spherical impacting projectile. Preliminary work has identified the most important parameters affecting the physical indentation of the particle bed.

A projectile with density of 6126 kg/m3 and diameter of 13.8 mm has been impacted at 4.5 m/s against a bed of fertilizer granules whose density is 1733 kg/m3 and mean particle diameter is around 3 mm. A qualitative comparison is shown in the figure below which shows a 2-D XMT slice (top) and a plane section from the computer simulation image (bottom). The computer simulations have been able to reproduce the depth penetration of the projectile with an accuracy of 10%. The densification of the material around the impacting particle, and the crater formed, have also been adequately reproduced by the simulations.

In the next steps, the initial bed structure (from XMT) will be used as an input parameter for the simulations, promising a very high fidelity comparison of the final state of the bed between experimental XMT images and DEM simulations. It is expected that accurate simulation of bed particle displacements as well as projectile penetration will be feasible.



a) 2-D tomography slice



b) Computer simulation image

Impact of a projectile at 4.5 m/s against a bed of particles

Auto Digital Gain Balancing for Minor Gas Species Measurement

Sandip Pal and Hugh McCann,
University of Manchester

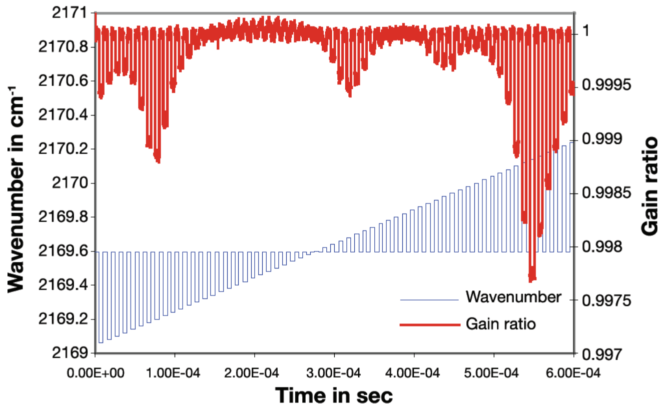
A new opto-electronic technique (DGB) has been invented for sensitive in-situ gas species measurement, using carbon monoxide (CO) as a case study. With its high-speed capability, DGB will have immediate applications in the design and control of combustion pollution abatement systems, and will be implemented in a chemical species tomography system. DGB exploits the fast embedded logic properties of FPGAs and programmable gain amplifiers to yield the concentration measurement as a ratio of electronic gain settings, thus providing calibration-free operation.

Imaging the distribution of minor pollutant species in combustion exhaust would be valuable for a range of industrial sectors and for environmental protection. This case study has addressed the imaging of an average concentration of 10 parts per million by volume (ppm) of carbon monoxide (CO) in an automotive exhaust pipe of 50mm diameter. The viable spectroscopic absorption lines are in the Mid-IR, exploiting the high absorption strengths of fundamental transitions (see *Proc. 5th World Congress on Industrial Process Tomography*, 2007 and *Measurement Science and Technology*, 19 (9), 2008). The task is then to achieve the single-path measurement sensitivity of 0.05 ppm-metre at kHz bandwidths. This is expected to be achievable with a new variation of the well-known Balanced-Ratiometric Detection (BRD) technique.

In BRD, one beam goes through the target gas onto a detector, a reference beam at the same wavelength goes directly to a second detector, and their signal-balanced ratio removes some noise effects, particularly that due to laser intensity fluctuations. The new auto Digital Gain Balancing (DGB) technique uses a new approach based on a Field-Programmable Gate Array (FPGA), but still using two optical paths just like BRD. The laser wavelength is stepped through an absorption line, but between each two scan steps, there is a step back to a reference wavelength. At every step, a feedback subtractor is applied to find the channel gains that balance the signals between the scan step wavelength and the reference wavelength. The absorption measurement is then encoded as a ratio of gains. DGB has the following features:

a) It cancels out optoelectronic noise effects (additive as well as multiplicative) and baseline fluctuation,
b) After initial set-up, it eliminates calibration requirements for the balanced ratio, and
c) Where there is more than one species present in the target gas, it separates their different absorption effects if the wavelength scan crosses an absorption line of each species.

The DGB electronic circuit is now built and is currently being tested.



Circuit simulation results: the wavelength is scanned in steps (blue square-wave) across a CO absorption line (2169.2 cm-1) and a nearby CO_2 line (2170.2 cm-1). The red signal is the gain ratio, showing the detection of both species during a 0.6msec scan.

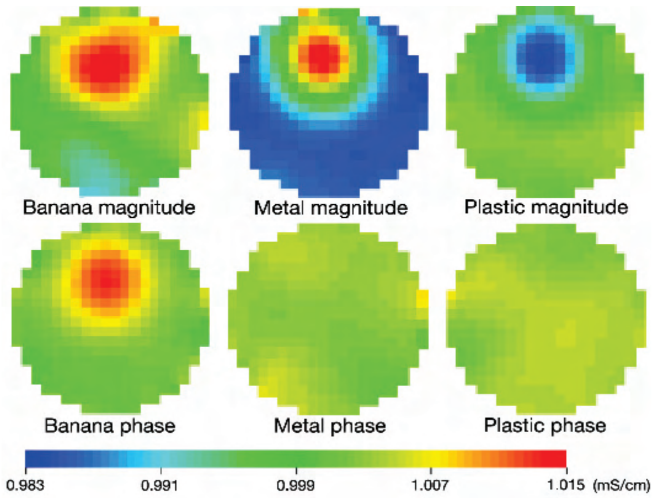
Electrical Impedance Spectroscopy Study on Charged Particles in Suspension/ Crystallisation Processes

Yanlin Zhao, University of Leeds

Electrical impedance spectroscopy of L-glutamic acid solution was studied in a crystallisation process. The aim of the project is to provide physical chemistry fundamentals for developing a technique for on-line measurement of spatial distribution of crystal size. In the experiments, complex impedance and phase angle were measured online and analysed using the equivalent circuit model.

Conventional process tomography (e.g. electrical impedance or ultrasound tomography) has demonstrated the capability of monitoring particle concentration distribution and super-saturation distribution during batch temperature-controlled crystallisation. However, current techniques may be seriously challenged to resolve on-line the spatial distribution of particle characteristics, e.g. the particle size distribution or the spatial distribution of polymorphic phase transformation processes. In the study, an electrical impedance spectroscopy method was used to obtain the complex electrical impedance, phase angle shift and characteristic relaxation time of the silica suspension. The charged silica particles have an electrical double layer on their surface, and can form an induced dipole moment with change of signal phase due to the polarization of electrical double layer. The phase shift and other dispersion properties are related to particle size by the electrical double layer. Therefore, by measuring the phase shift the particle characteristics can be obtained.

In the preliminary experiments, the complex electrical impedance and phase angle shift have been investigated on the silica suspension with different particle sizes. The electrical impedance was measured using a four electrode system at the frequency range of 1 Hz – 10 MHz, with exciting voltage of 1 volt. We also used the Fast Impedance Camera system to get the imaging not only based on conductivity but also based on the phase angle shift. We tested three different materials: metal, plastic and banana. Only banana showed phase shift imaging, which should be due to the electrical double layer property of the banana skin. The figure below shows the impedance magnitude and phase imaging for the three materials.



Sinogram Recovery Applied to Irregular Sampled 2D Radon Transform

Eugenio P. A. Constantino,
University of Manchester

We introduce a new data processing scheme addressing the problem of limited data in hard-field industrial tomography. The scheme is implemented by the inclusion of a sinogram processing algorithm based on the Hough transform and the information on the sensor geometry. The algorithm has been verified using experimental data from a Photonic Guided-Path Tomography system yielding a severely sparse sinogram from a set of 32 independent measurements grouped in 4 angular projections. The sinogram is then recovered to a degree suitable for standard hard-field data inversion, such as the Filtered Back-Projection.

An image reconstruction algorithm that is suitable for irregular imaging sensor configuration can be valuable to many industrial imaging applications in which limited access and data deficit are problematic. A 2D irregular sensor configuration generates a 2D rectangular sinogram that is irregularly (under-) sampled. The physics of the imaging process and measurement data do not warrant the use of ordinary 2D interpolation techniques to recover the missing samples. Therefore, a sinogram recovery algorithm is being developed that uses the Hough transform to identify sinusoidal trajectory signals that are connected by the samples in the sinogram. As a result, the missing samples along the sinusoidal trajectory signals of the sinogram can be interpolated without interaction with the crossing signals. The remaining missing samples are then interpolated along each projection to recover the complete sinogram. The algorithm uses the Ludwig-Helgason consistency condition to ensure that the recovered sinogram is consistent with the 2D Radon transform.

The current task is to verify its applicability to smooth subjects. We present results from the application of the algorithm to the measurement data from the Photonic Guided Path Tomography system (PGPT). The sensor head geometry was designed to generate four parallel projections each consisting of 8 optical fibres, positioned at four different angles (-45°, 0°, 45°, 90°), resulting in a total of only 32 path integrals. Two different sampling periods were used and they were 10cm