Development and deployment of a non-nuclear densitometer, based on electrical resistance tomography

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ABSTRACT

Measurement of density and flow are two important parameters to optimise the performance of hydraulic conveying in dredgers. At present almost all densitometers use attenuation of nuclear sources as a measurement principle and this presents operational, cost and safety implications. These limitations have led to a widespread interest in developing non-nuclear alternatives.

This paper presents the development and deployment of a density meter based on electrical resistance tomography.

The measurement principle is based on scanning an array of electrodes placed around the inside circumference of a pipe and analysing these data to determine the distribution of electrical conductivity in a cross-sectional volume of the pipe.

Industrial Tomography Systems has pioneered the deployment of this measurement methodology in industry and over the last seven years has worked with Van Oord to apply ERT to dredging.

Initial tests were made in laboratory, flow loop and temporary land-based installations. A major step forward was then made in the design and manufacture of a robust sensor which was deployed on a dredger operated by Van Oord where the sensor was tested against a gamma densitometer.

Parallel programmes were then undertaken for verification of equivalent performance information to densitometers traditionally used for marine sludges; marinise the electronics; and transfer the software from a Windows platform to a robust industrial user interface suitable for use on dredgers.

It has now been used on four vessels with pipe diameters up to 1.2m; flow rates in excess of 8.5 m/s and slurry densities of 2.0 T/m^3

This paper presents the performance of the resultant instrument – the *Dens-itometer* in field conditions, comparing density measurements with in-line gamma densitometers and showing dynamic flow profiles of hydraulically conveyed slurries.

It is believed that this work has led to the development of a viable alternative to nuclear based density meters.

Keywords: Gamma densitometer, Electrical tomography, Non-nuclear instrumentation.

INTRODUCTION

The measurement of slurry density – along with bulk flow velocity is a fundamental parameter for the efficient operation of modern dredgers. Many dredgers will use these two control parameters to ensure that solids are mobilized and are present at a sufficient level in the pipeline for effective transport, but are not at too high a level to endanger operations through settling and subsequent blocking of pipelines

Gamma densitometers are nearly universally used as the basis of in-line density measurement. Nuclear sources have been in use for decades as a measuring tool and The use of a radioactive source on board a vessel is often seen as a technique of last resort due to the inherent perceived and actual concerns of such materials.

Issues that arise with nuclear instrumentation include

- regulatory requirements for the
    - transport
    - maintenance and
    - disposal of radioactive sources
- Restrictions on access around the nuclear source
- Frequency calibration, whilst different systems require different procedures, frequently a full calibration will require off-line measurements with standardized plates. As well as normal calibration of instrumentation, recalibration is required due to wear of the pipe-wall and natural depletion of the source.
- Single, fan-beam measurements places restrictions on either the orientation of the sensor or limits to its accuracy. This is due slurry falling outside the fan beam not being measured. If flows are heterogonous this will bring an inherent error / uncertainties to the resultant density measurement
- Differing absorptions levels of different elemental species in the solid slurry lead to uncertainties in the density data
- Partially filled pipes lead to uncertainties over the density of the slurry as the single measurement of density is a composite of air, water and solids

In addition to the above, the gamma densitometer is not able to provide information on the distribution of solids and / or flow regime. Nor does it provide information on flow velocities.

Of the above issues, the regulatory burden over the operation of nuclear sources is the most significant. It is frequently very challenging to transport a replacement source to particular countries, requiring dredgers to be moved to a separate location, at significant cost. In addition, a small number of countries (for example Russia or Nigeria) limit or prohibit the use of nuclear instrumentation by overseas dredging operators.

In addition, it should be noted that nuclear sources present a possible terrorist threat, with recent reports in 2015 of Cesium sources being trafficked in Turkey and Moldova [CBS and New York Post]. Such events and increased tension are likely to increase the regulatory burden on the transport, use and disposal of sources for legitimate purposes.

For the above reasons, there has been a long-standing interest in the development of alternative to gamma-densitometers. Standard density measurements such as Coriolis flow meters and vibrating forks are not suitable to dense phase slurries. So a range of other techniques have been tried, however no alternative has effectively met the market’s requirements. For example:

- Ultrasound / acoustic methods are limited by the high levels of attenuation and scattering of such ultrasound presenting difficulties. The signal can also be highly dependent on the positioning of the transducer which can also present issues with respect to pipe orientation.
- Microwave sensors based on phase difference have been deployed in the pulp & paper sector, however the issues associated with large pipe sizes and process variabilities in dredging have prevented the successful deployment of these sensors
- Mass flow – a load-cell sensor was presented a number of years ago and whilst some tests appeared promising the bulkiness of the sensor, limitations with respect to its installation, and other factors prevented it from being a commercially viable alternative

The limitations of nuclear sources and difficulties with the above methods have meant that there remains an ongoing requirement to develop an alternative to nuclear based density meters.

In 2005 a dredging research group, through Van Oord, approached the recently formed company Industrial Tomography Systems plc to see if electrical resistance tomography could be used as the basis for a nuclear-free density meter.

This paper describes the development of this new measurement technique in one of its first widespread commercial applications. Effectively spanning the transition from Technology Readiness Level 3/4 [EC 2014] – research to demonstrate applicability at a laboratory level; through to Technology Readiness Level 9 where the system is proven in successful operations.

ELECTRICAL RESISTANCE TOMOGRAPHY

Background to the technology

Electrical resistance tomography (ERT) is a relatively new instrumentation technique which although proposed in late 1980s has only recently been fully commercialised. ERT sensors utilize low frequency electric field to sense the electrical conductivity property of materials. The term ‘tomography’ implies that the technique is able to extract the cross sectional conductivity distribution information of a measuring object. ERT has several advantages over other traditional tomography techniques such as X-ray and γ-ray. For example, ERT is low cost, high speed (> 1000 fps), appropriate for large scale applications and non-invasive (no radio-active source). Due to the above mentioned advantages, ERT has attracted many attentions in industrial sectors since the concept was proposed [Sharifi 2013].

A typical ERT system consists of the following components (Figure 1):

- Sensor: It contains a series of electrodes that can transmit and receive AC signals.
- Instrument: It contains a signal generator, data acquisition hardware and switching electronics. The instrument is responsible of injecting the AC current into the transmitting electrode pair and acquires the AC voltage measurement from the receiving electrode pairs.
- Reconstruction software: It contains linear algebraic inverse algorithms which can convert the measurement values into a conductivity tomogram.

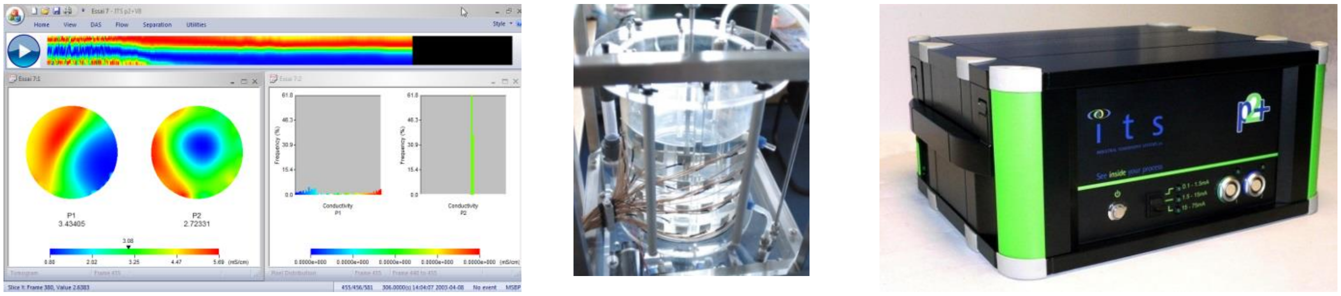

Figure 1 Tomography system configuration; software, sensors, instrument

Conventional ERT sensor comprises of a series of electrodes that are equally attached around the circumference of a cylindrical process region. By injecting a sinusoidal AC current through an adjacent electrode pair into a conductive medium, the current path will induce potential differences across all the remaining electrode pairs. These voltage measurements contain essential conductivity information of the measuring process. After measuring the voltage measurements from all possible adjacent electrode pair combination, these measurements can then be fed into an inverse algorithm to reconstruct a conductivity tomogram. In process industries, the standard linear back projection (LBP) algorithms are often chosen for tomogram reconstruction, due to its mathematical simplicity and robustness [Wang 2002, Lionheart 2004]. The reconstructed tomogram will then be interpreted by site engineers to determine the condition of the measuring process. The principle of ERT measurement process is shown in Figure 2.

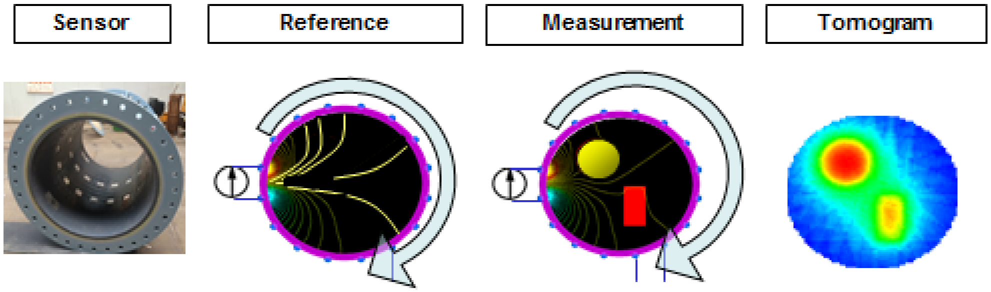

Figure 2 Measurement principles of electrical resistance tomography

Although a conductivity tomogram can accurately represent the process condition, the tomogram often needs to be further post-processed to extract other more useful information. For example, in dredging sectors, density value is a better indicator to determine the condition of the process. In such cases, the effective medium approximation equations need to be employed to extract the density information from conductivity tomograms. In this paper, Maxwell Garnett formulas are implemented (Equation 1 and Equation 2) to obtain the concentration values [M Wang 2015]:

$$\alpha = \frac{2\sigma_1 + \sigma_2 - 2\sigma_{mc} - \dfrac{\sigma_{mc}\sigma_2}{\sigma_1}}{\sigma_{mc} - \dfrac{\sigma_2}{\sigma_1}\sigma_{mc} + 2(\sigma_1 - \sigma_2)}$$

Equation 2: Maxwell Garnett quation relating conductivity and concentration of a 2 phase fluid

$$\alpha = \frac{2\sigma_1 - 2\sigma_{mc}}{\sigma_{mc} + 2\sigma_1}$$

Equation 1 Simplified Maxwell equation with one non-conductive phase

where α is the calculated concentration values, σ1 and σ2 are the electrical conductivity value of the primary phase material (e.g. water) and secondary phase material (e.g. sand) respectively. σ_mc is the reconstructed conductivity from the conductivity tomogram. After obtaining the concentration information, the density value can then be obtained through standard density calculation.

DEVELOPMENT PROGRAM

Initial trials

– Technology Readiness Levels 5-6 Technology validated in relevant environment

Following initial lab-scale tests, trials were carried out at TU Delft slurry flow research facility **Figure** 4 [Talmon et al, 2010]. The process conditions are summarized in

Table 1. The results have been previously presented and showed that the tomography system was able to reliably measure bulk and local solid concentrations. In addition, dynamic data sets were able to characterize different flow regimes as flow velocities increased.

2 phase loop	Sand – median density 350 micron, up to 30% solids Water - plant
Closed loop circuit	ø 150mm Slurry velocity from 1-10 ms-1
Instrumentation	Temperature Slurry density Flow (emf) Conductivity concentration measurement

Table 1 - TU Delft Flow Loop Configuration for Tomography validation study

Figure 3 TU Delft Slurry Flow Loop

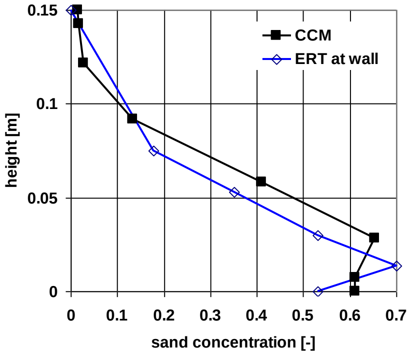

Figure 4 Tomogram & CCM system with stationary bed layer: U = 1.6m/s

Figure shows one of the results of the concentration profiles as measured by a Deltares conductivity concentration measurement (CCM) system which was installed in the same section, for comparison. The CCM system had already been demonstrated over many previous studies as a reliable technique for measuring solids concentrations at pipe walls.

As can be seen from the figure, the local concentrations are consistent with each measurement method. In addition, other studies have shown the reliability of the tomography measurements [Pullum, 2006].

The trials also showed the sensitivity of the tomography system to changes in the electrical conductivity of the bulk fluids. For the work in Delft, it was shown that off-line calibration files could be used to accurately process condition, for example when water temperature rose due to the pumping of dense phase media.

At the same time, field trials were carried out on dredging projects to determine the system's performance under operating conditions.

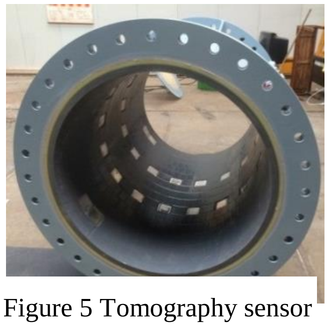

Figure 5 Tomography sensor with ceramic liner and duplex electrodes

Requirement for in-line calibration

Following successful trials at TU Delft, two programs were initiated

- the first to enable real-time calibration updates,
- and the second to ruggedize a sensor suitable for long term use on dredgers

The sensor shown (Figure 5) illustrates a design of 16 duplex steel electrodes arranged around the internal circumference of a standard pipe fitting with ceramic tiles to provide a hard wearing non-conductive liner and finished with PU liner.

These projects were completed in 2012 and an on-board installation was implemented on board a full scale dredger.

An in-line conductivity probe was positioned in clear water to provide ongoing measurements of the carrier fluid. These were integrated in real time into the tomography control program and the outputs adjusted in real time to deliver accurate density data. Comparisons against the in-line gamma densitometer confirmed the system's accuracy.

The sensor's reliability has been shown through and extended usage over the last four years (the sensor is still operational in 2016) confirmed the unit's robustness.

Instrument development

– Technology Readiness Levels 7-8 Prototype developed and demonstrated in an operational environment

The final stages in the development of what was colloquially called the "gamma buster" was to move from what was effectively a hardened lab-based instrument to an industrial unit designed for dredging and dense phase conveying. The two development stages consisted of

- transfer of the operating system from a PC to an industrial plc
- development of a purpose built user interface
- installation into a standard marinised protective

From Microsoft to Industrial plc

The core operating program has been developed in C++ and following discussions with end-users, Bachmann was selected as the most suitable operating platform for the final system. In addition to its usability and support, a key factors in arriving at this decision was a proven development path from Bachmann in developing control solutions in the dredging sector.

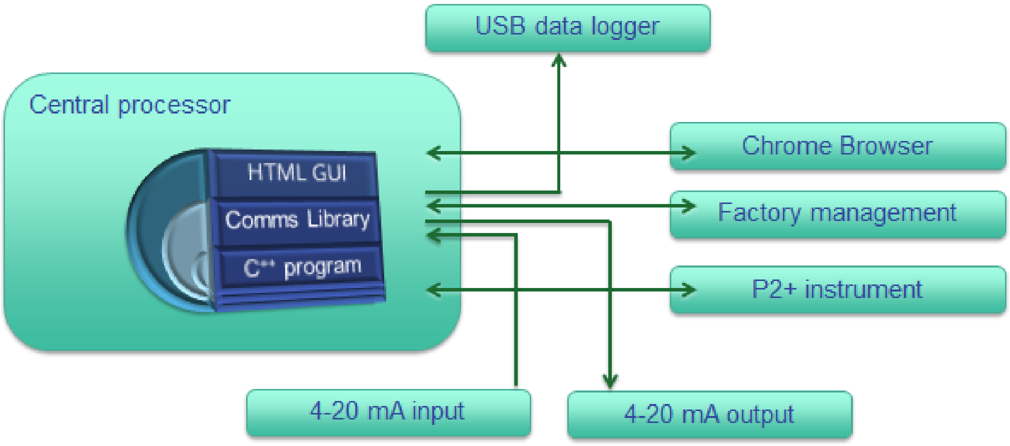

Figure 6 System architecture

The system architecture is shown above in Figure 6 and consists of a central Bachmann processor with tiered data modules

- Ethernet connection to access HTML based browser
- Ethernet connection to access text based data for integration to customer ship management software
- RS232 connector to primary tomography instrument
- 4-20mA output for density data
- 4-20mA input for secondary conductivity input
- USB data port to archive raw tomography data for subsequent analysis

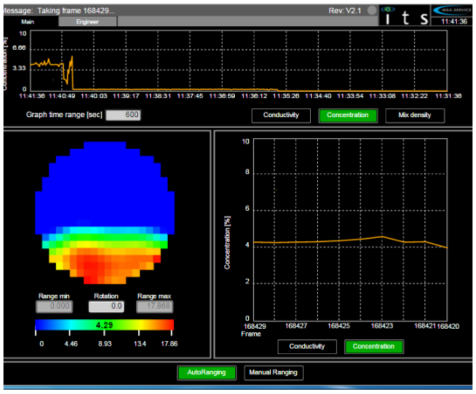

Figure 7 Standard operating window

Suitable software - operating screens

The core instrumentation will operate continually without user intervention, providing density data on the 4-20mA channel and both density and tomography information for flow visualization on a dedicated Ethernet channel.

A chrome based HTML browser is available as a separate display of instrument status and readings.

The standard window (Figure **2**7) shows:

- Instrument status, data point
- Time history of either concentration, conductivity or density
- Circular tomogram showing solids distribution
- Detailed density or concentration window

The user can toggle between views, but not interrupt data collection or change system settings

A set of engineering windows are also available (Figure 8). These allow much more control over the instrument, allowing a suitably trained engineer to:

- Optimise data collection under specific operating environments
- Adjust standard slurry parameters (for different solids)
- Recalibrate from current environment or factory settings

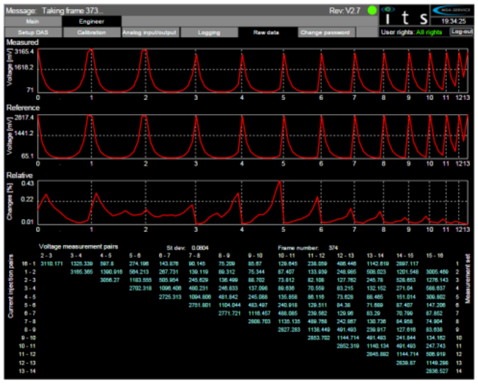

Figure 8 Engineering window - showing raw data

- Specify archiving modes
- Set input and output channels
- Inspect raw data

This combination of user levels allows standard operation to be undertaken from a day to day basis without the need for trained technicians. However the system has sufficient configurability to be optimized for different operating environments.

As noted, data outputs and a number of control features can be configured directly from Ethernet inputs from a proprietary control system.

Suitable enclosure

ITS co-operated with MSA, an established marine instrumentation house, to develop a robust enclosure which would be suitable for the range of duties expected for any dredging operation (Figure 8).

This addressed IP rating, temperature compensation, suitable cables and connectors, vibration damping, environmental management for moisture, heat and cold operating conditions.

Final trials

Final trials were carried out on a proprietary flow loop to test the compatibility between the Windows and Bachmann based platforms and also to test a wider range of materials.

Figure 8 Marine-based enclosure

SEA BASED OPERATIONS

The developed instrument has now been installed on a number of dredgers with Van Oord. In addition a range of enquires and further installations are underway with other operators. Pipe diameters have been fitted ranging from less than 0.5m to 1.2m and operations carried out around the world on at least 5 continents.

Figure 9 shows a recent installation on board such a vessel. It should be noted that the sensor is horizontal, which would cause difficulties for a nuclear based instrument

Figure 9 Sensor on board a dredger

Figure 10 shows a sample of the most recent output from the instrument and its performance against an established gamma instrument. There are some small discrepancies between the two data sets. As noted above, there are fundamental differences between the two different measurement technologies, however in this case it should be particularly noted that pipes are in different positions and there is an offset in the position of each unit.

In terms of comparative measurements, over the most recent one-day data set received by ITS (at the end of 2015) the average difference between the 2 instruments was 0.31%.

Data was captured at similar measurement frequencies (slightly less than 1 Hz).

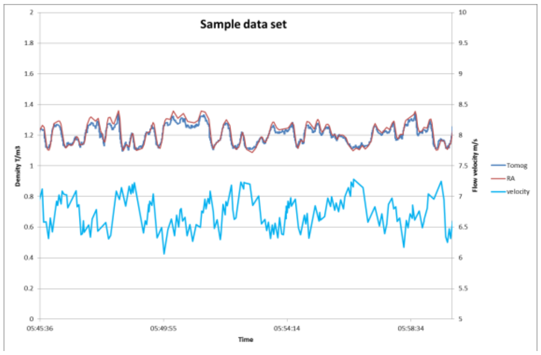

Figure 10 Sample output of Dens-itometer compared to gamma densitometer

CONCLUSIONS

In conclusion, this project has led to the development and validation of electrical tomography as an alternative to nuclear densitometers in field operation of dredgers.

Sensors have been installed over a number of years in both cutters and dredgers and shown to be robust to a range of operating conditions.

Data has been shown to be compatible with that taken by existing gamma instruments.

In addition to the benefits of being non-nuclear, advantages of the tomography based system include its performance at different pipe orientations; flow profile information for example providing solids concentration in sliding beds; simplicity of operation, allowing built in compensation and recalibration options.

Future work will address the use of dual tomography planes, high speed data acquisition and cross-correlation in order to provide measure both flow and density.

REFERENCES

Technology readiness levels (TRL) (PDF). European Commission, G. Technology readiness levels (TRL), HORIZON 2020 – WORK PROGRAMME 2014-2015 General Annexes, Extract from Part 19 - Commission Decision C(2014)4995.

6th World Congress on Industrial Process Tomography Visualisation and measurement of 3 phase (air water oil) flow and two phase flow (sand water) with electrical tomography K M Primrose, C Qiu, G T Bolton, A M Talmon, N Glen, A Ross, D Learmouth

High concentration suspension pumping, Minerals Engineering 19 (2006) 471–477
Lionel Pullum, Lachlan Graham, Murray Rudman, Ross Hamilton

New York Post, 7th Oct 2015
http://nypost.com/2015/10/07/the-smugglers-trying-to-help-isis-make-a-dirty-bomb/

CBS News 19th June 2015
http://www.cbsnews.com/news/turkey-detains-georgian-men-smuggling-radioactive-cesium-across-border/

Industrial Tomography: Systems and Applications, Elsevier Ltd (2015), Chapter 2: Electrical Impedance Tomogarphy, 49-50, *M. Wang*

EIT reconstruction algorithm: pitfalls, challenges and recent developments, Physiological Measurement (2004) 25, 125-142, *W. R. B. Lionheart.*

Inverse solutions for electrical impedance tomography based on conjugate gradients methods, Measurement Science and Technology (2002) 13, 101-117, *M. Wang*

Electrical Resistance Tomography (ERT) applications to Chemical Engineering, Chemical Engineering Research and Design (2013) 9I, 1625-1645, *M. Sharifi, B Young*

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