



Validation Process for Electrical Charge Tomography System Using Digital Imaging Technique

Mohd Daud Isa

Electrical Engineering Department, Politeknik Kota Bharu
KM.24 Kok Lanis, 16400 Ketereh, Kota Bharu, Kelantan, Malaysia
Tel: 60-9-788-9126 E-mail: peppkb@yahoo.com

Mohd Fua'ad Rahmat

Faculty of Electrical Engineering, University Technology Malaysia
81310 Skudai, Johor Bharu, Johor, Malaysia
Tel: 60-7553-5900 E-mail: fuaad@fke.utm.my

Kamaruzaman Jusoff (Corresponding author)

TropAIR, Faculty of Forestry, Universiti Putra Malaysia
43400 Serdang, Selangor, Malaysia
Tel: 60-3-8946-7176 E-mail: kjusoff@yahoo.com

Tengku Ahmad Raja Hussin

General Studies Department, Politeknik Kota Bharu
KM.24 Kok Lanis, 16400 Ketereh, Kota Bharu, Kelantan, Malaysia
Tel: 60-930-0198 E-mail: tabs2104@yahoo.com

This project is funded by Ministry of Higher Education, Malaysia (Sponsoring information)

Abstract

Electrical charge tomography (EChT) is a non-invasive imaging technique that is aimed to reconstruct the image of material being conveyed based on data measured by electrodynamic sensor installed around the pipe. The method to ensure the stability and accuracy of the image reconstruction should be applied to obtain a meaningful image reconstruction results. In this paper, Least square with regularization (LSR) method was introduced to reconstruct the cross-section image of material in gravity mode conveyor pipeline. Numerical analysis result based on data measured by sensor indicates that the algorithm is efficient to overcome the numerical instability. Instead of image reconstruction process, validation of the images is very important. It would be parts of verification process to the new image reconstruction method. In this system, digital imaging technique was used to interrogate the flow in pipeline around sensing area using CCD camera. It was found out that there is a good match between LSR method of image reconstruction and image capture by CCD camera due to the similarity of both images. This study implies that LSR method produced images that are stable and accurate as well as applicable for industrial use. It is suggested that another validation process should be conducted using duty ratio, signal to noise ratio and structure correlation to validate the quality of image produced by LSR method.

Keywords: Tomography, Digital imaging technique, Least square, Validation, Regularization method

1. Introduction

Electrical charge tomography (EChT) is a non-invasive imaging technique that is aimed to reconstruct the image of material being conveyed in pipeline. Electrical tomography has many advantages over other tomography modes due to

its high-speed, low-cost, non-intrusive sensors, no radiation, rapid response and robust as well as suitable for industrial applications (Yang & Liu, 2000).

Many image reconstruction techniques have been extensively developed over the last two decades as reliable tools for electrical tomography. Examples are system linear back projection (Dyakowski, et. al., 1997), filter back projection (Isa et. al, 2008), singular value decomposition (SVD) (Hua, et. al. 2004). Tikhonov regularization (Jinchuang et. al. 2002), simultaneous algebraic reconstruction technique (Jiang et. al. (2003), landweber iteration (Yang et. al. 2003) and etc.

In electrical charge tomography, although there are numbers of work been done applying electrostatic charge carried by particles in solid/powder conveyor pipeline to tomographic imaging, only three methods were introduced - namely linear back projection (LBP), filter back projection (FBP) and least square method (Bidin et. al., 1995; Machida et. al. 200; Green et. al.,1997).

In this paper, novel algorithm for electrical charge tomography is presented. Basically, the previous method will be discussed and the advantages of the new method will be highlighted. All discussion will be based on similarity of the image being reconstructed by these methods as compared to image captured by CCD camera that has been processed using digital imaging technique.

2. Methods & materials

2.1 Background to EChT image reconstruction

EChT image reconstruction process involves two problems which have to be solved i.e. forward modeling problem solution and inverse problem solution. In electrical charge tomography, imaging forward modeling is pre-described as the theoretical of the system in sensing area. It is related to sensor's sensitivity to the three-dimensional charge which contains a uniformly distributed charge in coulomb per square meter (C/m^2). Process tomography system by electrical charge is given one measurement from each of the sensors; the amount of information available is equal to the number of the sensors (Green et. al., 1997). Therefore, forward modeling of the pipe and the sensing area are mapped equally to the number of the sensor i.e sixteen by sixteen rectangular arrays consisting of 256 pixels or elements. The length between sensors is divided equally and located around the pipe at respective coordinates. The sensitivity map, S derived from the modeling and the summation of complete sensitivity map for sixteen sensors in two and three-dimensional is shown in Figure 2.

Inverse problem is the solution to provide an image of the charge concentration distribution within the sensing area. The data captured by 16 sensors is used to generate an image concentration. This image concentration is generated using analytical and statistical approaches such as linear back projection (LBP), filter back projection (FBP), and least square with regularization (LSR) methods.

2.2 Linear Back Projection (LBP)

Linear back projection is a straight forward solution which refers to the relationship between the distribution of charge, q and the detection of voltage by the detector as in equation (1).

$$V = Sq \quad (1)$$

S is the sensitivity map or sensitivity matrix with a dimension of 16×16 (as discussed in section 2.0). The measurement data, V and the charge distribution q are unknown.

To reconstruct the images in this system, the inverse problem has to be solved using equation (1). However, there are some difficulties in calculating the inverse matrix of the sensitivity matrix S . The concept of general inverse has to be introduced. Moore proposed the concept of general inverse matrix, and Penrose gave the definition of Moore general inverse matrix in a definition form (Yong et. al., 2007). Thus, the equation (1) becomes $q = S^{-1}V$, known as back projection. In practice, the concept of pseudo-inversion is used by assuming that $S^{-1} = S^T$ (Dyakowski et. al., 2000). In the reality, S is a symmetry value, so this is formulated as equation (2).

$$q_{LBP} = SV \quad (2)$$

2.3 Filter Back Projection (FBP)

The major limitation of linear back projection method arises due to the non-linear sensing mechanism of the electrostatic charge transducer. Filter can be determined by combining with the back projection method to provide filtered back projection. This filter provides weighting to individual pixels to provide a uniform concentration profile when the sensor has equal outputs (Green et. al.,1997).

The filter matrix is obtained by taking the maximum value of pixel divided by each value of pixel within the pipe mapping as shown in equation (3).

$$\text{Filter} = S_{\max}/S_i \quad (3)$$

Filtered back projection is a result of linear back projection multiplied by filter matrix of S , written as equation (4).

$$\mathbf{q}_{FBP} = \mathbf{q}_{LBP} \times \text{Filter} \quad (4)$$

2.4 Least Square with Regularization Method (LSR)

Least square (LS) method is almost the solution to the inverse problem of equation when measurement error are considered. It is meant to minimize the equation (1).

$$\text{Min} \|\mathbf{S}\mathbf{q} - \mathbf{V}\|^2 \quad (5)$$

$$\text{Where, } \mathbf{q} = (\mathbf{S}^T \mathbf{S})^{-1} \mathbf{V} \quad (6)$$

The solution of equation (6) is not unique. This is because the matrix $(\mathbf{S}^T \mathbf{S})^{-1}$ is not invertible. Therefore, the equation (6) is not a stable solution. A general principle of dealing with the instability of the problem is regularization (Yan et. al., 2001), imposing additional information about the solution. A penalty term can be added to the optimization problem as in equation below.

$$E(\mathbf{q}) = \text{argmin} \|\mathbf{S}\mathbf{q} - \mathbf{V}\|^2 + \beta^2 \|\mathbf{R}(\mathbf{q} - \mathbf{q}_0)\|^2 \quad (7)$$

A simple choice for the regularization penalty term is Tikhonov regularization (Jing et. al. 2008). The aim of this regularization is to dampen the contribution of small singular value in solution. The matrix $\mathbf{R}$ is a regularization matrix which penalizes extreme changes in parameter $\mathbf{q}$, removing the instability in the reconstruction. The parameter β called regularization parameter control the trade-off between the data fitting and violates the prior assumption. The solution of equation (7) would be written as a simple form of the standard Tikhonov where $\mathbf{R} = \mathbf{I}$ and assuming $\mathbf{q}_0 = 0$. Thus, equation (8) called Least square with regularization (LSR) method is introduced

$$\mathbf{q} = (\mathbf{S}^T \mathbf{S} + \beta^2 \mathbf{I})^{-1} \mathbf{S}^T \mathbf{V} \quad (8)$$

For the described algorithm, the choice of regularization is important. In general, a small value of β gives a good approximation to the original problem but the influence of errors may make the solution physically unacceptable. Conversely, a large value of β suppresses the data but increases the approximation error. At present, in most cases, β is chosen empirically (Tarantola, 2004). The value of regularization parameter 0.025908 is obtained.

2.5 Singular Value Decomposition (SVD)

The SVD will reveal all the difficulties associated with the ill-conditioning of the matrix (Soleimani, 2005). Let $\mathbf{K}$ be the matrix of reconstructed image with $M \times N$ rectangular matrix where $M \geq N$, Then, the SVD of $\mathbf{K}$ is a decomposition of the form (Hansen, 2007).;

$$\mathbf{K} = \sum_{i=1}^{\text{Min}(m,n)} u_i \sigma_i v_i^T \quad (9)$$

Where $\mathbf{U}_i = (u_1, \dots, u_n)$ and $\mathbf{V}_i = (v_1, \dots, v_n)$ are matrices with orthonormal columns, $\mathbf{U}^T \mathbf{U} = \mathbf{V}^T \mathbf{V} = \mathbf{I}_n$, where $\Sigma = \text{diag}(\sigma_1, \dots, \sigma_n)$. σ_i are the singular values of $\mathbf{S}$, while $\mathbf{U}_i$ and $\mathbf{V}_i$ are the left and right singular vectors of $\mathbf{S}$.

Discrete ill-conditionings will be considered if condition number of $\mathbf{K}$ is large. The condition number is equal to the ratio as equation (10).

$$\text{Cond}(\mathbf{S}) = \sigma_1 / \sigma_n \quad (10)$$

2.6 Digital imaging technique by CCD camera

Other than the image reconstruction process, the validation of image is also very important. It would be part of verifying process of the new image reconstruction method. In this system digital imaging technique is used to interrogate the flow in pipeline around the sensing area using CCD camera. When materials or particles flow through a pipeline, it is possible to acquire images using CCD camera with suitable illumination light source (Carter et. al. 2003).

CCD camera is used to capture image of particles (Carter et. al. 2003; Sugita et. al., 2003; Cater et. al., 2005) for various purposes such as particle size analysis, particles size distribution, mass flow rate and etc. It is quite a simple matter to focus a CCD camera on this system and acquire digital images. This general concept is illustrated in Figure 2. CCD camera will capture video of materials moving through the pipe hole as shown in Figure 2. Meanwhile, the electrodynamics sensor will be induced with charge from the material that passes through the sensors. This charge will be converted into voltage by electrical conditioning circuit attached to the sensor. The voltage will be sent to image reconstruction of computer system through Keithly STA-1800HC data acquisition card. Image reconstruction process is conducted off-line using Matlab programming language. These two types of measurements will be treated separately. Video captured by CCD camera will be processed using digital image processing and measured data from the sensor will be used to reconstruct the cross-section image of the pipe through sensing area using LBP, FBP and LSR methods. Image reconstructed by these methods will be compared to image captured by CCD camera. Validation of the image reconstruction methods will be based on similarity to the image produced by the CCD camera. The length between the point of the video captured by the CCD camera and the point of the electrodynamics sensor location is very short.

Therefore, image captured by the CCD camera and image reconstructed from the measured data by electrodynamic sensor are assumed similar.

The video captured by the CCD camera will go through several processes to produce a single image and to produce the concentration of particles in the pipeline. The processes involving algorithms for image processing are shown in Figure 3. Figure 3 shows the schematic flow of the algorithm for image processing. Materials being moved through the pipe are captured by a CCD camera. This is continuously recorded in videos with an image size of 1000 x 1000 pixels in color. The data measured by the electrodynamic sensor are also recorded with both processes occurring at the same time. All the preprocessing and processing stages of the image are done off-line. Preprocessing such as video framing, frame background selection and frame with particles selection are performed using Virtual Dub application program. Meanwhile, processes to produce image with absolute value and threshold are done using Matlab. The process to identify the sensing area, image conversion and scaling are done using Adobe Photoshop. Finally image is displayed using Matlab.

3. Results & discussion

This section focuses on the digital image processing from the video data captured by CCD camera and image reconstruction processes based on LBP, FBP and LSR methods. Images produced by both techniques will be compared. Figure 4 shows the results obtained from the preprocessing and processing stages using digital imaging technique. Based on the data measured by the electrodynamic sensor, image reconstruction is performed using the LBP, FBP and LSR methods. Figure 5 shows the comparison among images captured by the CCD Camera and reconstructed by the LBP, FBP and LSR methods.

Figure 5 (a) shows the image captured by the CCD camera with the highest image concentration area at the middle and top of the image as shown in circle and labeled A. The other high concentration areas are shown in circles with labels B, C and D. This means that in real situation the particles dropped in conveyor pipeline are scattered around the pipe with many concentration areas.

Figure 5 (b) shows high image concentration area for LSR method which is similar to the image recorded by the CCD camera area as being labeled A, B, C and D. It means that the LSR method is capable of differentiating between two or more charges in sensing area. It shows that charge concentration area detected by LSR method is scattered around the sensing area just like the image presented by the CCD Camera. Although the value of concentration is different, the pattern is almost similar. This is because of the different in sensitivity with every electrodynamic sensor, and also depends on the properties of the particles (size, shape, conductivity, chemical composition, moisture content and so on). To overcome the problem with the electrodynamic sensor, its design and fabrication should be made using high technology rather than using discrete electronic components and manual fabrication process.

Figure 5(c) shows that the image reconstructed using FBP method is accurate in detecting the high concentration area which is almost similar to image shown by label A in Figure 5 (a). However, it is detected as a huge point. Another problem with FBP is it produces high concentration near the sensor while reducing the value away toward the centre. As a result, FBP cannot be differentiated between two or more charges in the sensing area.

In Figure 5(d), image reconstructed using LBP method shows that the high concentration values of the image are not focusing on the area as shown by real image in Figure 5 (a). Instead the values focus on sensors 16, 1, 2 and 3. It means that LBP method is not suitable to reconstruct the image for electrical charge tomography because of its non-linearity to the sensing mechanism.

Stability analysis of the images is conducted using singular value decomposition (SVD) method. Table 1.0 shows the condition number of ill-posed for every method. From the result, it shows that LSR produces the lowest condition number with 224.53. The result reflects that LSR method produces better image stability than any other methods including CCD camera.

4. Conclusion

The results from image reconstruction processes by LBP, FBP and LSR methods and validation process above have highlighted some information. Firstly, the image reconstructed using least square with regularization method is similar with the image captured by CCD-camera whereby condition number obtained by LSR method is better than others. Secondly, the image reconstructed using FBP is accurate in detected the location of the charge but it did not distinguish between two separately charge in sensing area. But LSR method has capability to solve this problem. Finally, the image reconstructed using LBP is focused on the sensor location. It means that LBP method is not suitable to reconstruct the image for electrical charge tomography because of its non-linearity to the sensing mechanism. Thus, it shows that LSR method provides good promising result in terms of accuracy and stability of the image being reconstructed. It means that this paper is success to achieve their objective as mention earlier. The image produced by LSR method is better in terms of its accuracy, stability and suitability to be used in industries. In addition, more work should be done in validating the proposed algorithm such as computation of image error and quality of the image using duty ratio, signal

to noise ration and structure correlation as well as improving ill-posed of sensitivity matrix in mathematical modeling. For this system to be used in real industry environment, more work on hardware and software systems should be carried out to warranty their data and algorithm is well organized and developed.

References

- Bidin, A.R., Green, R.G., Shackleton, M.E, Stoot, A.L. and Tylor, R.W. (1995). Electrodynamic sensors for process tomography, in *Process Tomography: Principles, Techniques and Application*. Butterworth-Heunemann Ltd.
- Carter R. M., Yan Y. (2003). On-line particle sizing of pulverized and granular fuels using digital imaginf techniques. *Measurement Sci. Technology*, 14, p. 1099-1109.
- Cater T.M., Yann Y, Cameron S.D. (2005). On-line measueremnt of particle size distribution and mass flow rate of particles in pneumatic suspension using combined imaging and electrostatics sensor. *Flow measurement and instrumentation*, 16, p.309-314.
- Dyakowski T., Laurent F.C. (2000). Application of electrical tomography for gas-solid and liquid-solids flows – a review. *Power technology*, 112, p.174-192.
- Dyakowski, T., R.B. Edwards, & C.G. Xie, R.A. William. (1997). Application of capacitance tomography to gas-solid flows. *Chemical engineering science*, Vol. 52, No. 13, p.2009-2110.
- Green, R.G., Rahmat, M.F., Evans, K., Goulde, A., Hennry, M., and Stone, J.A.R. (1997). Concentration Profiles of dry powders in a gravity conveyor using an electrodynamic tomography system. *measurement Science of Technology*, Vol. 8, No. 2, p.192-197.
- Hansen P. C. (2007). Regularization tools: A MATLAB package for analysis and solution of discrete ill-posed problem, Version 4.0. *Numerical Algorithms*, 46, p.103-120.
- Hua Y. Chunting L. Jing G. (2004). *Electrical Capacitance tomography reconstruction based on singular value decomposition*. Proceeding of 5th word congress on intelligent control and automation, Jun 15-19, China, p. 3783-3786.
- Isa, M.D., Rahmat M.F. (2008). *Image reconstruction algorithm based on least square with regularization for process tomography system using electrical charge carried by particles*. Proceeding of 2008 student conference on research and development (SCORED 2008), 26-27 Nov. Johor, Malaysia. p.98(1-4).
- Jiang M. Wang G. (2003). Convergence of the simultaneous algebraic reconstruction technique (SART). *IEEE transaction on image processing*, Vol. 12, No. 8, August.
- Jinchuang Z., Wenli F., Taoshen L., Shi W. (2002). An image reconstruction algorithm based on a revised regularization method for electrical capacitance tomograpgy. *measurement science and technology*, 13, p.638-640.
- Jing L., Shi L., Zhihong L. Inaki S. Meng S. (2008). An image reconstruction algorithm based on new objective function for electrical capacitance tomography. *Measurement science and technology*. 19 015505 (5pp).
- Machida, M., Scarlett, B. (2005). Process Tomography System by Electrical Charge Caried by Particle, *IEEE Sensors Journal*, Vol. 5, No. 2, April, p.252-259.
- Soleimani M. (2005). Numerical modeling and analysis of the forward and invec problems in electrical capacitance tomography. *International journal of information and system sciences*, Vol. 1 No. 1, p.193-207.
- Sugita T., Kamimura M., Kitayama Y. (2003). *A particles size distribution measuring method for pulverized particle*, SICE Annuul conference in Fukui, August 4-6.
- Tarantola A. (2004). *Inverse problem theory and methods for model parameter estimation*. SIAM.
- Yan H., Hiu L J etc. (2001). Image Reconstruction in Electrical Capacitance Tomography Using Multi Linear Regression and Regularization, Measurement. *Science and technology*, 12, p.575-581.
- Yang, W.Q, & Liu, S. (2000). Role of tomography in gas/solid flow measurement. *Flow measurement and Instrumentation*, 1:237-244.
- Yang, W.Q, Lihui P. (2003). Review Article: Image reconstruction Algorithms for Electrical Capacitance Tomography. *Measurement Science and Technology*. Institute of Physics Publishing. 14, p.1-13
- Yong W. D., Dong F. (2007). *An Image Reconstruction Algorithm Based On Regularization Optimization For Process Tomography*. Proceeding of sixth International Conference on Machine Learning and Cybernetics, Hong Kong, 8, p.19-22.

Table 1. Condition number from various regularization parameter β for LSR images

Images	Condition Numbers of ill-posed
Image captured by CCD camera	1.63×10^3
Image reconstructed by LSR	224.53
Image reconstructed by FBP	5.15×10^5
Image reconstructed by LBP	7.63×10^5

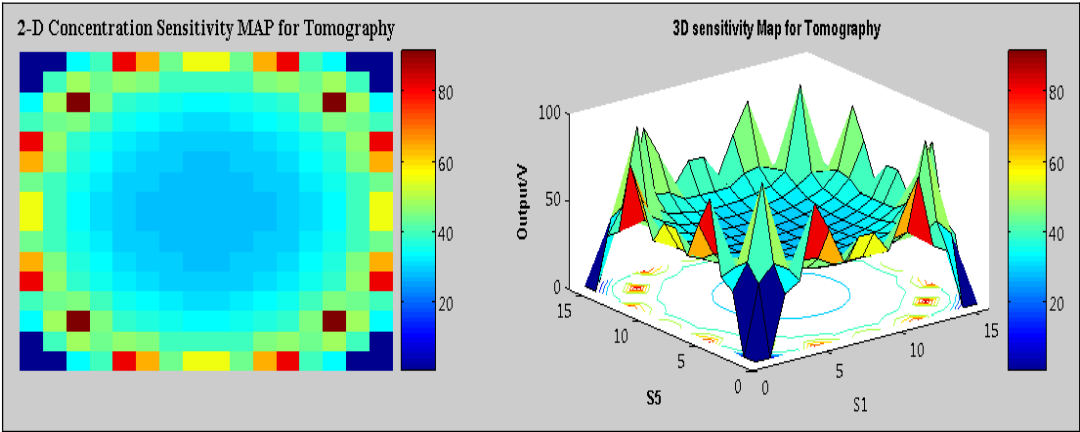


Figure 1. Two and three-dimensional Total Sensitivity map, S.

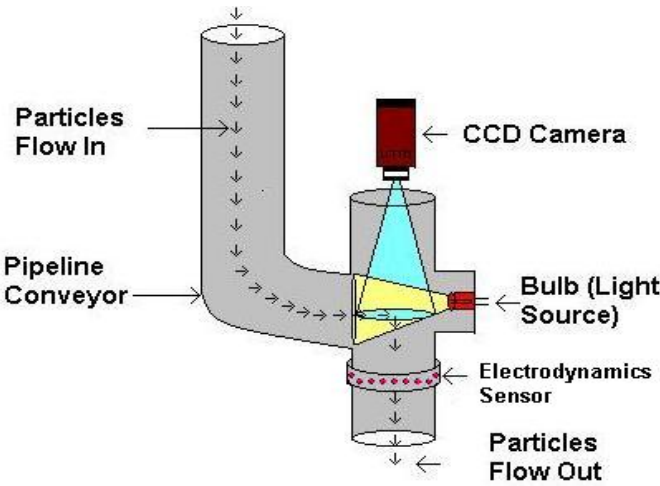


Figure 2. Particles imaging technique

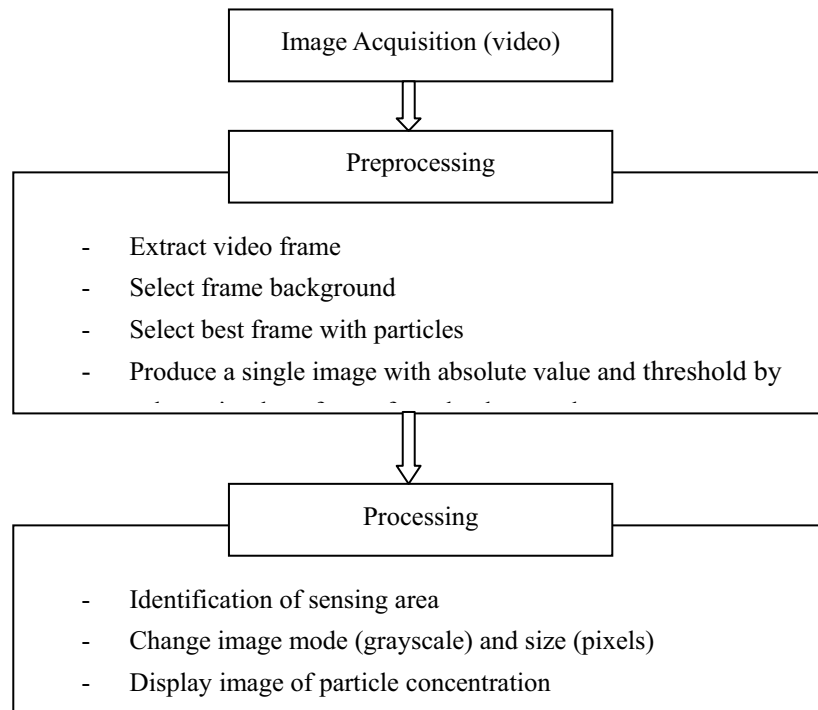
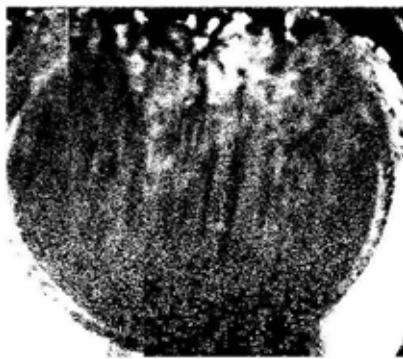
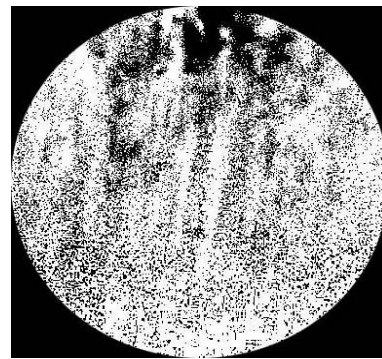


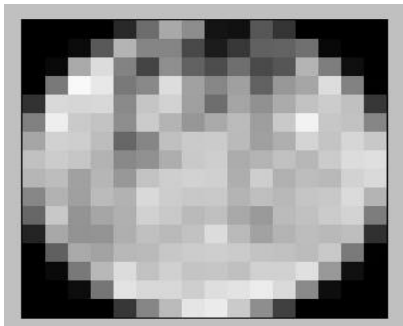
Figure 3. Schematic flow of the algorithm for image processing



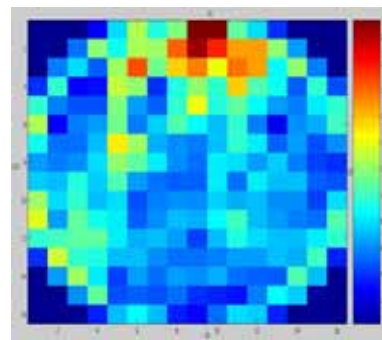
(a) Image with absolute value and threshold



(b) Image with identified sensing area

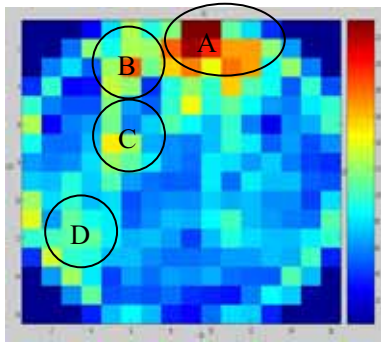


(c) Image with mode (grayscale) and size (16 X 16 Pixels)

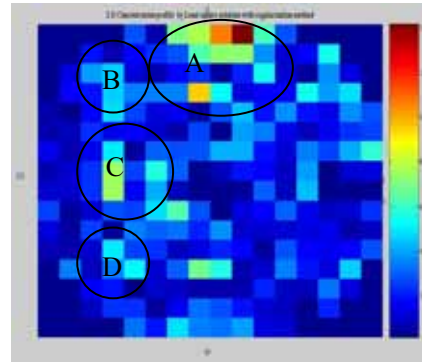


(d) Image of particle concentration

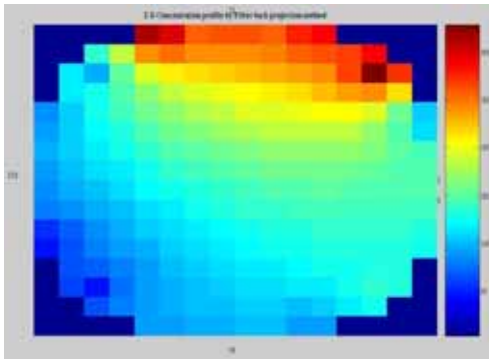
Figure 4. Images produced from preprocessing and processing stages



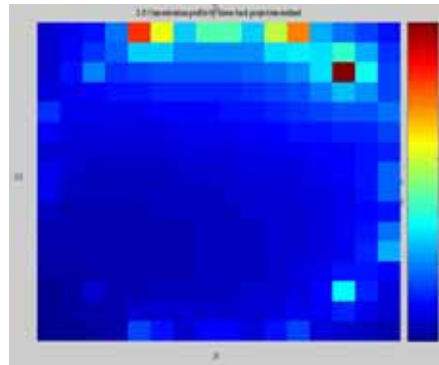
(a) Image captured by CCD Camera



(b) Image reconstructed by LSR method



(c) Image reconstructed by FBP method



(d) Image reconstructed by LBP method

Figure 5. Image being compared: (a) Image recorded by CCD Camera (b) Image reconstructed by LSR method (c) Image reconstructed by FBP method and (d) Image reconstructed by LBP method