Image Reconstruction Validation for CMOS Linear Image Sensor Based Tomography System

M. S. Ang, N. Ramli and M. R. Abd Rahim
Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Malaysia.
hafizah@fke.utm.my

***Abstract*—Nowadays, the fast-moving industries need a low cost, accurate, low power consumption, non-invasive and safe method for monitoring and tracking of the conveying and manufacturing process. There is many tomography based systems available in the industry, however, with limitations. This project aims to solve industrial problems of monitoring objects inside a transparent conveying pipe and determine the characteristic of the objects such as size, quantity and position. This is done through the image reconstruction of data acquired from Complementary metal-oxide-semiconductor (CMOS) linear image sensor based on optical tomography system. Data from four projections of laser are used to avoid the aliasing problem that may occur due to fewer projections. The image can be reconstructed by using linear back projection technique. The image will undergo image processing to enhance the image for better visualization of the object. Theoretical and experimental image are compared to validate the image reconstruction. As a result, the position, size and number of a symmetrical and solid object can be determined accurately from the reconstructed image. For further improvement, the number of projection may be increased.**

***Index Terms*—CMOS; Image Reconstruction; Linear Back Projection; Tomography.**

I. INTRODUCTION

Nowadays, tomography is widely used in the medical field as well as in industry. For example, it is commonly applied in scanning the body of the patient using X-Ray computed tomography. However, in industry, tomography techniques used are known as Industrial Process Tomography (IPT). These techniques aim to provide unparalleled internal information of industrial process, both quantitatively and qualitatively [1]. It is similar to Computed Tomography (CT) scan in the medical field which obtain data to give real-time information of flows and distributions through multi-point measurement and image processing. One of the common tomography methods used in industry is optical tomography.

Throughout the years, the industry has developed towards automation to effectively characterize and monitor their products during conveying and manufacturing process. For instance, concentration profile, velocity, mass flow rate, and particle size distributions need to be known to improve the product quality and productivity [2]. Since the tomography system is non-invasive, the objects can be observed and characterized without disturbing the industrial process, for example, to characterize objects in pneumatic conveying pipe [3].

There are a few sensors available for optical tomography include LED sensor, infrared sensor, laser sensor, fiber optic sensor, phototransistor sensor, Charged Couple Device (CCD) and Complementary metal-oxide-semiconductor (CMOS) array sensor [4]. Right choice of sensor needs to be made based on the object to be detected. CMOS linear image sensor S10077 which contains 1024 pixels is used to detect the shadow of an object due to back projection of laser light from a laser source. To generate the image as an output, optical tomography deals with a mathematical relationship of image reconstruction algorithm. Data acquired from the sensor in ASCII code is converted to pixel values and further processed to obtain an image reconstructed.

This project aims to validate that object or particle inside a pipe can be characterized correctly into different quantity, size and position using optical tomography system. Image reconstruction will be done to the data collected and the image simulated will be compared to the theoretical image. This project can be applied in industry with pneumatic conveying, for example, transportation of granular solids and dried powder in a gas stream and stamping of a chip on printed circuit board automatically for mass production of specialized electronic circuit boards [5]. The other applications of optical tomography include flame imaging and bubble detection.

II. LITERATURE REVIEW

A. Tomography System

The term Tomography is derived from an Ancient Greek letter which means a slice of image [1]. Generally, it is an imaging by sectioning through a solid object to obtain the cross-sectional view of the object. There are many methods derived from tomography such as X-Ray tomography, gamma ray tomography, electrical capacitance tomography, optical tomography and ultrasonic tomography. Each of these methods has their own source and limitations. For example, electrical capacitance tomography requires fluid flowing in the pipe to have low electrical conductivity. Tomography system consists of three parts which is sensors, data acquisition system and image reconstruction.

B. Optical Tomography

Optical tomography is one of the computed tomography techniques that is used to create a digital volumetric model of an object by reconstructing from light transmitted. It can be categorized into three groups, which are optical emission tomography, optical tomography for low scattering media and optical tomography for high scattering media [6]. There are different kind of light sources available for tomography. For instance, light-emitting diode (LED) and fluorescence can be used. The right choice of light sources and sensors is based on the object that need to be detected. The advantages of optical tomography include fast response due to the speed of light, immunity to electrical noise or interference, high performance and resolution, simple construction and non-invasive and it is cheaper and safer [7]. This type of tomography is applied in a few industries such as the gas industry to examine the pipeline, detect blockages and verify particles flow.

C. Image Reconstruction

Image reconstruction is the combination of the data obtained from the sensors capturing images of an object measured from different angles and views. Generally, it is used to form 2-Dimensional or 3-Dimensional images from a set of 1-Dimensional projections of an object. Image reconstruction method is classified into Finite Series Expansion and Transform Method. For optical tomography, its algorithm is divided into Fourier inversion and filtered back projection. Some common image reconstruction algorithm are iterative algorithms, heuristic algorithm and the linear back projection (LBP) algorithm [8].

D. Linear Back Projection

Linear back projection (LBP) algorithm comes from medical tomography and is performed through a process of transposed sensitivity matrix multiplication. It is a simplest and fastest method that commonly applied in optical tomography system. However, limited accuracy of image formed and image distortion are the problems encountered when this method is used to obtain images of material with lower contrast ratios. Usually, it is implemented in optical tomography to obtain the concentration profile of tomography image [9]. From a combination of data of projection for each sensor, we can obtain the concentration with computed sensitivity map. From sensitivity map, the algorithm will be modelled into matrix form and used for image plane representation [10]. The LBP algorithm is applied in the forward problem equation (1) and the inverse problem equation (2) in the next methodology section.

E. Linear Image Sensor

The linear image sensor is commonly used in obtaining images. An optical image is converted into an analog signal using linear image sensor. CMOS and CCD are the examples of linear image sensors that convert light to electrons. CCD was developed in 1970 by Dr. Boyle at the Bell Research Laboratory, U.S.A. CCD is able to transport charge across the chip without distortion using a special manufacturing. In turns, the sensors are high in quality, fidelity and light sensitivity. The CMOS image sensor is a mixed-signal circuit which contains pixels, analog-to-digital converters, analog signal processors, timing generators, bias generators, digital logic and memory. Similar as CCD, light in the form of electric charges is converted in electric signals and stored in a photodiode. Compared to CCD image sensor, CMOS image sensor consumes low power, has the high integration capability and need only single power supply. Also, CMOS image sensor has advantages of lower cost, single master clock and random access.

III. METHODOLOGY

Data obtained from the CMOS linear image sensor in the form of .txt file for each projection will be passed to MATLAB for simulation. Before the simulation of data, the image reconstruction process must be understood. Firstly, forward problem is solved to obtain the sensitivity map. Then, the sensitivity map is generated and validated. The inverse problem is then solved using linear back projection where theoretical data and real data is processed.

When 4 projections of data are acquired in the form of pixel values in .txt file, the data is converted and stored in Excel file. Due to big data from CMOS sensor, the data is resized to quarter of the original data size using MATLAB function. Then, the image will be reconstructed through pseudo inverse or transpose method followed by a combination of segmented data. Image reconstruction process involved the multiplication of measured CMOS data represented as [M] matrix and the inverse sensitivity map, $[S]^{-1}$. The sensitivity map or the [S] matrix is the mathematical modelling that predict the behaviour of the CMOS sensor data according to optical attenuation of light passing through the cross-section area of a pipe. The [S] matrix is not a square matrix; hence, pseudo inverse and transpose method are used to generate the inverse matrix [S]. The image is further processed using image processing techniques such as image enhancement, thresholding and morphological operation. A real image formed will be compared with theoretical image for verification of results.

A. Forward Problem

Forward problem is important to obtain the theoretical measurement data or the M vector, using predicted sensor behaviour known as the sensitivity map or S vector to solve the reconstruction equation [11]. The purpose of forward problem is to find out the equation with variables to assist the calculation of measurable data before the real data acquisition. Reconstruction coefficients and sensitivity maps of the object is estimated. In forward problem, sensitivity map is one of the crucial elements. It can be constructed from estimating the projections style to form estimated image with n x n number of pixels. For instance, a square is divided into 3x3 parts of equal size and labelled with row and column. Since four projections will be used to overcome the aliasing effect, the collimated light beams are projected from four sides through CMOS linear image sensor S10077. Figure 1, shows the different paths of collimated light beams from four projections towards CMOS linear image sensor S10077.

Based on Figure 1, the relationship of matrix [M], which represents a measurement constant and matrix [α] which represents the attenuation coefficient can be formed. The summation of α_{nm} assigned to each pixel is equal to M_n forming linear algebraic equations. From the combinations of equations from four projections, matrix equation can be formed. From the matrix equation formed, mathematical equation from all sizes of the matrix can be generated. The general equation is shown below:

$$[M]_{4n\times 1} = [S]_{4n\times n^2} \times [R]_{n^2\times 1} \quad (1)$$

where: M = Measurement vector of CMOS linear image sensor
S = Sensitivity matrix/Sensitivity map
R = Reconstruction vector of object model
n = Square factor number of pixel (n x n resolution)

From Equation (1), sensitivity matrix and attenuation coefficient are predicted and validated to solve inverse problem. Auto-generation of sensitivity matrix is developed from the pattern of sensitivity map because the process involves huge data and generation of sensitivity matrix cannot be done manually. The four projections of laser-sensor pairs are best represented by an octagonal shape with equal side as shown in Figure 1.

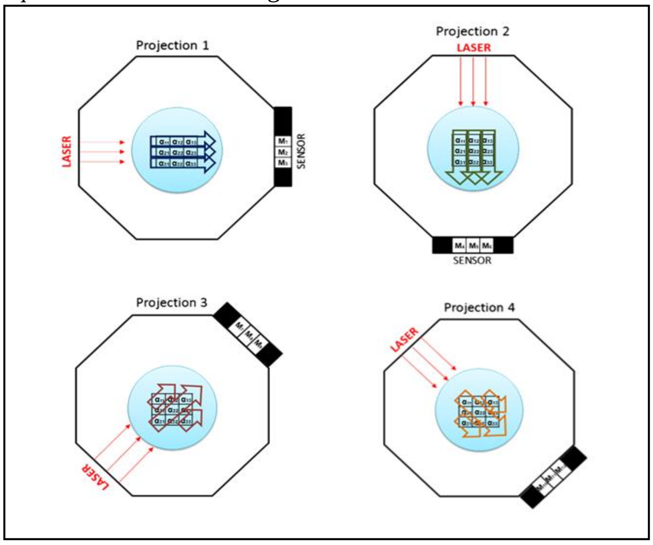

Figure 1: Projections from four different directions

Theoretically, estimation of attenuation for reconstruction vector is important to reconstruct a theoretical image to be comparable to the image reconstructed from real data. Figure 2, shows the example of how the value of α is located in a 7x7 resolution of image in excel form. Alpha value when object is present and absent are set to 10 and 0.00036 respectively.

	1	2	3	4	5	6	7
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	10	10	10	0	0	0	0
6	10	10	10	0	0	0	0
7	10	10	10	0	0	0	0

Figure 2: Example of attenuation coefficient representing the presence of the object.

B. Inverse Problem

In this research, the inverse problem is used to reconstruct the image of an object detected from a set of measurement values, M_n. In order to solve the inverse problem, Equation (1) that is constructed earlier must be solved in a reverse way. The equation of new reconstruction vector, NR can be formed from the general equation, as in Equation (2).

$$[NR]_{n^2\times 1} = [M]_{4n\times 1} \times [S^{-1}]_{4n\times n^2} \quad (2)$$

However, an equation with the inverse matrix cannot be solved with direct inverse operation neither through manually nor simulation since sensitivity matrix with size ($4n \times n^2$) is not a square matrix. Thus, an alternative approach is needed to replace the inverse function. It can be solved either by pseudo inverse method or transpose method.

C. Simulation using MATLAB GUI

MATLAB GUI is developed to ease the process of monitoring the output of the simulation. The data collected from the CMOS linear image sensor is input into MATLAB by .txt filename. The data is then resized to a quarter of the original size using MATLAB function 'imresize' to reduce the simulation time since the matrix involved which will be too large if original data size is input. The reason is each CMOS sensor contain 1024 pixels that represent the n value in Equations (1) and (2). Therefore, the sensitivity map or the size of the S vector will become a 4096 by 1024^2 such that the rest of the MATLAB computation will be very large and time consuming. Since the assumption of solid symmetrical object that will block light from passing through fully is made, the data can be binarized to 0 and 255 by applying threshold value of 80. This is to reduce unwanted noise. Users can manually select pseudo inverse method or transpose method to be applied to image reconstruction to compare the image accuracy and its computation time. For image processing part, users can choose a threshold value from the slider and simulate grayscale. Image processing method such as thresholding and morphological operations are applied to show to final grayscale image. Users can select to display coloured image too. Processing time of each operation will be shown in the GUI to indicate the operation has completed. Also, user can choose to clear GUI by clicking "Clear Axes" button available in the GUI. Also, the object size estimated from the image will be displayed in the GUI. This process is done by counting the white pixels which represent object in the image.

IV. RESULT AND DISCUSSION

The result is divided into two parts, using both theoretical data and real experimental data.

A. Theoretical Data Simulation

To obtain theoretical data, reconstruction vector of size 255x255 with attenuation coefficient is manually generated and stored in excel using the technique as shown in Figure 2. With the presence of auto-generated sensitivity matrix and reconstruction vector, theoretical measurement vector can be obtained using Equation (1). The measurement vector obtained is then solved using inverse problem, where the new reconstruction vector is obtained and resized. An image is generated from the new reconstruction vector and display using MATLAB. The algorithm is validated using different position, different size, different shape and different quantity of object. Figure 3 shows an image simulated from theoretical data for right angle triangle using transpose method, Figure 4 shows the image simulated for circle using pseudo inverse method and Figure 5 shows image simulated for 3 different objects.

From the result, the reconstructed image for right angle triangle and different position of the circle are identical to their actual images reconstruction vector which are manually generated in excel. Both images are simulated using a different method, which is transposed and pseudo inverse method. Pseudo inverse method took longer time to simulate in MATLAB compared to transpose method which takes only less than 20s.

However, from the reconstructed image shown in Figure 5, the output is not accurate. This is due to the aliasing occurred because the number of projections is not enough for the algorithm to detect more than 1 objects accurately. Thus, the algorithm of this project is only suitable for single object only.

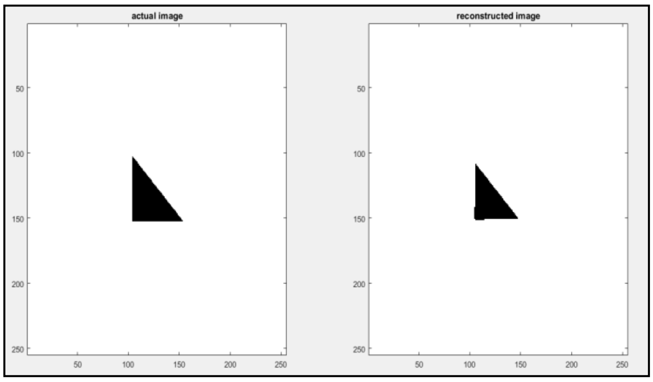

Figure 3: Image simulated from theoretical data for right angle triangle.

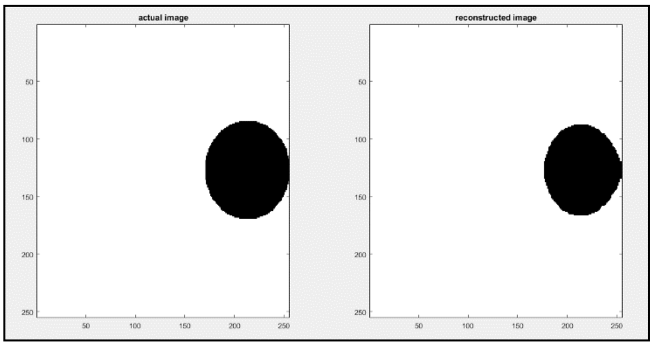

Figure 4: Image simulated from theoretical data for different positions of the circle

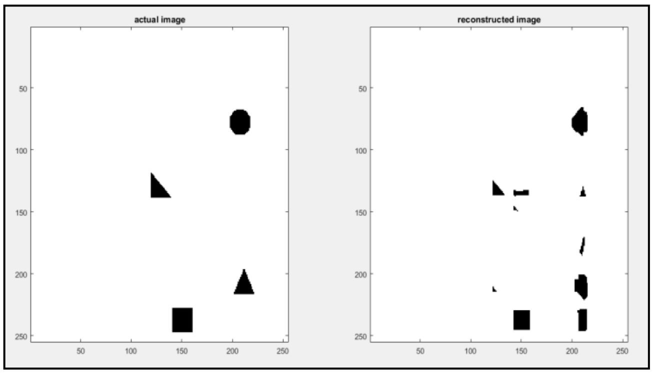

Figure 5: Image simulated from theoretical data for four different objects.

B. *Real Data Simulation*

Firstly, to make sure the algorithm works for real data, object of square shape of 4mm diameter, which contains 285 pixels blocked each projection at the middle is assumed. Figure 6 and Figure 7 shows the result of reconstructed images.

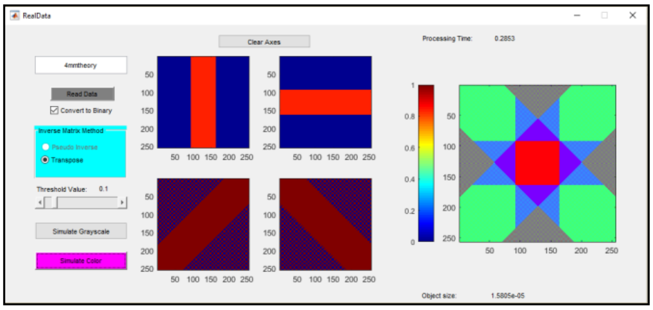

Figure 6: Reconstructed image of 4mm theoretical square shape in color.

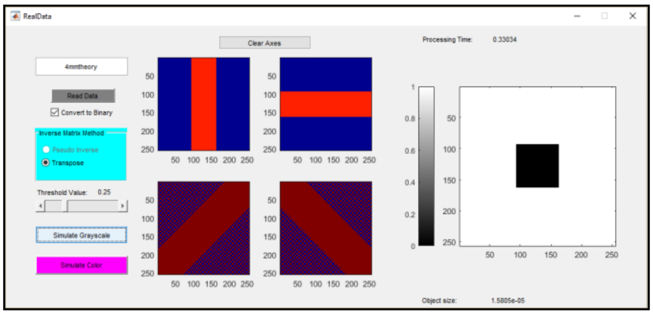

Figure 7: Reconstructed image of 4mm theoretical square shape in black and white after some image processing done to eliminate unwanted ray and show the reconstructed object only

From Figure 6 and Figure 7, it is proved that the image reconstruction algorithm works for real data simulation. For this project, the objects in the pipeline of hardware are assumed solid and in symmetrical shape which will block laser light completely from piercing through. Thus, the pixels value will be either 0 or 255.

Real data obtained from CMOS linear image sensor for different shapes, size and position of object is stored in .txt file in decimal form for each projection. Figure 8, Figure 9, Figure 10 and Figure 11 show the results of real data simulation from MATLAB GUI using transpose method.

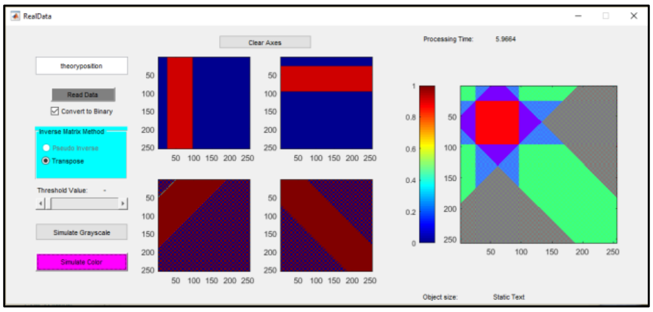

Figure 8: Reconstructed image of the square located at the top left for different position simulation

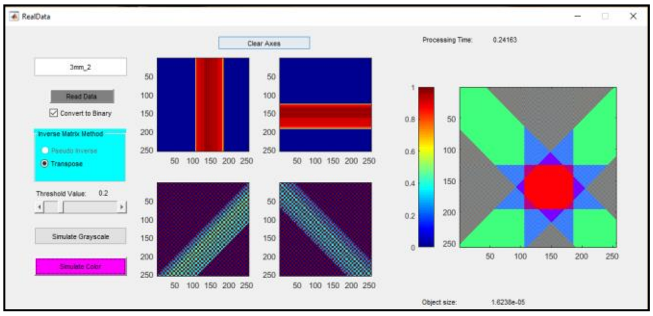

Figure 9: Reconstructed image of 3mm bead.

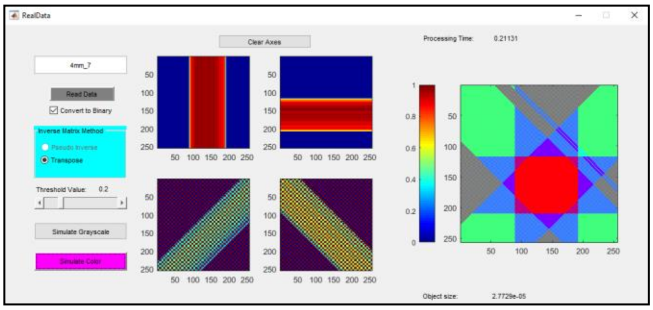

Figure 10: Reconstructed image of 4mm bead.

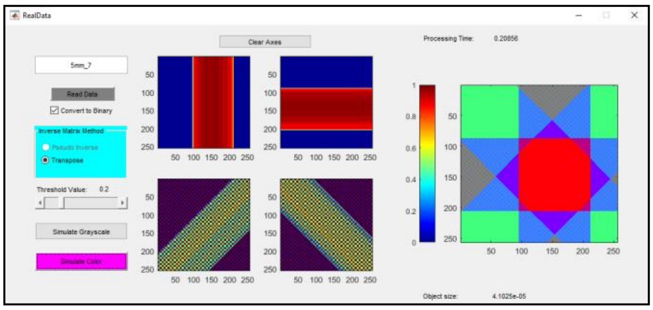

Figure 11: Reconstructed image of 5mm bead

From Figure 8 to Figure 11, we can see that position and the size of the beads located in the transparent pipeline can be determined from the reconstructed image. There is an obvious difference in size between 3 mm, 4 mm and 5 mm beads. However, the shape of beads appears to be nearly square shape. This is due to the limited number of projection, which is 4 linear projections. Also, there are some unwanted noise that can't be removed using a thresholding technique. The line noise may be due to the laser light diffraction. After some image processing using morphological operation for a binarized image using 'imbinarize' MATLAB function, the noise can be removed and the shape and size of the object can be determined clearer in grayscale. The threshold value for thresholding may need to be altered for different reconstructed images. Figure 12, shows the result of the reconstructed image after some image processing operation to better visualize the object detected.

In order to verify whether multiple number of objects can be detected accurately using a CMOS linear image sensor, multiple beads are positioned in the transparent pipe and images are reconstructed from the data obtained. Figure 13 shows image reconstructed for 2 beads and Figure 14 shows image reconstructed for 3 beads.

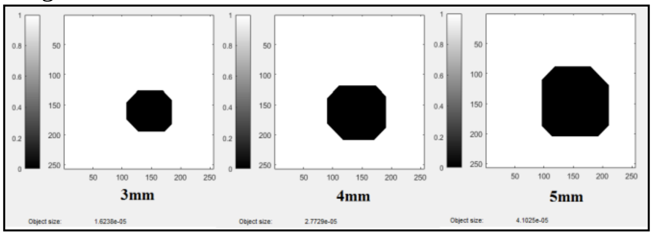

Figure 12: Reconstructed image for 3 different objects in binary form

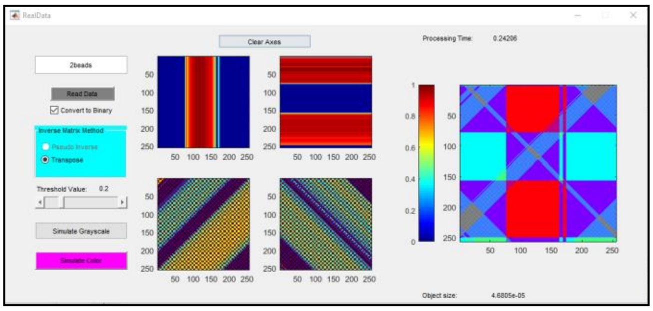

Figure 13: Reconstructed image for 2 beads.

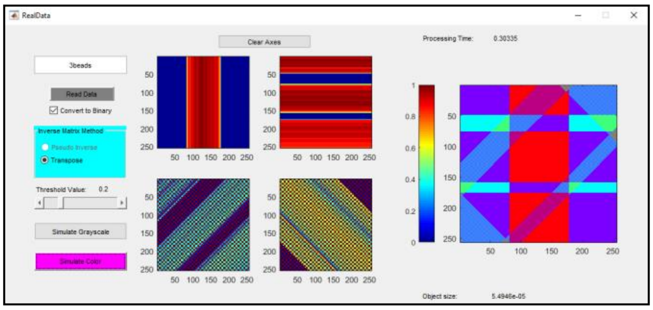

Figure 14: Reconstructed image for 3 beads

From Figure 13 and Figure 14, the number of beads can be visualized from the image reconstructed. However, due to aliasing problem and limited number of projections, the shapes, position and size of the bead are not accurate. Also, there are some noise occurred due to the diffraction of laser light. During the experiment, the size of the pipe is bigger than the sensor size. Thus, there are some portion of the pipe cannot be detected by the sensor. This means that the data received by the sensor is not complete to be reconstructed to show accurate image.

V. Conclusion

The image reconstruction algorithm using linear back projection for CMOS linear image sensor based tomography has been validated using theoretical data and real data. For theoretical data, since the reconstruction vector is drawn manually without considering the CMOS linear image sensor and light source behaviour, the reconstructed image shows that different shapes, size, position can be detected using the algorithm except for more than one objects.

From the real data results, the research is able to differentiate the size, position and numbers of solid available in a pipeline. The algorithm is unable to differentiate between different shapes of object due to the limited number of projections. If there is more projection from different angle, for example top view of the object, the detection of object shape will be possible. On the other hand, for real data simulation, reconstruction vector is obtained from the measurement vector from the CMOS linear image sensor. Measurement vector blocked by an object will be 0 and 255 when it is not blocked. Thus, the reconstructed image from overlapping of four projections will appear to be nearly square shape even though the actual object is an oval shape bead.

In this project, a MATLAB GUI is developed to ease the simulation of real data. It is beneficial when different types of data need to be simulated since auto-reading of real data from four projections can be implemented. It can be applied in the real world to detect and monitor the object in the transparent pipeline for different size and position of object. Different thresholding value and image reconstruction method can be chosen for different data

ACKNOWLEDGMENT

The authors would like to thank Universiti Teknologi Malaysia and the Ministry of Higher Education for their support. This project is supported by Research University Grant Vote Q.J130000.2623.12J63.

REFERENCES

[1] G. A. Johansen and M. Wang, "Industrial process tomography," *Measurement Science and Technology*, vol. 19, pp. 090101, Sep. 2008.

[2] R. A. Rahim., *Optical Tomography System: Principles, Technique and Applications*. Malaysia: Penerbitan UTM Press, 2011.

[3] R. A. Rahim. "A Tomography Imaging System for Pneumatic Conveyors using Optical Fibers," *Phd Thesis,* Sheffield Hallam University, England, 1996.

[4] N. Ramli, S. S. M. Sobani, "Four projections CMOS linear image sensor tomographic image reconstruction," *Jurnal Teknologi (Sciences & Engineering)*, vol. 61, no. 2, pp. 19- 25, 2013 .

[5] N. Ramli, M. Idroas, M. N. Ibrahim and N. H. Shafei, "Design of the optical tomography system for four projections CMOS linear image sensor," *Jurnal Teknologi (Sciences & Engineering)*, vol. 61 no. 2, pp. 79-85, 2013.

[6] C. Haisch, "Optical tomography," *Annual Review of Analytical Chemistry*, vol. 5, pp. 57-77, 2012.

[7] R. G. Jackson. "The development of optical system for process imaging," in *Process Tomography: Principle, Technique, and Applications*, R. A. Williams and M. S. Beck, Eds. Oxford: Butterworth-Heinemann. 1995, pp. 167-180.

[8] G. L. Zeng. "Image reconstruction - a tutorial," *Computerized Medical Imaging and Graphics*," vol. 25, no. 2, pp. 97–103, 2001.

[9] R. A. Williams and M. S. Beck, *Process Tomography: Principles, Techniques and Applications*, London: Butterworth-Heinemann, 1995, pp. 624.

[10] S. Z. M. Muji, R. A. Rahim, M. H. F. Rahiman, S. Sahlan, M. F. A. Shaib, M. Jaysuman and E. J. Mohamad, "Optical tomography: a review on sensor array, projection arrangement and image reconstruction algorithm," *International Journal of Innovative Computing Information and Control*, vol. 7, no. 7, pp. 1-18, 2011.

[11] T. Tarvainen, M. Vauhkonen and S. R. Arridge. "Gauss-Newton reconstruction method for optical tomography using the finite element solution of the radiative transfer equation," *Journal of Quantitative Spectroscopy & Radiative Transfer,* vol. 109, no. 28, pp. 2767–277, 2008.