Imaging of Solid Particle in Air using Optical Tomography based on CMOS Area Image Sensor

S. M. Najib¹, Mariani Idroas²*, M. N. Ibrahim¹ and M. A. H. Ab Ghani¹

¹Department of Electrical Engineering, University Teknologi Malaysia, 81310, Johor Bahru, Johor, Malaysia
²Department of Petroleum and Renewable Energy Engineering, University Teknologi, Malaysia, 81310, Johor Bahru, Johor, Malaysia; mariani@petroleum.utm.my

Keywords: CMOS Area Image Sensor, Image Reconstruction, Optical Tomography

1. Introduction

Tomography was originated from the Greek word ‘tomo’ which means ‘to slice’¹. Tomography imaging system is a method of viewing and analyzing a cross sectional image with wave or radiation for observing the internal characterization of an object²⁻⁵. In optical tomography, light is projected through different medium of an object and the output signal is detected through the level of light received by the optical sensor². This type of tomography is based on non-intrusive characteristic and safe to be applied in food industry since its transducer does not required direct contact with the measured⁴. Moreover, it provides high resolution images which is about 1% of diameter of cross section⁴. It has the advantages of a straightforward and inexpensive method⁵. Generally, an optical tomography system consists of a lighting system, optical sensors, signal measurement circuitry, a data acquisition system and an image reconstruction system for processing and displaying the image.

2. CMOS based Optical Tomography System

Figure 1 shows the optical tomographic instrumentation system used in this study that consists of a lighting system, a measurement system, a data acquisition system and an image reconstruction system. In the measurement section, two CMOS area image sensors were positioned opposite to their respective lighting system. The CMOS area image sensor used in this system was MT9M001C12STM, manufactured by Aptina.

A well-collimated beam of light was traversed through the measurement system that contains particles. For the test purpose, a known-size sphere was used. The image of the sphere was captured by the CMOS area image sensor in the measurement system. The data acquired by the data

*Author for correspondence
acquisition system was sent to the image reconstruction system.

3. Image Reconstruction System

An image reconstruction process in any tomography system is important to give complete information about the internal behavior in the process flow pipe. The image was represented by the attenuation coefficients of each material inside the pipe. The image generated by the CMOS area image sensor can be visualized without disturbing the process (non-intrusive) or rupturing the wall of the pipe (non-invasive).

Modeling of the image reconstruction is needed in order to have a better understanding on the algorithm used in the reconstruction process. The method used for the image reconstruction process was Layergram Back Projection (LYBP).

3.1 Layergram Back Projection Method (LYBP)

As stated by Idroas et al.\cite{7}, there was a mathematical relationship between an attenuation coefficient of a material and the distance that the light traversed, when the total intensity hit an optical sensor (Equation (3))\cite{7}. It is referring to the Beer-Lambert Law theory, which stated that absorbance of a sample is directly proportional to the path length of the sample ($x$) and the properties of material ($\alpha$) (Figure 2).

\[
\ln \left( \frac{I_{in}}{I_{out}} \right) = \alpha x \quad (3)
\]

Before LYBP is applied, a forward problem needs to be done first. The forward problem provides the measurement value for each pixel in the CMOS area image sensor. To acquire the real attenuation coefficient of the internal pipe, the solution of the forward problem was used in the Layergram method.

The solid particle was assumed to have high value of linear attenuation coefficient (which is assumed to be 10mm$^{-1}$) and the pipe contained air that has an attenuation coefficient of 0.00142mm$^{-1}$. Two projections that are passed through $3 \times 3$ square cells are shown in Figure 3. The square cell was modeled based on the pixel of CMOS area image sensor. The dimension of the square cell was the pixel size of the CMOS area image sensor, which was 5.2 micron $\times$ 5.2 micron. Based on this configuration, each projection had three optical sensors. Therefore, the total number of optical sensor for two projections was nine (9), which was represented by M1-M9. Each cell was labeled as $\alpha_{ij}$ where $i$ was the row number whilst $j$ was the column number.

Based on the Beer-Lambert Law, M1 until M9 can be calculated as follows:

**Projection 1:**

\[
M1 = 0.0052[a_{00} + a_{00} + a_{00}] \quad (4)
\]

\[
M2 = 0.0052[a_{10} + a_{11} + a_{12}] \quad (5)
\]

\[
M3 = 0.0052[a_{20} + a_{21} + a_{22}] \quad (6)
\]
Projection 2:

\[
\begin{align*}
M4 &= 0.0052 \left( a_{00} + a_{10} + a_{20} \right) \quad (7) \\
M5 &= 0.0052 \left( a_{01} + a_{11} + a_{21} \right) \quad (8) \\
M6 &= 0.0052 \left( a_{02} + a_{12} + a_{22} \right) \quad (9)
\end{align*}
\]

Equations (4) until (9) can be simplified into a matrix form:

\[
[S] \ast [A] = [M] \quad (10)
\]

where \([S]\) is the sensitivity matrix, \([A]\) is the attenuation coefficient and \([M]\) is the measurement value.

The voltage reading from each sensor was added according to the intersection at the respective cell \(a_{ij}\). For instance:

\[
a_{00} = M1 + M4 \\
a_{01} = M1 + M5
\]

And so on until \(a_{22}\).

The image reconstruction process was modeled using 3x3 pixels, 7x7 pixels, 21x21 pixels and 101x101 pixels to see the pattern of the reconstructed image using LYBP method. Figures 4(a) until (d) show the actual image, while Figures 5(a) to (d) show the reconstructed images of the object.

By referring to Figure 5, it can be seen that more pixels will produce more accurate and precise reconstructed images. The reconstructed images in Figure 5(a)-(d) have smearing effects due to the two projections system being applied. According to Dhawan, the more projections used in a system will produce better images.11

3.2 Image Reconstruction of the CMOS Area Image Sensor

A known-size of sphere was placed in front of the CMOS area image sensors (Figure 6). The output measured from the CMOS area image sensor showed the sphere's shadow captured by the sensor. The light intensity was measured in volts, where 3.3V was the maximum value (for total darkness i.e. shadow) and 0V was the minimum value (for total light). Figure 7 shows an image captured by the CMOS area image sensor for Projection 1.

For the experimental purpose, a smaller area from the whole area of image sensor has been extracted to ease the reconstruction process as it acquired low processing...
time and memory space. The area involved was 250x168 pixels. This value indicates that the CMOS area image sensor produced 168 slices of 250 measured data.

Measured data for the object has been reconstructed for every slice, but the image was only reconstructed at row 18, 34, 80, 141 and 15, to show different tomogram images at different locations. Figure 8 shows the images at different positions of image slices.

Table 1 shows the reconstructed images for row 18, 34, 80, 141 and 152. The reconstructed image contained smearing effect as it only involved two projections. Table 1(a) and 1(e) illustrate the images at row 18 and row 152, when there was no object. The images for row 34 and row 141 show smaller diameter of sphere, as shown in Table 1(b) and 1(d). Table 1(c) shows the center image of sphere at row 80 that has a larger diameter.

As we can see in Table 1, the use of two projections made the reconstructed images visualized a square shape of particle, rather than a circular shape. However, this drawback was not obvious when the system involved with a very high number of pixels. Figure 9 shows the final 3D image of the particle in air.

By comparing the developed system with a system that used a linear image sensor, the optical tomography system

![Image](image_url)
used CMOS area image sensors can cut short the processing time, because less tomogram images are need in order to produce a 3D image of an object\textsuperscript{2,3}. Moreover, the use of CMOS area image sensor as an optical sensor produced a high resolution image, due the small pixel size compared to the linear image sensor and optical fibers\textsuperscript{7,9,10}.  

4. Conclusion

The developed optical tomography based on CMOS area image sensor is capable of monitoring internal behavior/process in a pipe. The two projections system is able to reconstruct tomogram image of solid particle in air, based on Layergram Back Projection method (LYBP).

5. References

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