## Image Reconstruction for Optical Tomography System based on Complementary Metal Oxide Semiconductor Image Sensor

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#### Abstract

Quality of food products is important and highly demanded by customers in food industry. All physical attributions (size, shape, texture, concentration and color) of food products have to be considered. Monitoring the particle parameters can affect food flavor, texture, appearance, product size and shelf life. Most of the monitoring systems used in the food industry are based on the grading and sorting inspection such as sampling and Computer Vision technique. However, each of them has their limitations. Therefore, an optical tomography based on Complementary Metal Oxide Semiconductor (CMOS) area image sensor is developed to monitor these particle parameters by visualizing the particle non-invasively inside a flow pipe. The complete optical tomography system has been fabricated to produce a reliable tool to monitor particle characterization and to detect solid particles in flow pipe. The system offers reliable reconstructed images in monitoring particle concentration in air and liquid flows, particle shape and size. The optical tomography system consists of a lighting system, a sensing system that contains a measurement section and CMOS area image sensors, a Data Acquisition System (DAQ) that made up from a microcontroller module, and an image reconstruction system based on MATLAB software. The results obtained are sufficient to collect the qualitative and quantitative information of the particles used in the system to monitor concentration profile in air and liquid.

Keywords: CMOS, Image, Reconstruction, Tomography

#### 1. Introduction

Quality of food becomes a determinant factor to the customers who are concerned with the nutrition, food safety and exterior characteristics of food (e.g., shape, texture and color)<sup>1</sup>. Quality of food is based on two types of perspective; objective quality and subjective quality<sup>2</sup>. Objective quality refers to the physical attributions of food product that can be classified as but not limited to shape, concentration, size, color and texture. Subjective quality is the customer's interpretation of food, where different people will have different perspective towards the physical characteristics of the food. Since the quality of food product is really significant to the company profit, many

interrelated where by upgrading the objective quality will affect the customers' subjective perspective.
 Particle characterization can increase quality in food production and optimize the manufacturing procession ing<sup>4</sup>. Particle characterization is an essential precursor

in food industry to control the output according to the specifications and the customers' requirements. There is a variety of conventional particle characterization techniques, where each technique has its limitation and only restricted to certain application. A separation technique is used to find the particle's properties that involve the

industries made a thorough research and improvement of their product to ensure that the customer rejection

rates and lost orders are decreased<sup>3</sup>. Both perspectives are

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conventional method (sieving and sedimentation)<sup>4</sup>. With higher expectations in food industry from the customers' awareness to have high quality of food and safe, the need for accurate, fast and precise process in measuring the physical properties of food is continues to grow. Physical properties such as size, shape, volume, density and concentration are prominent in order to ensure the quality of the food.

Food quality has been traditionally obtained from the human visual perception, for example, the color or flavor of food sample will be accessed by the food technologist to ascertain that the product follows its specifications. Unfortunately, human perception could easily be fooled<sup>5</sup>. Such methods are high labour costs, time-consuming and inconsistent. With the increasing demand of the food products, it is pertinent to employ an automatic inspection system. Application of computer vision to food processing fields evolved first in 1989 for grain quality inspection<sup>6</sup>.

There must be a system that has an ability to view the objects in the process vessel without interrupting the process itself. The best approach is by applying a tomography technique because it can continuously monitor the flow measurement in non-intrusive and non-invasive ways, by providing the information of the internal process. In this paper, the implementation of Complementary Metal Oxide Semiconductor (CMOS) area image sensor in the development of optical tomography system is presented.

## 2. Experimental Setup

An optical tomography system was designed based on Complementary Metal Oxide Semiconductor (CMOS) area image sensor for monitoring concentration profile of solid particles in liquid and air flow. A complete system was formed in two main parts; hardware and software. Hardware and software are mutually dependent on each other. Software implementation is important to ensure that the hardware will produce a reliable output. Figure 1 shows the flowchart of the hardware and software development in the developed optical tomography system.

To design a complete optical tomography system, three stages of hardware development were involved. The CMOS area image sensor circuit was designed first and a program to capture, sample and display the image from the CMOS area image sensor was built based on Visual Basic 6.0 platform. After that, a Data Acquisition System (DAQ) was developed based on Arduino Mega 2560. A code to synchronize and sample the pixels from the CMOS area image sensor was programmed using an open-source Arduino Software (IDE). The last stage consists of the development of the system rig, which include the lighting system and the measurement section.



Figure 1. Flowchart of hardware and software development.

A complete optical tomography system is based on two projections (Figure 2), and each projection has a lighting system, a sensing system that contains a measurement section and a CMOS area image sensor, a DAQ system that made up from microcontroller module, and an image reconstruction system that is based on MATLAB software.

## 3. Image Reconstruction Process

#### 3.1 Image Technique

The internal cross-sectional of an object can be created from an image reconstruction process. The image reconstruction system used raw data that were acquired during the experimental process. In the optical tomography, the light intensity that passed through an object makes it possible to calculate the internal distribution of the optical density<sup>7</sup>. The complete image reconstruction system consists of two projections, where each projection has a lighting system and the corresponding CMOS area image sensor at the other side of the flow pipe.

In the optical tomography, Linear Back Projection (LBP) was frequently applied in image reconstruction system<sup>7</sup>. As proved by Idroas (2004), the LBP was not suit-

able for larger array of pixel<sup>7</sup> because it required complex image reconstruction process as well as bigger memory space and high speed processing unit. Therefore, the image reconstruction algorithm implemented in the system was based on a Layergram Backprojection (LYGBP) method. This algorithm is a simplification of the back projection method. Other than simple, it provides a better image in terms of brightness and contrast. Besides, it also produces more accurate values of attenuation coefficient,  $\alpha^8$ .



Figure 2. A complete optical tomography system.

Figure 3 illustrates the condition of the two overlapped projections applied in LYGBP. First, a forward problem must be considered. The function of forward problem is to predict an output value (measured) for known attenuation coefficient that requires a sensitivity map for each sensor's projection and a distance being measured. It can be shown by the following equation:

 $[S]^{*}[A] = [M]$ 

(1)

where [S] is the sensitivity matrix based on cross-section for all projections, [A] is the matrix of attenuation coefficients of the object and [M] is the measurement values, which is equal to ln (Iin/Iout), as in Equation (1).

Next, the Layergram method used output measurements [M] to estimate the optical density distribution by obtaining a summation of the measurement output value for each projection in order to produce the expected attenuation coefficient ( $\alpha$ ). The highest pixel value indicates the location of the object.

Figure 4 shows the process flowchart on how to implement the LYGBP algorithm in order to identify the location of the object inside the flow pipe. First, the sensitivity matrix based on the desired size cell and the model of the optical attenuation coefficient ( $\alpha$ ) is determined to

find the measured output value. Next, a nested for-loop is conducted to find a summation of measured output value for each matrix cell to determine the unknown optical attenuation coefficient.



Figure 3. Overlapping two light sources.



Figure 4. Flowchart of LYGBP process.

#### **3.2 Simulation Results**

A solid particle is assumed to have high value of linear attenuation coefficient (which is assumed to be 10 mm-1) and the pipe volume contained air with an attenuation coefficient of 0.00142mm-1<sup>7</sup>. Two projections that are passed through the 3x3 square cells are visualized in Figure 5. The square cell is modelled based on the pixel of CMOS area image sensor. The dimension of the square cell is referring to the pixel size, which is 5.2 micron x 5.2 micron. Based on this configuration, each projection has three optical sensors. Therefore, the total numbers of optical sensors for two projections are six (6), represented by M1-M6. Each cell is labeled as aij where i is the row number whilst j is the column number.

Based on the Beer-Lambert Law, M1 until M6 can be calculated as follows.



Figure 5. Projection arrangement for 3x3 pixels.

Projection 1:

$$M = 0.0052 [\dot{a}_{\emptyset} + \dot{a}_{\theta} + \dot{a}_{\theta}]$$

$$M = 0.0052 [\dot{a}_{\psi} + \dot{a}_{\theta} + \dot{a}_{\theta}]$$
(2)

$$\mathbf{M} = 0.0032 [\mathbf{a}_0 + \mathbf{a}_1 + \mathbf{a}_2] \tag{3}$$

$$\mathbf{M} = 0.0052 [\dot{\mathbf{a}}_{\mathcal{D}} + \dot{\mathbf{a}}_{\mathcal{I}} + \dot{\mathbf{a}}_{\mathcal{I}}] \tag{4}$$

Projection 2:

$$\mathbf{M} = 0.0052 [\dot{a}_{0} + \dot{a}_{0} + \dot{a}_{p}] \tag{5}$$

$$\mathbf{M} = 0.0052 [\dot{a}_0 + \dot{a}_1 + \dot{a}_2] \tag{6}$$

$$\mathbf{M} = 0.0052 [\dot{a}_{a} + \dot{a}_{2} + \dot{a}_{2}] \tag{7}$$

The measured output value from each sensor will sum up by intersection at the respective cell  $\alpha_{ii}$ . For instance:

$$\dot{a}_{0} = M1 + M4 \tag{8}$$

$$\dot{a}_0 = M1 + M5$$
 (9)

$$\alpha_{\mathbf{a}} = \mathbf{M}\mathbf{1} + \mathbf{M}\mathbf{6} \tag{10}$$

$$\alpha_0 = \mathbf{M} + \mathbf{M4} \tag{11}$$

$$\alpha_{1} = M2 + M5 \tag{12}$$

$$\alpha_{\rm p} = \rm M2 + \rm M6 \tag{13}$$

$$\alpha_{\mathfrak{D}} = M3 + M4 \tag{14}$$

$$\alpha_2 = M3 + M5 \tag{15}$$

$$\alpha_2 = M3 + M6 \tag{16}$$

Figure 6 shows the tomogram image of  $3 \times 3$  arrays of pixels that is generated based on the LYGBP method. The actual image of the particle can be seen in Figure 6(a) whereas its reconstructed image is shown in Figure 6(b). The blue color indicated the presence of air whilst the red color represented a solid particle in the middle of the matrix cell. There was an aliasing effect occurred, which denotes by green color because the reconstruction process involved only two projections.



**Figure 6.** Tomogram images of 3x3 pixels. (a) Actual image. (b) Reconstructed image based on LYGBP method.

Modelling on the image reconstruction process for 7x7 pixels and 21x21 pixels are shown in Figure 7 and Figure 8, respectively. The effect of aliasing can be minimized by using a three-dimensional image from the multiple two-dimensional images (tomograms).



**Figure 7.** Tomogram images of 7x7 pixels. (a) Actual image. (b) Reconstructed image based on LYGBP method.



**Figure 8.** Tomogram images of 21x21 pixels. (a) Actual image. (b) Reconstructed image based on LYGBP method.

#### 4. Experimental Results

Concentration measurements were performed using two CMOS area image sensors that were arranged 90 degree from each other to provide the information about the solid particle inside the vertical pipe flows for two projections. The measurements were used for reconstructing area images produced by Visual Basic 6.0 and for generating tomogram images by MATLAB software.

The colorbar on the tomogram images represents the color scalar mapping for the respective data values. It is used to clarify the data values in human understandable notation. The colorbar follows jet color table. Figure 9 shows the level of jet colorbar. The maroon color represents liquid or air (depends on the experiment) and the blue color denotes the existing of the solid particle. It is important to note that these data samplings were done on-line and the reconstruction and analysis are performed off-line. Five different conditions of solid particles in air flows are performed to validate the capability of the developed optical tomography system.

Solid		Ι	liquid

Figure 9. Representative jet colorbar definition.

#### 4.1 Condition 1: Empty Pipe

Figure 10 shows the 2D and 3D reconstructed images of an empty pipe. The results showed that the reconstructed image has all maroon color that indicated the existence of total air in the pipe.





Figure 10. 2D and 3D reconstructed images for an empty pipe.

# 4.2 Condition 2: Pipe Full with Solid Particles

Figure 11 shows the 2D and 3D reconstructed images of a pipe full with solid particles (i.e., nuts). The results showed that the reconstructed image has all blue color, to show that the pipe was full with solid particles.



**Figure 11.** 2D and 3D reconstructed images for a pipe full with solid particles.

#### 4.3 Condition 3: Solid Particles in Air Flow

Figure 12 and Figure 13 show the 2D and 3D reconstructed images of a pipe that was half filled with solid particles. The results showed that the reconstructed image has blue and maroon color, to show that the existence of the particles in the pipe.

#### 4.4 Condition 4: A Thin Wire in the Pipe

Figure 14 shows the 2D and 3D reconstructed images of a thin wire in a pipe. The results showed that the reconstructed image has a blue colored line in the middle of the pipe.



**Figure 12.** 2D and 3D reconstructed images for solid particles in air flow.



**Figure 13.** 2D and 3D reconstructed images for solid particles in air flow.



**Figure 14.** 2D and 3D reconstructed images for a thin wire in air.

#### 4.5 Condition 5: A Solid Bead in the Pipe

Figure 15 shows the 2D and 3D reconstructed images of a solid bean in the pipe. The results showed that the reconstructed image has a blue colored with circular shape in the middle of the pipe.

### 5. Conclusions

The image reconstruction algorithm and program developed for the 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 Backprojection method (LYBP), the reconstructed images for 2D and 3D resembled the actual process occurred in the pipe.





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